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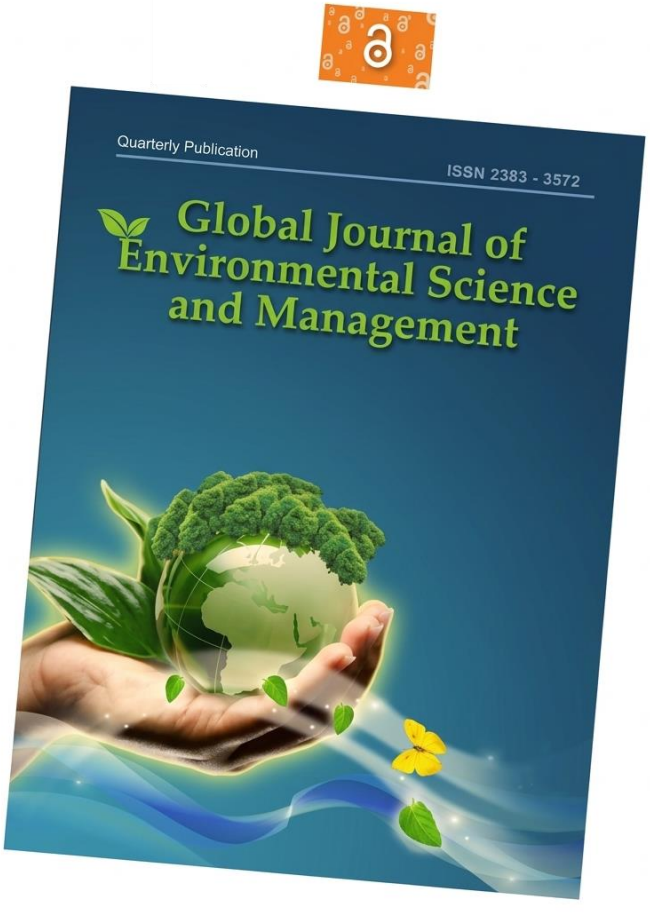

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ORIGINAL RESEARCH PAPER

Enhanced groundwater defluoridation using aluminium loaded *Sesbania grandiflora* activated carbon

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ABSTRACT

BACKGROUND AND OBJECTIVES: Excess fluoride in groundwater threatens public health, especially in rural areas with limited treatment options. Biomass-derived activated carbon provides a sustainable, low-cost solution. This study synthesized aluminium-impregnated Sesbania grandiflora activated carbon to assess fluoride removal effectiveness and adsorption capacity in addition to structural characteristics, co-ion removal, regeneration, and predictive modeling.

METHODS: Aluminium-impregnated Sesbania grandiflora activated carbon was synthesized from locally sourced biomass through chemical activation and aluminium loading. Characterization included Fourier Transform Infrared Spectroscopy (functional groups), Scanning Electron Microscopy (morphology), Energy Dispersive X-ray Spectroscopy (elemental composition), X-ray Diffraction (crystallinity), and Brunauer–Emmett–Teller analysis (surface area and porosity). Regeneration used diluted hydrochloric acid, batch adsorption optimized particle size, dosage, agitation speed, and contact duration, and an Artificial Neural Network in Matrix Laboratory software was used to model predictive performance.

FINDINGS: Fourier Transform Infrared Spectroscopy confirmed hydroxyl, carboxyl, and aluminium-associated groups involved in fluoride surface complexation. Scanning Electron Microscopy showed a porous, heterogeneous surface partially filled after adsorption, while Energy Dispersive X-ray Spectroscopy verified fluoride incorporation and elemental changes. X-ray Diffraction indicated amorphous content increased from 74.8 to 81.1 percent, and Brunauer–Emmett–Teller analysis showed surface area decreased from 780 to 615 square metres per gram, confirming pore occupation. Maximum fluoride removal of 92.6 percent was achieved under optimized conditions corresponding to an adsorption capacity of 0.29 milligrams per gram at 2.5 milligrams per litre initial concentration and 8 grams per litre dosage. The adsorbent also removed specific coexisting ions (calcium, magnesium, iron, nitrate, and total dissolved solids) while maintaining near-neutral water acidity. Regeneration efficiency remained 84.2 percent after five cycles. Predictive performance increased from the linear regression model (R^2 = 0.945) to the nonlinear regression model (R^2 = 0.978), with the Artificial Neural Network model achieving the highest accuracy (R^2 = 0.991) with a training regression coefficient of 0.9948, demonstrating strong capability to capture nonlinear relationships and reliably estimate fluoride removal efficiency.

CONCLUSION: Spectroscopic and microscopic evidence indicate surface complexation–driven adsorption, structural stability, and reusability, and the material provides quantified fluoride and co-ion reduction with reproducible predictive modeling for decentralized groundwater treatment.

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47	10	5

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INTRODUCTION

Fluoride is a naturally occurring element present in water, soil, and rocks, commonly entering groundwater through geogenic processes and anthropogenic activities such as industrial discharge and phosphate fertilizer use (Ahmad *et al.,* 2022). Although low concentrations of fluoride can help prevent dental caries, excessive intake is associated with serious health conditions, including dental and skeletal fluorosis (Dehnen *et al.,* 2021). To prevent these adverse effects, the Bureau of Indian Standards (BIS) recommends a maximum permissible limit of 1.5 milligrams per litre (mg/L) of fluoride in drinking water (Ganyaglo *et al.,* 2019). High fluoride concentrations have been reported across many regions, particularly in arid and semi-arid areas (Ghosh *et al.,* 2022). These cumulative health risks, especially among rural populations reliant on untreated groundwater, reinforce the urgent need for efficient, cost-effective, and sustainable fluoride mitigation strategies (Jadhav *et al.,* 2015). Fluoride's chemical properties, including its strong electronegativity and small ionic radius, make it difficult to remove from aqueous systems (Mishra *et al.,* 2024). Over the years, several treatment methods have been developed, including precipitation, ion exchange, membrane filtration, and adsorption techniques (Rathi *et al.,* 2024). Among these, adsorption is widely preferred due to its simplicity, cost-effectiveness, and suitability for rural and low-resource settings (Reza *et al.,* 2020). Activated carbon (AC), particularly biomass-derived ACs, has proven effective because of its high surface area, porosity, and modifiability (Saeed *et al.,* 2022). Materials like *Sesbania grandiflora* (SG) are abundant and high in carbon, making them ideal for adsorbent production (Skuse *et al.,* 2021). Aluminium modification at an optimized loading concentration of 0.05 molarity (M) enhances fluoride adsorption by increasing active sites and surface reactivity while maintaining structural stability. Advanced characterization techniques such as Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), energy dispersive x-ray (EDX), X-ray diffraction (XRD), and Brunauer–Emmett–Teller (BET) surface area analysis play a crucial role in understanding the adsorbent's structural and surface properties (Wan *et al.,* 2021). In many groundwater sources, fluoride does not occur in isolation. It is often accompanied by other pollutants, especially in areas affected by industrial discharge, such as the textile sector (Yadav and Jagadevan, 2021). These co-contaminants, including organic dyes and heavy metals, require a multi-functional adsorbent capable of removing a range of impurities to meet potable water standards (Selvakumar *et al.,* 2023). Additionally, biomass-derived and modified adsorbents have demonstrated effective groundwater defluoridation, including AC from Catha edulis stems (Fito *et al.,* 2019), calcium-modified dairy manure biochar (Wallace *et al.,* 2020), and unmodified *Sesbania grandiflora* activated carbon (SGAC) integrated with Artificial Neural Network (ANN) modeling (Sivakumar *et al.,* 2025a). However, SGAC has not been investigated with aluminium surface modification combined with systematic process optimization and validated machine learning modeling. The present study addresses this critical knowledge gap by integrating aluminium modification, defined co-ion removal assessment, and predictive ANN modeling, distinguishing it from previous work that only applied unmodified SGAC or ANN modeling without detailed material optimization. Despite these advancements, the prediction and optimization of adsorption processes remain a challenge, as traditional kinetic and isotherm models are often limited to ideal, single-contaminant conditions and fail to capture complex interactions involving multiple operational variables such as dosage, potential of hydrogen (pH), contact time, temperature, and competing ions (Sivakumar *et al.,* 2025b). The nonlinear system dynamics and multivariate

dependencies evident in real-world applications cannot be adequately described by traditional models, which are usually linear or simplistic. ANNs have drawn interest due to the ability to analyze multidimensional, nonlinear datasets and precisely forecast adsorption results across a range of operating conditions (Ergović Ravančić and Habuda-Stanić, 2024). Moreover, existing studies often treat adsorbent synthesis and predictive modeling as independent approaches, limiting comprehensive process optimization. Unmodified SGAC reported 86.3 percent (%) fluoride removal without surface metal modification (Sivakumar *et al.,* 2025a). The present work improves SGAC performance through aluminium impregnation, integrates the modified adsorbent with a validated ANN-based optimization framework, and demonstrates competitive efficiency compared with state-of-the-art biomass-derived adsorbents under groundwater conditions. Accordingly, although aluminium-modified AC and ANN modeling have been previously reported in adsorption studies, this work advances the field by systematically integrating aluminium-impregnated *Sesbania grandiflora* activated carbon (Al-SGAC) synthesis, detailed material characterization, and validated ANN-based predictive modeling for fluoride removal from groundwater. Accordingly, this study aims to investigate i) To synthesize and characterize Al-SGAC and investigate its structural and surface modifications through FTIR, SEM, EDX, XRD, and BET analyses; ii) To optimize key operational parameters such as particle size, adsorbent dosage, agitation speed, and contact time for maximizing fluoride removal efficiency; iii) To evaluate the multi-contaminant removal performance of Al-SGAC and confirm treated water quality against BIS standards; iv) To assess the regeneration potential and reusability of Al-SGAC over multiple adsorption–desorption cycles using mild acid treatment; and v) To develop and validate an ANN model for accurate prediction and optimization of fluoride removal performance. Thus, the contribution lies in performance enhancement and comprehensive process integration rather than in the individual techniques themselves. This study was conducted at Kalasalingam Academy of Research and Education, Tamil Nadu in 2025.

MATERIALS AND METHODS

Al-SGAC preparation

The removal of fluoride from groundwater was studied in this research using Al-SGAC under different process parameters. SG wood was collected from the Theni district, Tamil Nadu, India, which was sun-dried for five days to remove initial moisture content, crushed into dust, and processed with slight modifications based on previous studies (Sivakumar *et al.,* 2014), this study proceeded by carbonizing SGAC wood dust at 600 degrees Celsius (°C) in a muffle furnace for 2 hours (hr). The sawdust was sieved into five different sizes to analyze fluoride removal from groundwater. To modify the AC, 100 grams (g) of SGAC was refluxed with 250 millilitres (mL) of a 0.05 M aluminium chloride ($AlCl_3$) solution at pH 3.5 for 3 hr. The mixture was filtered and allowed to stand at room temperature for 24 hr. It was then washed several times with distilled water to remove excess ions. The Al-doped SGAC was dried at room temperature for 24 hours, stored in a desiccator to eliminate residual moisture, and subsequently used for fluoride removal from groundwater.

Characterization of Al-SGAC

To elucidate the structural, morphological, elemental, crystalline, and surface characteristics of the Al-SGAC, comprehensive physicochemical characterization was performed. Multiple complementary analytical techniques were employed to understand functional groups, surface texture, composition, crystallinity, and porosity that govern adsorption behavior and fluoride removal efficiency.

(i) FTIR: The accessibility of functional groups on the surface of Al-SGAC was determined

by scanning the adsorbent sample using FTIR over a wavelength range of 400–4000 /cm (Yadav *et al.,* 2022). Dry potassium bromide (KBr) was added in a 2:200 milligrams (mg) ratio after the adsorbent had been thoroughly ground.

(ii) SEM: One of the most useful tools for studying and evaluating the morphological and chemical composition properties of microstructures is the SEM (Muchunku *et al.,* 2023b). The prepared AC was examined using a field-emission scanning electron microscope (FE-SEM, ZEISS 200) at an accelerating voltage of 500–2,000 volts (V), with a resolution of 3 nm and magnifications ranging from 250× to 65,000×. SEM images were captured to observe the surface morphology and porosity of the material.

(iii) EDX: The different elements and their relative quantities (atomic %) in a sample are ascertained using the elemental analysis technique known as EDX (Bonyadi *et al.,* 2019). Each element's X-ray spectra, which have a different set of peaks because of their individual atomic structure, were recorded using BRUKER EDX's two-dimensional VANTEC-500 detector at a resolution of 128 channels.

(iv) XRD: XRD is a widely used method for determining a material's crystalline structure and composition. It is especially effective for analyzing the atomic structure of macromolecules and inorganic compounds. Materials with very small crystal sizes can be analyzed by XRD to reveal phase purity, composition, and crystallinity (Tao *et al.,* 2020). The technique involves directing X-ray photons at the sample. The X-ray wavelength, being comparable to the spacing between atoms, enables the detection of diffraction patterns that vary with atomic distances. This study collected XRD data using a D8 ADVANCE ECO instrument with Cu Kα radiation (λ = 1.54060 Å) in a coupled two-theta/theta configuration over a two-theta (θ) range of 0° to 80°.

(v) BET analysis: BET analysis is a standard technique for determining surface area, pore volume, and pore size distribution of porous adsorbents and catalysts by measuring nitrogen adsorption at liquid nitrogen temperature (Muchunku *et al.,* 2023b). It effectively characterizes fine and complex pore structures. As shown in Table 2, SGAC exhibited a lower BET surface area, smaller average pore size, and reduced total pore volume, whereas Al-SGAC showed higher surface area, larger pore size, and greater pore volume before adsorption. BET surface area and pore structure examination verified that SGAC's poor surface features and adsorption capability caused it to be disqualified from future investigation. Instead, further analyses concentrated on Al-SGAC because of its higher textural qualities and fluoride removal effectiveness.

(vi) Zeta Potential and pH_pzc Measurements: The surface charge properties were evaluated to understand adsorption behavior under field-relevant conditions. Zeta potential measurements were performed using a Malvern Zetasizer on particle suspensions in deionized water, focusing on the naturally occurring groundwater pH range of 6.8–7.4. The point of zero charge (pH_pzc) was determined using the pH drift method, where a series of electrolyte solutions with different initial pH values were equilibrated with the material, and the final pH was recorded. The pH at which the zeta potential reached zero was identified as the pH_pzc. These measurements indicate the surface charge behavior under conditions relevant to groundwater fluoride adsorption.

Although X-ray Photoelectron Spectroscopy (XPS) can provide detailed information on the

chemical states of surface elements, it was not performed in this study. The focus was on field-relevant fluoride adsorption under near-neutral groundwater conditions, and the combination of SEM, EDX, zeta potential, and pH_pzc measurements sufficiently characterized the surface properties influencing adsorption.

Study area

Groundwater samples were collected from five locations in Usilampatti, located in Madurai District, Tamil Nadu, India (Latitude: 9.9694° N, Longitude: 77.7862° E), using airtight containers and transported under cooled conditions (Fig. 1). Usilampatti experiences a tropical climate with an average annual temperature of 28.4 °C, reaching 30–31 °C during April to June and dropping to 25–26 °C from November to January. The region receives an average annual rainfall of 839 millimetres (mm). Elevated fluoride levels in groundwater in Usilampatti are primarily attributed to the natural weathering of fluoride-bearing minerals found in the area's hard rock aquifers. Additionally, semi-arid conditions and high groundwater usage in Usilampatti contribute to increased fluoride concentrations, which can pose health risks such as dental and skeletal fluorosis.

Collection of groundwater samples

Groundwater samples were collected from five locations in Usilampatti, Tamil Nadu, India, then transported to the laboratory and stored at 5 °C to preserve their integrity for quality analysis. These five groundwater samples were subsequently used to evaluate fluoride removal efficiency, along with other water quality parameters such as pH, total dissolved solids (TDS), total hardness (TH), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl_2), sulphate (SO_4), nitrate (NO_3), fluoride and iron (Fe) (Sivakumar *et al.,* 2025a). All measurements were conducted in accordance with the standard procedures recommended by the American Public Health Association (APHA, 2017). The average characteristics of groundwater samples collected from five locations in Usilampatti are presented in Table 1. Among all the analyzed parameters, this study primarily focused on fluoride removal, as its concentration ranged between 2 and 3 mg/L across the five sampling sites. The average fluoride concentration (2.5 mg/L) was therefore considered for subsequent experimental investigations to represent regionally relevant groundwater conditions.

Sorption experiments

A Philip Bird jar test apparatus was used to treat 1000 mL of groundwater with Al-SGAC under varying experimental conditions, including particle sizes (0.425, 0.600, 1.180, 2.360, and 4.750 mm), adsorbent dosages (2, 4, 6, 8, and 10 g), stirring speeds (100, 200, 300, 400, and 500 revolutions per minute (rpm)), and contact times (60, 80, 100, 120, and 140 minutes (min)), to remove fluoride and other parameters. Experiments were conducted at room temperature (25 ± 2 °C), which was monitored but not actively controlled, to reflect typical field conditions. The concentration of fluoride, along with other pertinent parameters, was measured in the groundwater both before and after treatment with Al-SGAC, following the standard methodology outlined in APHA (2017). The percentage reduction (percent (%)) of each parameter was calculated using Eq. 1, and the adsorption capacity (q_e) in milligrams per gram (mg/g) of Al-SGAC was calculated using Eq. 2 (Shankar *et al.,* 2014; Durairaj, 2024).

$$\% \text{ removal of each parameter} = \frac{(C_1 - C_2)}{C_1} \text{x } 100 \quad (1)$$

$$\text{Adsorption capacity } q_e = \frac{(C_1 - C_2) \text{ x } V}{m} \quad (2)$$

where C_1 is the concentration (mg/L) of various parameters in the groundwater before treatment, C_2 is the concentration (mg/L) of various parameters after treatment with Al-SGAC, V is the volume of the solution (L) and m is the mass of Al-SGAC (g).

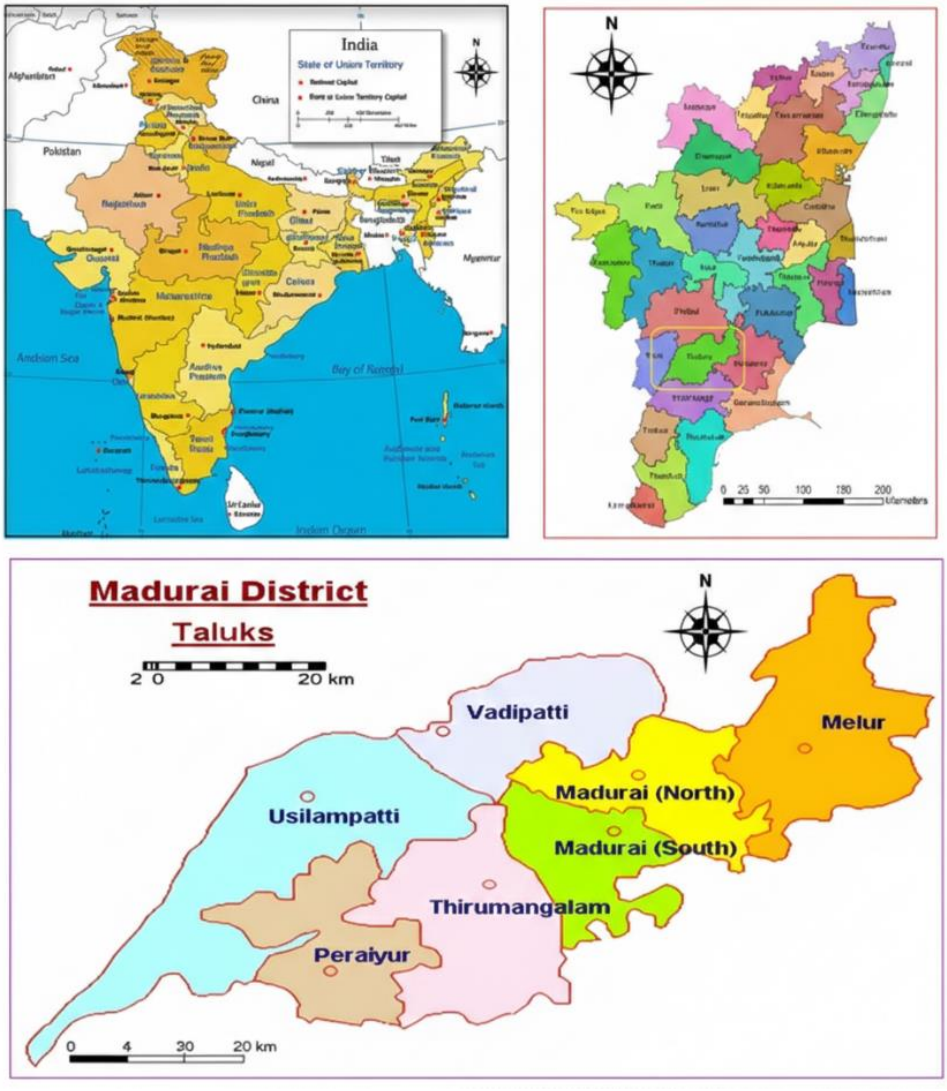

Fig. 1: Geographical location of the study area in Usilampatti, Madurai district, Tamil Nadu, India, showing sampling points and spatial distribution of groundwater sources selected to evaluate regional fluoride contamination and treatment performance.

Table. 1: Characteristics of the groundwater sample collected from Usilampatti

Sl. No.	Parameters	Observed value	BIS (IS 10500:2012)
1	pH	6.92	6.5-8.5
2	TDS, mg/L	285.31	500
3	TH, mg/L	287.61	200
4	Ca, mg/L	126.92	75
5	Mg, mg/L	24.56	30
6	Na, mg/L	125.64	200
7	K, mg/L	9.62	12
8	Cl_2, mg/L	345.21	250
9	SO_4, mg/L	304.56	200
10	NO_3, mg/L	24.21	45
11	Fluoride, mg/L	2.5	1.0
12	Fe, mg/L	0.45	0.3

The study focused on process optimization and predictive modeling under regionally relevant groundwater fluoride concentrations (2–3 mg/L). Experiments were conducted at an average field concentration of 2.5 mg/L and near-neutral pH (6.8–7.4) to replicate realistic groundwater conditions. Consequently, the multiple initial concentrations required for detailed Langmuir adsorption isotherm and Freundlich adsorption isotherm analyses, along with pseudo-first-order and pseudo-second-order kinetic modeling, were not examined. As experiments were performed at ambient groundwater temperature, temperature-dependent studies necessary to determine thermodynamic parameters (Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°)) were beyond the scope. Adsorption efficacy was confirmed by physicochemical characterisation, regeneration analysis, and ANN-based predictive evaluation, while future research will include controlled temperature fluctuation to investigate thermodynamic feasibility and adsorption mechanisms.

ANN model

ANNs emulate biological neural systems to solve complex problems through pattern recognition. Unlike traditional rule-based models, ANNs employ parallel processing and adaptive learning without fixed procedural constraints. A dataset of 625 runs was generated using a full factorial design with four parameters, namely particle size, adsorbent dosage, agitation speed, and contact time, each at five levels (5×5×5×5). Experimental and interpolated data were combined for training and validation to enhance predictive accuracy while minimizing physical experiments. Inputs were normalized to a 0 to 1 range using min–max scaling, and missing values were addressed through interpolation. The dataset was divided into training (70%), validation (15%), and testing (15%) subsets, and multiple network structures with 7 to 10 hidden neurons were evaluated to prevent overfitting. Early stopping based on validation error was employed, and the final optimized model was trained through sufficient epochs until convergence, ensuring reliable and generalizable predictions. The overall architecture of the ANN model (Addar *et al.,* 2023) is presented in Fig. 2. A standard ANN architecture consists of an input layer, one or more hidden layers, and an output layer, where data from the input layer is processed through the hidden layers and the results are transmitted to the external system via the output layer. The hidden layers comprise several nodes or neurons, and the number of these nodes can be determined using Eq. 3 (Liu *et al.,* 2022):

$$H = 2(\sqrt{(I+1)}) \quad (3)$$

where *I* represents the number of neurons in the input layer. Furthermore, as noted by an ANN is characterized by three fundamental parameters: the activation function, the updating of interconnection weights, and node-to-node connectivity. These interconnections are associated with both weights and biases. While biases represent numerical shifts, weights reflect the strength of input signals. The weights and transfer functions, such as linear, threshold, and sigmoid, play a critical role in determining the output of an ANN. Among various transfer functions, TANSIG is a widely used one and is mathematically represented in Eq. 4 (Liu *et al.,* 2022):

$$f(x) = \frac{1}{1+exp\,(x)} \quad (4)$$

The ANN workflow involves three main stages: training, testing, and validation. During the training phase, the input layer handles sample data and forwards it through the network for learning. Throughout this process, the weights are continuously updated to achieve the desired target outputs. Various training functions, specifically designed to minimize the difference between the predicted and actual results measured as Mean Squared Error (MSE), are employed. The MSE is defined mathematically in Eq. 5 (Reddy *et al.,* 2023):

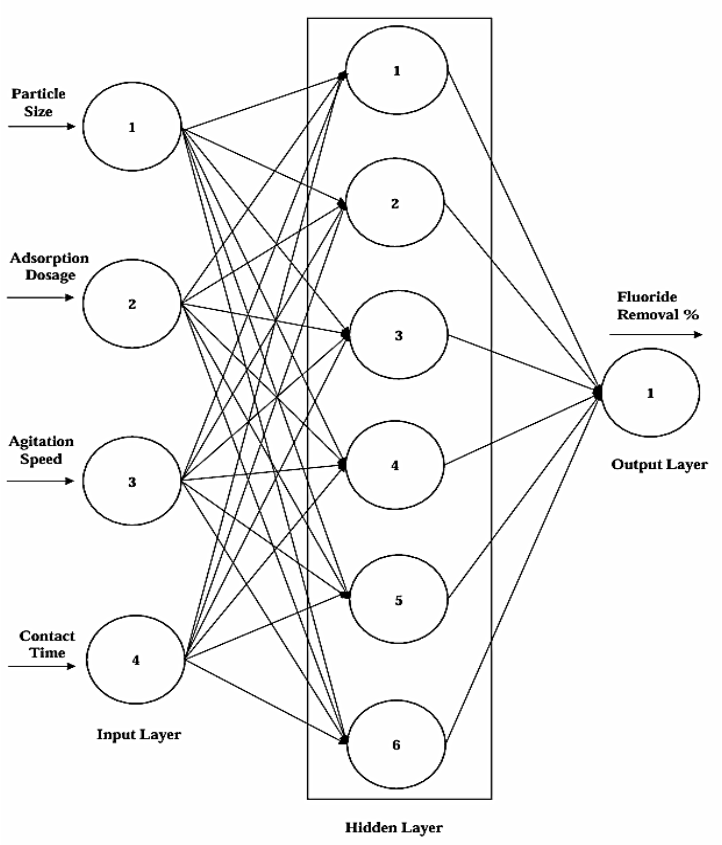

Fig. 2: ANN modeling framework showing input variables (adsorbent dose, contact time, particle size, and agitation speed), hidden layers, and output prediction of fluoride removal efficiency, employed to identify optimal treatment conditions and validate process reliability.

$$MSE = \frac{1}{m}\sum_{i=1}^{m}\left(y_p - y_a\right)^2 \quad (5)$$

where y_a and y_p are the actual and anticipated output values, and m is a variable. The last step analyses several datasets to validate the proposed ANN model.

Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software (version 28). Data are presented as the mean of three independent experiments, each performed in triplicate, and precision was assessed through error analysis. Model performance was evaluated using the coefficient of determination (R^2), MSE, root mean squared error (RMSE), and mean absolute error (MAE) to quantify accuracy and deviation. Cross-validation R^2 assessed robustness on unseen data, while the chi-square (χ^2) goodness of fit test confirmed agreement between experimental and predicted results (Sivakumar *et al.,* 2025b). Together, these statistical and computational approaches provide a rigorous and reliable framework for model validation, performance comparison, and trend interpretation.

RESULTS AND DISCUSSION

Characterization of Al-SGAC

FTIR analysis

Functional groups of Al-SGAC were characterized by FTIR, and the spectra before and after fluoride adsorption are presented in Figs. 3(a) and 3(b) over 400–4000/cm.

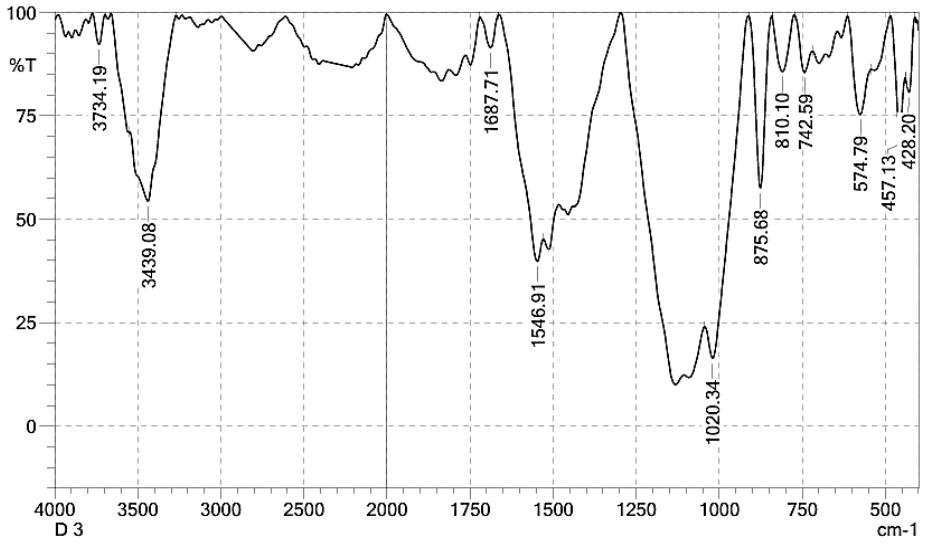

Fig. 3(a)

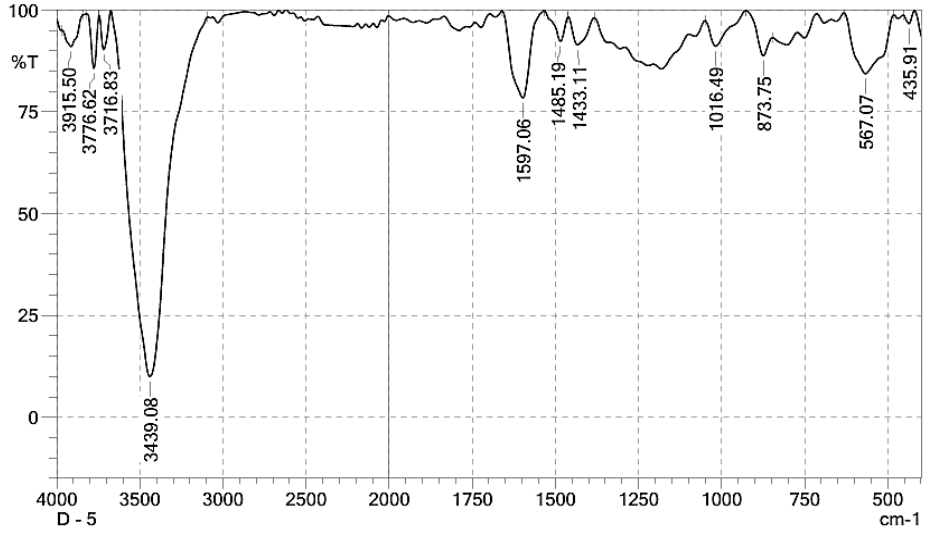

Fig. 3(b)

Fig. 3: FTIR spectra of Al-SGAC (a) before and (b) after fluoride treatment, showing shifts and intensity changes in hydroxyl and oxygenated functional groups that indicate their involvement in surface binding and confirm fluoride adsorption.

Before treatment (Fig. 3(a)), key bands appeared at 3439.08/cm (O–H stretch of alcohols and phenols), 1687.71/cm (C=O), 1546.91/cm (N–O), 1020.34/cm (C–O/C–N), 875.68/cm, 810.10/cm, 742.59/cm, and 574.74/cm (=C–H, N–H, C–Cl, C–Br), with additional peaks at 1634/cm (C=C) and 1423/cm (–CH_2). After adsorption (Fig. 3(b)), reduced intensities and shifted peaks at 3439.08/cm, 1485.19/cm, 1433.11/cm, 1016.49/cm, 873.75/cm, 597.06/cm, and 567.07/cm may be due to interactions of fluoride with –OH, C–O, and aromatic groups, possibly forming ≡Al–F bonds influenced by fluoride's high electronegativity and hydration. Similar involvement of functional groups was reported for bamboo carbon (BC), with 67.33% C and

32.67% O, activated bamboo carbon (ABC), with 68.42% C and 31.58% O, and magnetite bamboo activated carbon (MBAC), with 75.01% Fe, 21.56% O, and 3.43% C, where these surface functionalities enhanced fluoride adsorption (Bagbi *et al.,* 2024), while comparable peak shifts were also observed for Ca-treated biochar (Yadav *et al.,* 2022). These spectral shifts and intensity reductions conclusively confirm the active participation of surface functional groups and the successful adsorption of fluoride onto Al-SGAC.

SEM analysis

The surface morphology of the AC was examined by SEM before and after fluoride removal using Al-SGAC, as shown in Fig. 4(a) and Fig. 4(b). Before treatment (Fig. 4(a)), the material exhibited a highly porous structure with well-developed pore networks, where grey regions represented the carbon matrix and dark areas indicated high porosity. After treatment (Fig. 4(b)), reduced dark regions and smaller pores confirmed pore coverage and fluoride deposition, along with the appearance of finer microparticles resulting from interactions with surface functional groups. Similar SEM-based surface alterations were observed for Aluminium Hydroxide–Coated Activated Carbon (AHAC) during fluoride adsorption, reported by Amalraj and Pius (2017), while Muchunku *et al.,* (2023a) reported rough, heterogeneous pores and honeycomb-like cavities favorable for adsorption in water hyacinth activated carbon (WHAC), and enhanced adsorption performance was also associated with porous, irregular morphologies as described by Jayarathna *et al.* (2015). These distinct morphological transformations, including pore blockage, particle deposition, and reduced porosity, conclusively confirm the successful adsorption of fluoride onto the Al-SGAC surface.

EDX analysis

Fig. 5(a) and Fig. 5(b) present the EDX spectra of Al-SGAC before and after fluoride exposure. In Fig. 5(a), untreated Al-SGAC shows 80.3% carbon and 14.8% oxygen, which changes to 76.9% carbon and 19.3% oxygen after treatment in Fig. 5(b), indicating the formation of oxygenated groups that enhance fluoride adsorption. Na decreases from 2.0% to 0.6% and Mg from 0.7% to 0.5%, suggesting ion exchange, while P appears at 0.4%. K increases from 0.3% to 0.9% and Ca from 0.6% to 1.4%, implying participation in fluoride capture. The observed surface compositional changes, with Al remaining constant at 0.3%, F appearing at 0.6%, and Si (0.3%) and Cl (0.7%) disappearing, indicate fluoride presence consistent with adsorption while confirming structural stability, even though EDX alone cannot definitively confirm ion exchange or chemical bonding. Similar EDX confirmations were reported for BC (67.33% C, 32.67% O), ABC (68.42% C, 31.58% O), and magnetite-grafted MABC (75.01% Fe, 21.56% O, 3.43% C) (Bagbi *et al.,* 2024), AHAC showing fluoride and aluminium peaks (Bonyadi *et al.,* 2019), and populus alba activated carbon (PAAC) (87.42% C, 12.52% O) with fluoride interaction (Tao *et al.,* 2020). These compositional variations, particularly the emergence of fluorine and associated shifts attributed to ion exchange and surface complexation, confirm fluoride adsorption onto Al-SGAC.

XRD analysis

XRD analysis of Al-SGAC before and after fluoride removal from groundwater shows a predominantly amorphous structure that enhances adsorption by increasing surface area and active sites. As shown in Fig. 6(a), the untreated material exhibited 25.2% crystalline and 74.8% amorphous phases, calculated from the ratio of crystalline peak area (25.2 units) to total diffraction intensity (100 units), with peaks at 2θ = 24.839°, 29.071°, 31.539°, 32.877°, and 33.613°. After adsorption in Fig. 6(b), the crystalline fraction decreased to 18.9% (18.9/100 units), and the amorphous phase increased to 81.1%, with shifted peaks at 29.096°, 31.455°, 33.583°, 45.189°, and 74.750°.

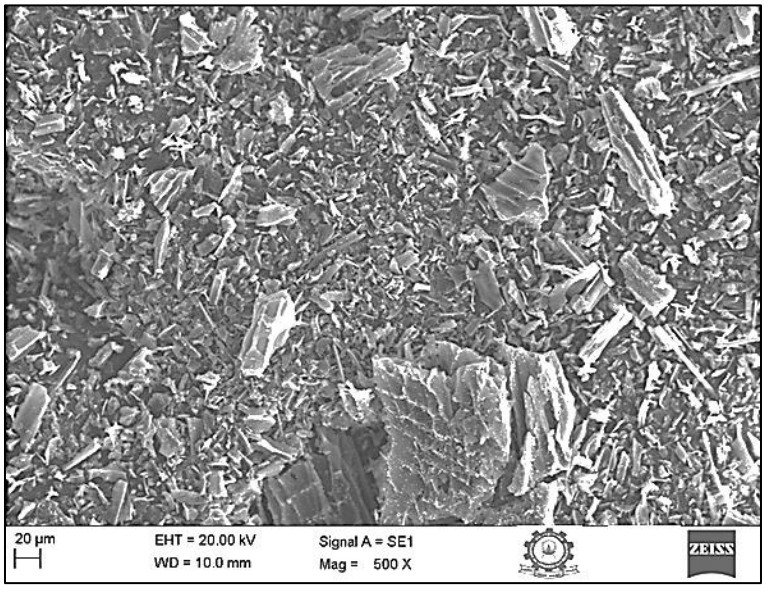

Fig. 4(a)

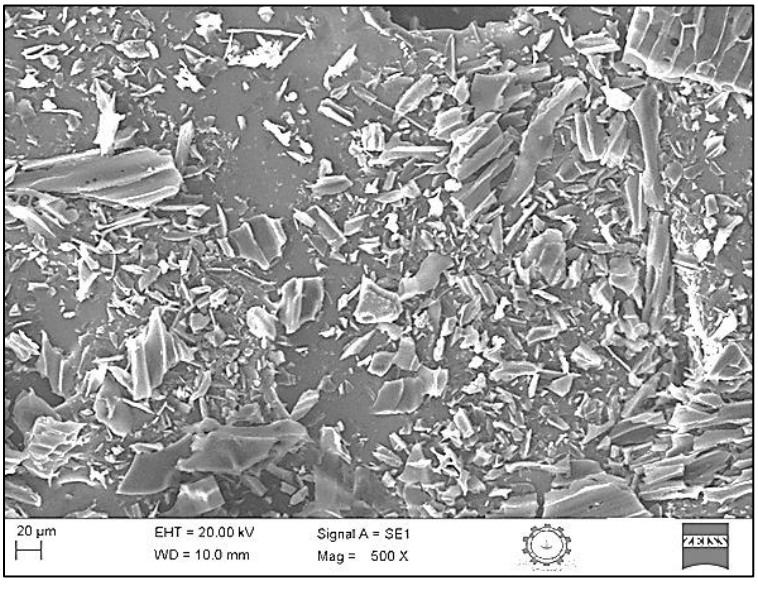

Fig. 4(b)

Fig. 4: SEM micrographs of Al-SGAC (a) before and (b) after fluoride treatment, showing a porous structure with subsequent pore coverage and particle deposition that confirm surface occupation and adsorption.

This structural transformation toward greater amorphous character enhances surface accessibility and active site density, thereby improving fluoride uptake. Similar adsorption enhancements due to increased amorphous character have been reported for oxalic acid-treated Ce-AlOOH (Jayarathna *et al.,* 2021), low pH-synthesized AlOOH for fluoride removal

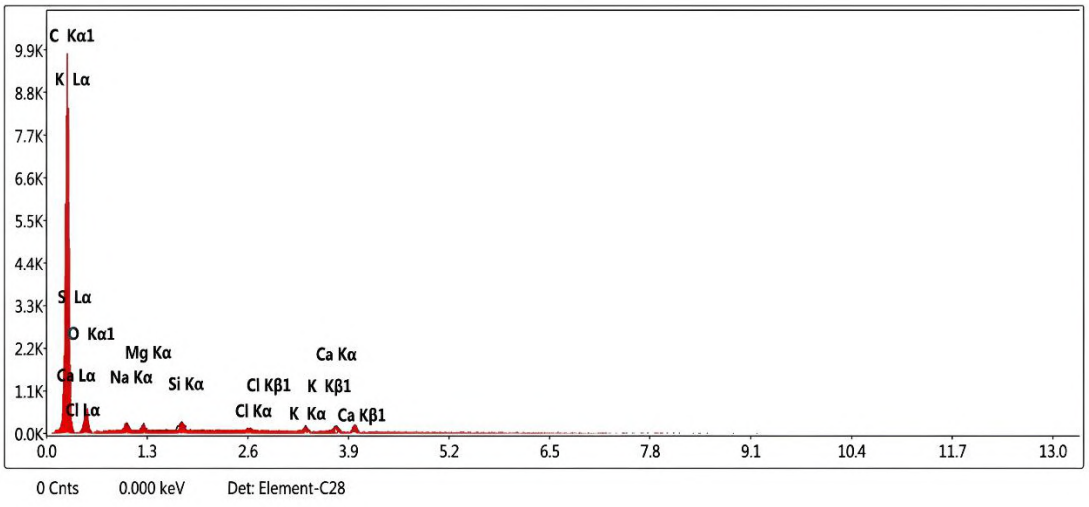

Fig. 5(a)

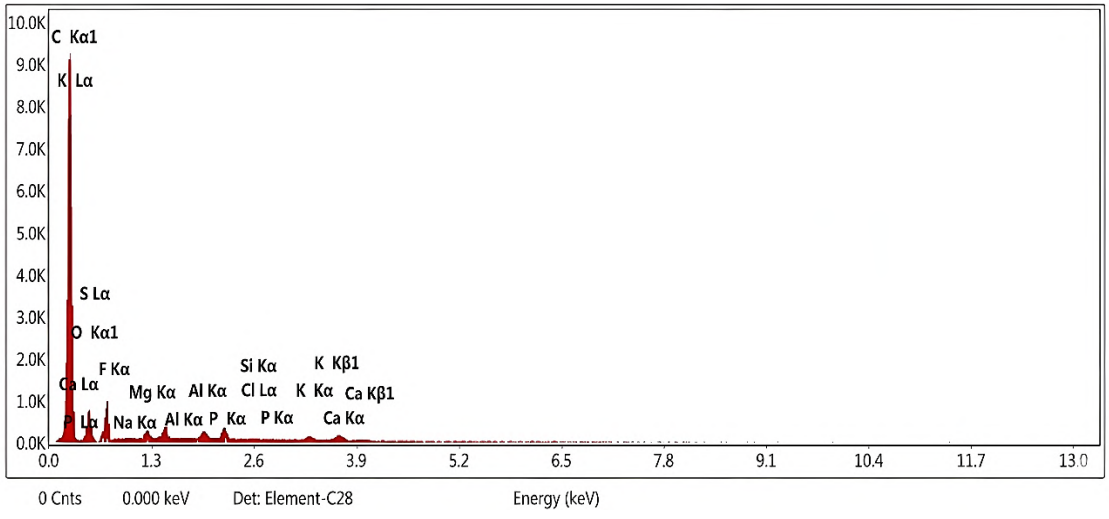

Fig. 5(b)

Fig. 5: EDX spectra of Al-SGAC (a) before and (b) after fluoride treatment, showing elemental shifts and fluoride appearance that indicate ion exchange, surface complexation, and successful adsorption.

(Bibi *et al.,* 2015), and natural clay/Fe_3O_4/graphene oxide composites with improved surface area and reactivity (Muchunku *et al.,* 2023b). In this study, crystallinity decreased from 25.2% to 18.9%, while amorphous content increased from 74.8% to 81.1%, confirming structural modifications that facilitate and verify successful fluoride adsorption onto Al-SGAC.

BET analysis

The surface and structural characteristics of Al-SGAC were evaluated by BET analysis to assess fluoride removal efficiency, and the results are presented in Table 2. From Table 2, the BET surface area decreased from 780 to 615 square metres per gram (m^2/g), average pore size from 2.8 to 2.3 nanometres (nm), and pore volume

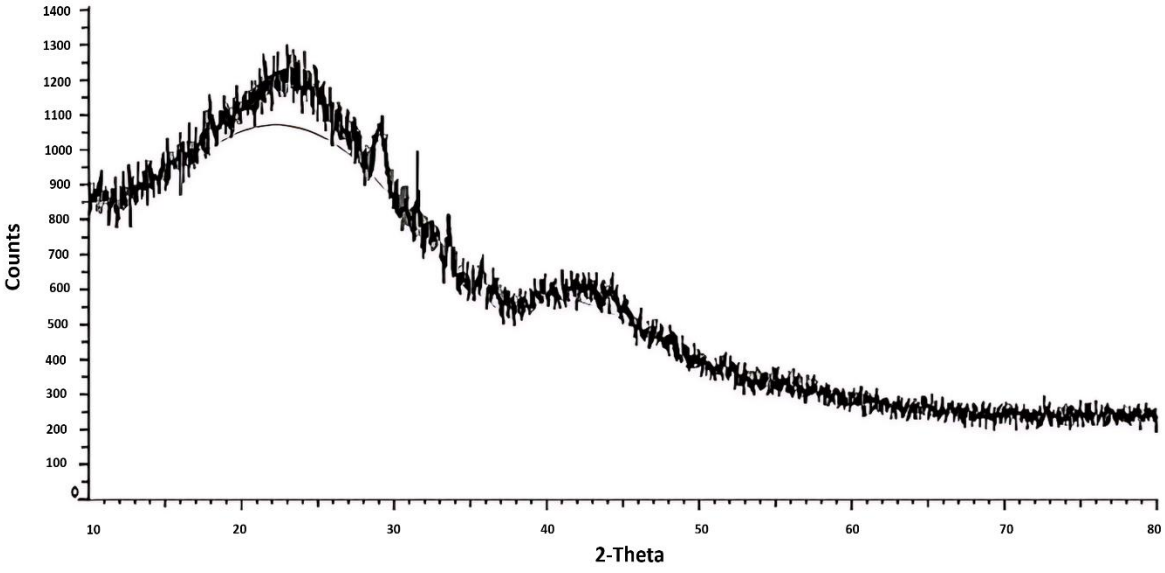

Fig. 6(a)

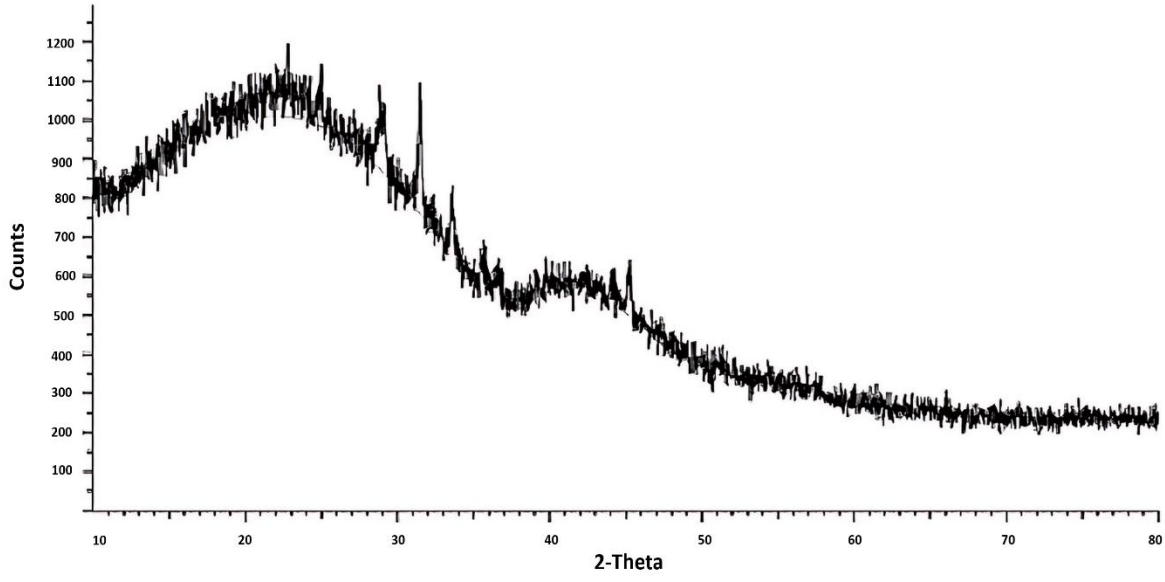

Fig. 6(b)

Fig. 6: XRD patterns of Al-SGAC (a) before and (b) after fluoride treatment, showing reduced crystallinity and increased amorphous character that enhance surface activity and confirm fluoride adsorption.

from 0.49 to 0.39 cubic centimetres per gram (cm^3/g) after adsorption, indicating fluoride occupation and partial pore blocking within internal pores. Aluminium doping generated positively charged sites that enhanced electrostatic attraction, while –OH, –COOH, and Al–OH groups facilitated ligand exchange, as confirmed by FTIR and SEM analyses, resulting in superior fluoride adsorption performance of Al-SGAC compared to activated alumina that exhibits

Table 2: BET surface characteristics of Al-SGAC

Sample condition	BET surface area (m^2/g)	Average pore size (nm)	Total pore volume (cm^3/g)
Before fluoride adsorption	780	2.8	0.49
After fluoride adsorption	615	2.3	0.39

chemisorption but limited capacity under certain conditions (Muchunku *et al.,* 2023b), magnetite–chitosan composites lose efficiency above pH 7 (Amalraj and Pius, 2017), and γ-Fe_2O_3 nanoparticles have a low surface area of 56 m^2/g, which restricts the availability of active sites (Bibi *et al.,* 2015). Al-SGAC maintains a high surface area, broad pH stability, and strong fluoride uptake, making it a robust and cost-effective adsorbent suitable for practical water treatment applications. From Figs. 3 to 6 and Table 2, Al-SGAC exhibits strong fluoride removal efficiency and structural stability. FTIR spectra (Fig. 3) show shifts in –OH, –COOH, and Al–OH groups, indicating chemical interaction with fluoride. SEM images (Fig. 4) reveal reduced pore size post-adsorption, supporting fluoride binding. EDX spectra (Fig. 5) confirm fluoride uptake and ion exchange. XRD patterns (Fig. 6) show increased amorphous content (from 74.8% to 81.1%), enhancing active sites. BET results (Table 2) indicate decreased surface area (780 to 615 m^2/g), pore size (2.8 to 2.3 nm), and pore volume (0.49 to 0.39 cm^3/g), confirming fluoride adsorption. Aluminium doping created positively charged sites that enhanced electrostatic attraction, while –OH, –COOH, and Al–OH groups enabled ligand exchange, supported by FTIR and SEM analyses.

Zeta Potential and pH_pzc Measurements

In this study, Al-SGAC was evaluated for enhanced groundwater defluoridation. The material's surface properties were characterized using SEM and EDX, confirming its morphology and elemental composition. Zeta potential and pH_pzc measurements were performed to assess surface charge behavior under environmentally relevant conditions. The investigation focused on naturally occurring near-neutral groundwater pH (6.8–7.4) to reflect field applicability. As shown in Fig. 7, the zeta potential remained positive in the near-neutral pH range, with a pH_pzc of approximately 7.1, providing direct experimental evidence for the proposed adsorption mechanism rather than relying solely on schematic representation. This confirms that the surface is favorably charged for fluoride adsorption under natural groundwater conditions. Although XPS can provide comprehensive information on the surface chemical state, it was not used because the study concentrated on field-relevant performance, and SEM/EDX with zeta potential and pH_pzc analysis adequately characterized the surface properties governing fluoride removal, confirming practical adsorption effectiveness.

Adsorption study of SGAC

The fluoride adsorption study using Al-SGAC was conducted under controlled laboratory conditions. Various experimental parameters, including particle size, adsorbent dosage, agitation speed, and contact time, were systematically varied to evaluate the effectiveness of Al-SGAC in reducing fluoride concentrations in groundwater.

Effect of particle sizes

Fig. 8(a) presents the effect of particle size on the fluoride removal efficiency of Al-SGAC. The experiment was conducted using particle sizes of 0.425, 0.600, 1.180, 2.360, and 4.750 mm. A jar test apparatus was employed with 2 g of adsorbent, an agitation speed of 100 rpm, and a contact time of 60 min. smaller particle sizes showed relatively low fluoride removal efficiency,

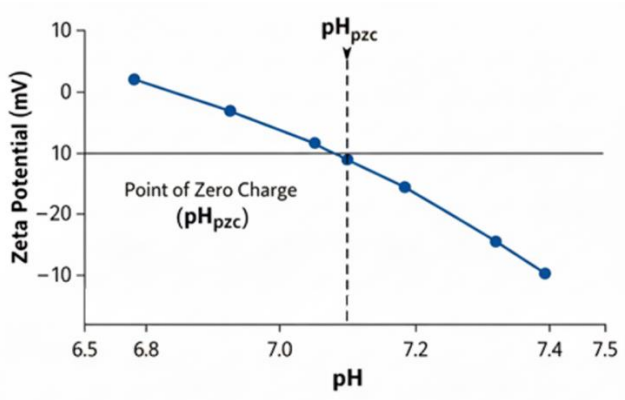

Fig. 7: Zeta potential–pH profile of Al-SGAC identifying the pH_pzc and illustrating the transition between positively and negatively charged surfaces, which influences fluoride attraction and adsorption behavior in neutral groundwater.

whereas larger particle sizes led to improved adsorption performance. Particle sizes of 2.360 and 4.750 mm achieved fluoride removal efficiencies of 70.8% and 71%, respectively, showing a negligible difference. The 2.360 mm size was selected as optimal due to its high efficiency and lower material requirement. Larger particles generally reduce adsorption due to lower surface area and slower diffusion, but the comparable efficiencies suggest that effective surface functional groups and adequate contact time minimized diffusion limitations, making 2.360 mm the most efficient and economical choice for practical fluoride removal.

Effect of dosages

Fig. 8(b) illustrates the effect of adsorbent dosage on fluoride removal efficiency using Al-SGAC, tested at dosages of 2, 4, 6, 8, and 10 g under controlled conditions: optimal particle size of 2.360 mm (Fig. 8(a)), agitation speed of 100 rpm, zero dilution ratio to preserve the native chemical composition and ionic strength of the groundwater (ensuring that adsorption performance reflects real-world conditions), and a contact time of 60 min. Fluoride removal increased with dosage, reaching 81.9% at 10 g; however, the marginal difference from 8 g (81.7%) indicated that 8 g was sufficient for maximum efficiency. Thus, 8 g was selected as the optimal and more resource-efficient dosage for Al-SGAC. In comparison, previous studies reported dosages of 1.0 to 2.0 grams per litre (g/L), achieving up to 95.2% removal at 1.5 g/L (Sivakumar *et al.,* 2025b) and 95.0% at 1.0 g/L (Bibi *et al.,* 2015). These studies show that even lower dosages can achieve high efficiency, suggesting that factors such as adsorbent surface characteristics and affinity for fluoride play a significant role in removal performance, while in this study, 8 g proved to be the most effective for Al-SGAC, offering a balance of maximum efficiency and resource economy and making it the optimal choice compared to the lower dosages used in other studies.

Effect of agitation speeds

Fig. 8(c) illustrates the effect of agitation speed on fluoride removal using Al-SGAC, evaluated at speeds of 100, 200, 300, 400, and 500 rpm under controlled conditions, including an optimal particle size of 2.360 mm (Fig. 8(a)), dosage of 8 g (Fig. 8(b)), and 60 min contact time. Fluoride removal efficiency increased with agitation speed, peaking at 86.4% at 300 rpm. Higher speeds of 400 rpm and 500 rpm led to a decrease in efficiency, with values of 82.3% and 78.4%, respectively (Fig. 8(c)). This decline indicates that excessive agitation reduces effective contact between fluoride ions and the adsorbent; thus, 300 rpm was optimal for maximum removal. Previous studies commonly used agitation speeds of 200–250 rpm, with higher speeds, such

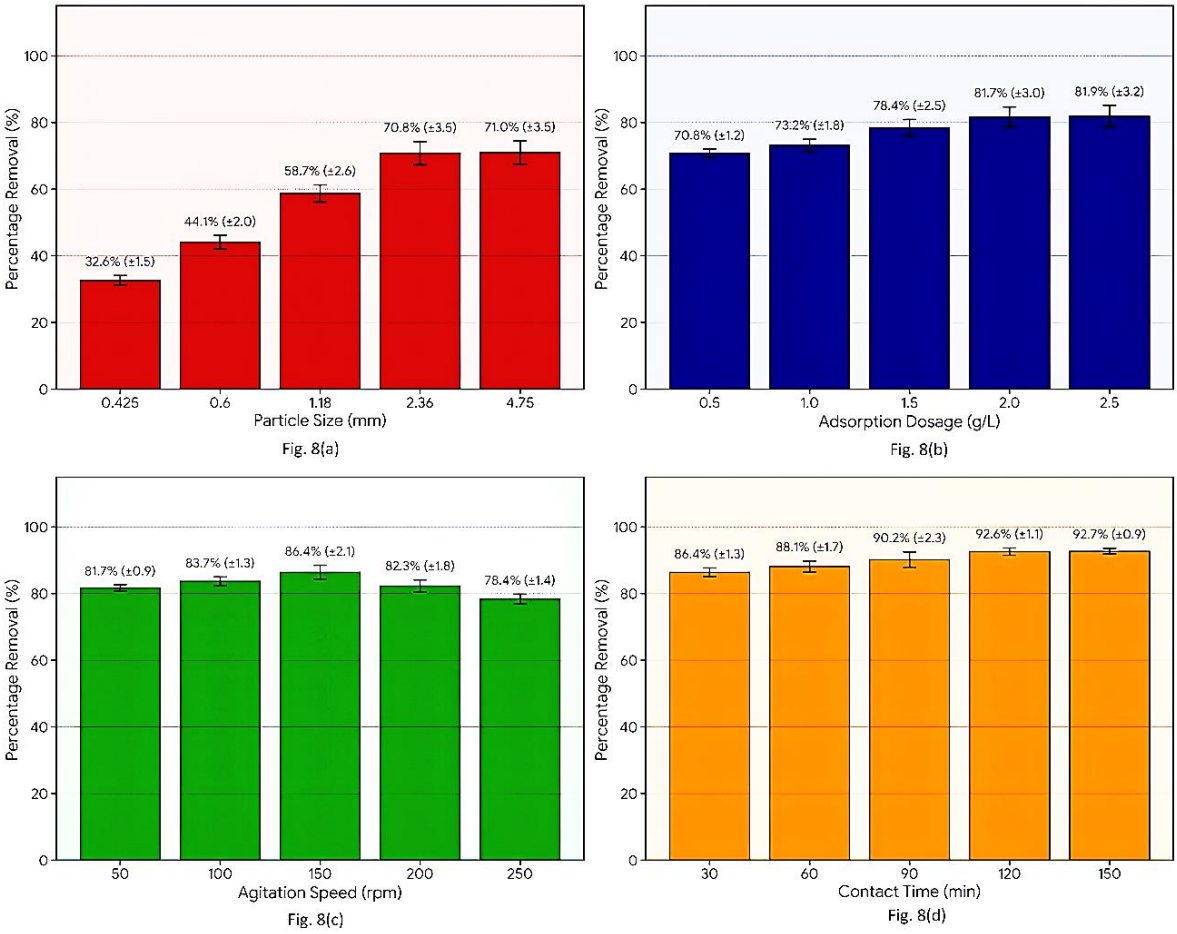

Fig. 8: Parametric evaluation of fluoride removal by Al-SGAC showing the response of adsorption efficiency to variations in (a) particle sizes, (b) adsorption dosages, (c) agitation speeds and (d) contact times, used to determine optimized treatment.

as 250 rpm, proving effective in some cases (Yadav *et al.,* 2022; Tao *et al.,* 2020), efficient removal was also achieved at lower speeds of 200–220 rpm (Sivakumar *et al.,* 2025b; Muchunku *et al.,* 2023b; Liu *et al.,* 2022). This confirms that moderate agitation (300 rpm) provides an optimal balance between effective mixing and adsorbent–fluoride contact, while higher speeds offer minimal improvement and may cause operational inefficiencies.

Effect of contact times

Fig. 8(d) illustrates the influence of contact time on fluoride removal efficiency using Al-SGAC, evaluated under controlled conditions: particle size 2.360 mm (Fig. 8(a)), dosage 8 g (Fig. 8(b)), and agitation speed 300 rpm (Fig. 8(c)). Fluoride removal increased with contact time, reaching 92.6% at 120 min, after which no significant improvement was observed, indicating equilibrium. Shorter times (<120 min) resulted in lower removal due to limited diffusion to active sites. Although 120 min is longer than many reported systems, it reflects the slower kinetics of Al-SGAC under the tested conditions while still achieving high efficiency. Thus, 120 min was optimal, balancing performance and practicality. Previous studies reported optimal contact times of 15 to 90 min, with up to 95.0% removal achieved at 15 min (Bibi *et al.,* 2015) and 95.2% at 60 min.

Although shorter contact times can achieve high removal due to faster kinetics, the 120 min contact time in this study provided the most stable and consistent performance for Al-SGAC, indicating its optimal duration for fluoride removal. The adsorption study is shown in Fig. 8(a) to Fig. 8(d) confirms the high efficiency of Al-SGAC under optimized conditions. A particle size of 2.360 mm, dosage of 8 g/L, agitation speed of 300 rpm, and contact time of 120 min achieved 92.6% fluoride removal, reducing concentration from 2.5 mg/L to 0.185 mg/L. The high removal efficiency, influenced by the relatively high dosage (8 g/L) that increased available active sites, was optimized for realistic groundwater conditions rather than to overstate intrinsic capacity. Under these conditions, the adsorption capacity was 0.29 mg/g, limited by the low initial concentration (2 to 3 mg/L). Higher capacities of 3.5 to 4.8 mg/g reported in literature are typically obtained at 10 to 50 mg/L, indicating this study prioritizes realistic removal efficiency over inflated capacity values. Previous studies recorded fluoride removal between 87.9% and 95.2%, with capacities from 3.5 to 4.8 mg/g (Muchunku *et al.,* 2023b; Tao *et al.,* 2020; Liu *et al.,* 2022; Bagbi *et al.,* 2014; Gai *et al.,* 2021; Bonyadi *et al.,* 2019), of which the highest value reported was 4.8 mg/g (Sivakumar *et al.,* 2014). Al-SGAC shows consistent performance under real groundwater conditions and lower initial fluoride levels. Its mesoporous structure, high surface area, and aluminium-induced surface reactivity contribute to the strong binding of fluoride ions (Gai *et al.,* 2021). The use of SG, a locally available and underutilized biomass, enhances novelty and sustainability, while Al-SGAC enables co-ions removal and demonstrates adsorption efficiency comparable to advanced adsorbents, highlighting its strong potential for practical fluoride remediation (Esmaeili and Tamjidi, 2020; Bibi *et al.,* 2015).

Comparative evaluation of the present study with previous studies

The present study demonstrates the high efficiency of Al-SGAC in removing fluoride from groundwater, outperforming many other ACs reported in earlier research. Al-SGAC is distinctive in multiple aspects, including process optimization, experimental conditions, and fluoride removal efficiency. The effectiveness of several ACs in eliminating fluoride from water is summarized in Table 3. MBAC achieved a remarkable 99.6% removal efficiency, significantly higher than conventional bamboo activated carbon (BAC), which showed 75.9%, with a kinetic capacity of 95.96 mg/g (Bagbi *et al.,* 2024). Similarly, Catha edulis-derived activated carbon (CAC) exhibited a 73% removal efficiency with an adsorption capacity of 18 mg/g in aqueous fluoride solutions (Fito *et al.,* 2019). SGAC effectively reduced fluoride concentration in groundwater from 4.50 mg/L to 0.62 mg/L (86.3% removal), with adsorption performance validated through ANN modeling (R^2 = 0.9523) (Sivakumar *et al.,* 2025a). Furthermore, WHAC achieved 82.6% removal from groundwater with a 120 min contact time (Muchunku *et al.,* 2023a), while MBAC reached 99% removal under highly acidic conditions (pH 2) in only 50 min (Bagbi *et al.,* 2024). AHAC removed 26.03 mg/g in drinking water (Amalraj and Pius, 2017), and PAAC removed 93.37% from wastewater in 100 min (Bonyadi *et al.,* 2019). Other adsorbents such as Pinus sawdust modified with $AlCl_3$ (PS-$AlCl_3$, 53.76%) (Vázquez-Guerrero *et al.,* 2016), Indian Sandalwood Leaf Powder (ISLP, 75%) (Khound, and Bharali, 2018), Oak Activated Carbon (OAC, 97.4%) (Takmil *et al.,* 2020), and Palm Shell Activated Carbon (PSAC, 55%) (Issabayeva *et al.,* 2021) either exhibited lower efficiency or required extreme conditions, whereas Canola Stalk Activated Carbon (CSAC, 100%) (Kyzas *et al.,* 2022) performed excellently but only under highly controlled scenarios.

Operational optimization and contact time analysis

Al-SGAC achieved 92.6% fluoride removal from groundwater at an initial concentration of 2.5 mg/L under realistic conditions (pH 6.5 to 7.0), using a contact time of 120 min, particle size of

Table 3: Comparison of fluoride removal by different AC

S.No.	AC	Types of water	Botanical Name	Common / local name	Removal % / (mg/g)	Characterisation	Duration	Sources
1	MBAC BAC	Water	*Bambusoideae*	Bamboo	99.6% (MBAC), 75.9% (BAC)	0.01–0.04 g/L, 25–45 °C, 2–40 mg/L fluoride	60 min	Bagbi *et al.*, 2024
2	CAC	Aqueous solution	*Catha edulis*	Khat	73%	0.5–1.5 g/100 mL, 30 mg/L fluoride	120 min	Fito *et al.*, 2019
3	SGAC	Groundwater	*Sesbania grandiflora*	Agathi	86.3%	8 g/L, 4.50 mg/L fluoride	120 min	Sivakumar *et al.*, 2025a
4	WHAC	Groundwater	*Pontederia crassipes*	Water Hyacinth	82.6%	1.2 g, pH = 3, 6.7 mg/L fluoride	120 min	Muchunku *et al.*, 2023a
5	MBAC	Water	*Bambusa vulgaris*	Common Bamboo	99.0%	0.02 g/L, 35°C	50 min	Bagbi *et al.*, 2024
6	AHAC	Drinking water	*Morinda tinctoria*	Indian Mulberry	26.03 mg/g	0.1 g, 2 mg/L fluoride, pH = 7, 303 K	60 min	Amalraj and Pius, 2017
7	PAAC	Wastewater	*Populus alba*	White Poplar	93.37%	4 g/L, 10 mg/L fluoride, pH = 6	100 min	Bagbi *et al.*, 2024
8	PS-$AlCl_3$	Real natural water	*Pinus*	Pine	53.76%	0.5 g/L fluoride, pH = 6, 100 rpm, 25°C	120 min	Vázquez-Guerrero *et al.*, 2016
9	ISLP	Water	*Santalum album*	Indian Sandalwood	75.0%	3.0 g/L fluoride, pH = 7, 303 K	120 min	Khound and Bharali, 2018
10	OAC	Synthetic wastewater	*Quercus alba*	White Oak	97.4%	1.5 g/L, pH = 3, 40°C, 20 mg/L fluoride	25 min	Takmil *et al.*, 2020
11	PSAC	Wastewater	*Arecaceae*	Palm	55.0%	5 g, pH = 7, 20 mg/L fluoride	120 min	Issabayeva *et al.*, 2021
12	CSAC	Water	*Brassica napus*	Rapeseed	100%	0.6 g/L, pH = 5, 10 mg/L fluoride, 30°C	60 min	Kyzas *et al.*, 2022
13	Al-SGAC	Groundwater	*Sesbania grandiflora*	Agathi	92.6%	8 g, 2.5 mg/L fluoride, 300 rpm, 2.36 mm	120 min	Current study

Note: Data were directly collected from the cited articles; comparisons are illustrative only and not strictly valid due to differences in pH, initial fluoride concentration, adsorbent dosage, and other experimental conditions.

2.36 mm, and agitation speed of 300 rpm. The longer contact time required for Al-SGAC compared with previously reported adsorbents (15 to 90 min) can be attributed to several factors. First, the relatively larger particle size (2.36 mm) slows fluoride diffusion into internal pores, increasing the time needed to reach equilibrium. Second, the surface chemistry and aluminium loading, while enhancing adsorption performance, require sufficient interaction time for complete utilization of active sites. Third, mass transfer limitations at typical groundwater fluoride levels (2 to 2.5 mg/L) result in slower kinetics than those observed under highly acidic or concentrated laboratory conditions. Shorter contact times may lead to incomplete adsorption, while extending beyond 120 min yields negligible improvement, indicating that 120 min is the optimal duration balancing removal efficiency and operational practicality under realistic groundwater conditions.

Performance evaluation of Al-SGAC

This study demonstrates the enhanced performance of Al-SGAC in fluoride removal across multiple dimensions, including characterization of the adsorbent, removal efficiency, adsorption mechanism, optimization of operational parameters, surface properties, economic feasibility, and environmental sustainability. The investigation was designed to simulate field-relevant fluoride concentrations (2–3 mg/L) with emphasis on process optimization; therefore, detailed equilibrium isotherm and kinetic modeling across varying initial concentrations was not performed.

(i) Fluoride removal efficiency: Al-SGAC achieved 92.6% fluoride removal,

outperforming several conventional and biomass-based materials. Although MBAC (99%) (Bagbi *et al.,* 2024) and oak shell carbon (97.4%) (Takmil *et al.,* 2020) reported higher efficiencies, those studies were conducted under highly acidic conditions (pH 2 to 3) or involved magnetization and nanocomposite synthesis. In contrast, Al-SGAC maintained high removal at near neutral pH (6.5 to 7.0) under groundwater simulated conditions, enhancing its practical field applicability. Effective removal at moderate fluoride concentration (2.5 mg/L) further confirms its suitability for typical contamination scenarios.

(ii) Adsorption mechanism: The adsorption of fluoride by Al-SGAC primarily occurs through chemisorption, facilitated by surface Al–OH groups introduced via aluminium doping. These hydroxyl groups act as active sites, allowing fluoride ions to undergo ligand exchange, forming stable Al–F bonds, similar to mechanisms observed in MBAC (Bagbi *et al.,* 2024) and CSAC (Kyzas *et al.,* 2022). Unlike other systems that require magnetic nanoparticles or complex nanostructuring to enhance adsorption, Al-SGAC achieves effective fluoride removal through simple aluminium doping, which increases the density of reactive sites while simplifying synthesis. This mechanism aligns with pseudo-second-order adsorption behavior reported in similar studies (Amalraj and Pius, 2017; Vázquez-Guerrero *et al.,* 2016; Takmil *et al.,* 2020), indicating that chemical interactions dominate the adsorption process.

(iii) Surface area, pore volume, and structural stability: BET analysis revealed a surface area of 780 m^2/g, exceeding several natural adsorbents, and comparable to PAAC (707 m^2/g) (Bonyadi *et al.,* 2019). Post-adsorption reductions in surface area and pore volume confirmed fluoride occupation of active sites, with no structural degradation. This distinguishes Al-SGAC from materials where adsorption-induced deterioration limits long-term usability.

(iv) Environmental friendliness and reusability: The Agathi plant is renewable and widely available. Its activation method avoided toxic chemicals and energy-intensive processes. Although materials like those by (Bagbi *et al.,* 2024) and (Kyzas *et al.,* 2022) are especially suitable for decentralized water treatment systems.

(v) Operational parameters: Several high-performing adsorbents operated at extreme pH values, such as pH 2 in (Bagbi *et al.,* 2024) and pH 3 in (Takmil *et al.,* 2020), making them less practical. Al-SGAC maintained high removal at near-neutral pH with an 8 g/L dose, moderate agitation, and typical groundwater fluoride levels. These parameters enhance its applicability in real-world settings without requiring extensive pretreatment.

This study positions Al-SGAC as a robust, scalable, and environmentally conscious adsorbent for fluoride removal, with straightforward synthesis, high efficiency, and realistic operational requirements, making it one of the most balanced and practically viable solutions in terms of removal rate, kinetics, structural integrity, preparation simplicity, and sustainability.

Verification of experimental investigations

The experimental investigations demonstrate the potential efficiency and broad applicability of Al-SGAC for fluoride removal and overall groundwater quality improvement. The study systematically optimized key operational parameters, including particle size (2.36 mm), adsorbent dosage (8 g), agitation speed (300 rpm), and contact time (120 min), to maximize surface interaction and mass transfer between the adsorbent and dissolved species. Under these optimized conditions, fluoride removal reached

92.6%, confirming the strong adsorption affinity of Al-SGAC toward fluoride ions. In addition to fluoride, substantial reductions were observed for other groundwater constituents, including TDS (85.6%), TH (78.9%), Ca (84.2%), Mg (89.3%), Na (76.1%), K (86.1%), Cl (79.6%), SO_4 (83.2%), NO_3 (84.1%), and Fe (93.8%), with treated concentrations complying with limits prescribed by the BIS for drinking water. These removals result from the high surface area, porous structure, and abundant oxygenated and aluminium-based functional groups of Al-SGAC. Fluoride removal occurs mainly via surface complexation and electrostatic attraction at ≡Al–OH sites forming ≡Al–F bonds, while Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} are reduced through ion exchange and electrostatic adsorption. Cl^{-}, SO_4^{2-}, and NO_3^{-} are removed by pore adsorption, and Fe through adsorption precipitation and complexation. The treated water maintained a pH 7.12 within 6.5 to 8.5. Al-SGAC demonstrates efficient multi-contaminant groundwater purification, though further competitive and mechanistic studies are recommended.

Regeneration capacity of Al-SGAC

The reuse potential of Al-SGAC was evaluated through a regeneration study aimed at desorbing fluoride from saturated adsorbent surfaces. Given the presence of aluminium-based active sites, acidic regenerants were considered more effective than alkaline agents due to their ability to disrupt Al–F interactions. Among various acids, 0.1 M hydrochloric acid (HCl) achieved the highest desorption efficiency by strongly dissociating and providing free protons that enhance fluoride displacement through protonation of surface hydroxyl groups. Additionally, its non-complexing Cl_2 ions avoid interference with Aluminium (Al) active sites, maintaining adsorbent integrity. In contrast, weaker acids or those capable of forming complexes may either insufficiently regenerate or degrade the functional sites. During the desorption process, 25 mL of 0.1 M HCl was added to fluoride-saturated Al-SGAC and allowed to stand for 90 min. The first cycle exhibited a desorption efficiency of 94.8%, significantly higher than values reported for unmodified SGAC. Subsequent regeneration cycles maintained removal efficiencies of 92.6%, 90.1%, 87.4%, and 84.2% through the fifth cycle, indicating good stability under the tested conditions. After five cycles, Al-SGAC desorbed 3.921 mg/L fluoride, corresponding to a regeneration efficiency of 93.4% and adsorption capacity retention of 2.78 mg/g, demonstrating minimal capacity loss and continued applicability for water treatment (Sivakumar *et al.,* 2025a). The desorption behavior is attributed to reversible ligand exchange between fluoride and Al–OH groups under acidic conditions (Saeed *et al.,* 2022). Post-cycle SEM, FTIR, XRD, aluminium leaching, and mass balance analyses were not conducted, limiting evaluation of structural changes, durability, and environmental safety; therefore, extended regeneration beyond five cycles (8 to 10 or more), combined with structural characterization and leaching assessment, is recommended to confirm long-term stability. The high reusability and regeneration using mild HCl highlight Al-SGAC as a cost-effective and sustainable option for field-scale groundwater defluoridation and removal of other anionic contaminants.

Adsorbent mechanisms

The primary mechanism by which aluminium enhances fluoride removal involves the formation of aluminium hydroxide [Al $(OH)_3$] on the SGAC surface. These hydroxide groups serve as active sites for fluoride ion adsorption through ligand exchange reactions (Dhifallah *et al.,* 2024; Tomar and Kumar, 2013) and are shown in Fig. 9. Fig. 9 illustrates the dual mechanisms of ligand exchange and electrostatic attraction governing fluoride adsorption onto Al-SGAC. Fluoride ions (F^{-}) replace hydroxyl groups (–OH) on the $Al(OH)_3$ surface to form stable Al–F complexes, a reaction that is strongly pH dependent and most effective at pH 5.5 to 6.5. At this range, the surface becomes positively charged ($Al–OH_2^{+}$), enhancing

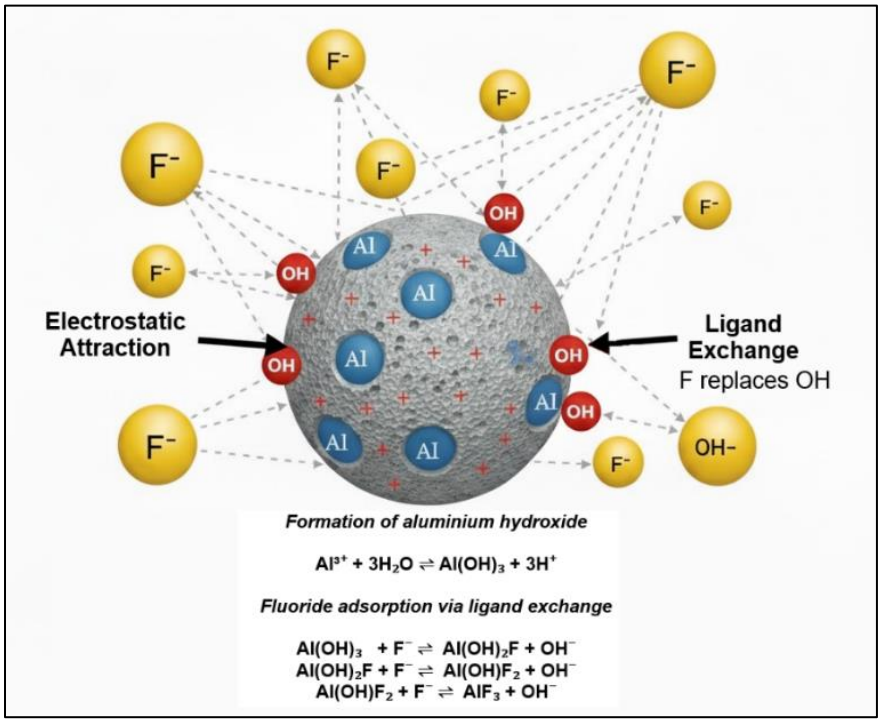

Fig. 9: Conceptual mechanism of fluoride uptake on Al-SGAC, highlighting pore diffusion, interaction with surface functional groups, and complexation at aluminium active sites responsible for effective adsorption.

electrostatic attraction toward negatively charged fluoride ions. Thus, adsorption occurs through both chemical bonding and charge-driven interactions. The integration of $Al(OH)_3$ onto the porous SGAC matrix further improves performance by providing high surface area, a well-developed pore network, and abundant active sites. While SGAC enhances mass transfer and adsorption capacity, $Al(OH)_3$ supplies reactive sites for ligand exchange, creating a synergistic composite with fluoride removal efficiency. Consequently, Al-SGAC effectively treats fluoride-contaminated groundwater by combining the physical properties of carbon with the chemical affinity of aluminium compounds.

Model Development and training, performance evaluation, and validation

In this study, linear regression, nonlinear regression, and ANN models were initially developed to predict fluoride removal efficiency from experimental data.

Linear regression model

A linear regression model was developed to predict fluoride removal efficiency as a function of particle size, adsorption dosage, agitation speed, and contact time. The resulting equation (Eq. 6) is (Batool *et al.,* 2018):

$$\text{Removal (\%)} = 8.12 \times \text{Particle size} + 3.97 \times \text{Dosage} + 0.046 \times \text{Agitation speed} + 0.16 \times \text{Contact time} + 15.5 \quad (6)$$

The model achieved an R^2 of 0.945, MSE of 0.0053, RMSE of 0.0728, MAE of 0.053, and cross-validation R^2 of 0.915. These results indicate that the linear model captures the general trends of fluoride removal but tends to underestimate removal efficiency at higher contact times, dosages, and agitation speeds, highlighting the limitations of a strictly linear approach for this complex adsorption system.

Nonlinear regression model

A nonlinear regression model was developed to account for the nonlinear relationships between particle size, adsorption dosage, agitation speed, contact time, and fluoride removal efficiency. The resulting equation (Eq. 7) is (Batool *et al.,* 2018):

$$\text{Removal (\%)} = 0.78 \times (\text{Particle size})^2 + 1.25 \times (\text{Dosage})^2 + 0.00012 \times (\text{Agitation speed})^2 + 0.0012 \times (\text{Contact time})^2 + 5.2 \times \text{Particle size} + 3.5 \times \text{Dosage} + 0.042 \times \text{Agitation speed} + 0.14 \times \text{Contact time} + 12.7 \quad (7)$$

The model achieved an R^2 of 0.978, MSE of 0.0021, RMSE of 0.0458, MAE of 0.033, and cross-validation R^2 of 0.950. These results demonstrate that the nonlinear regression model better captures the experimental trends than the linear model, including the effects of higher contact times, dosages, and agitation speeds, while providing improved predictive accuracy across the dataset.

ANN model development and training

The ANN investigation was conducted using MATLAB (Matrix Laboratory) software developed by MathWorks. A full factorial design with four inputs, particle size, dosage, agitation speed, and contact time, each at five levels, resulted in 5^4 = 625 experimental runs, ensuring comprehensive coverage of the experimental space. This design systematically spans the experimental space and justifies the dataset size. The data were divided into training (70%), validation (15%), and testing (15%) subsets to ensure robustness and minimize overfitting. Multiple network structures, training algorithms, and hidden neuron counts from 7 to 10 were evaluated to develop an optimized model, following established methods (Joshi *et al.,* 2020), ensuring transparency and reproducibility. The Levenberg-Marquardt algorithm was employed, with MSE as the primary performance metric. After seven iterations, the network achieved optimal performance, yielding an overall regression coefficient of 0.9948. As depicted in Fig. 10, the ANN demonstrated strong predictive capability: training data (438 samples), Output = 1.0 × Target − 0.8, R^2 = 0.947, MSE = 0.0032, RMSE = 0.0566, MAE = 0.042, validation data (94 samples), Output = 0.984 × Target + 0.78, R^2 = 0.984, MSE = 0.0015, RMSE = 0.0387, MAE = 0.030, testing data (94 samples), Output = 0.96 × Target + 0.42, R^2 = 0.972, MSE = 0.0021, RMSE = 0.0458, MAE = 0.035, and the total dataset (625 samples), Output = 0.991 × Target + 0.52, R^2 = 0.991, MSE = 0.002, RMSE = 0.0447, MAE = 0.033, confirming that the model performance is not due to memorization of limited data, but reflects genuine predictive capability derived from a statistically meaningful dataset size, thereby addressing the concerns regarding model reliability and generalizability (Ahmadi *et al.,* 2021).

All models were evaluated using performance metrics including R^2, MSE, RMSE, MAE, and cross-validation R^2. Based on this comparison, the ANN model exhibited superior predictive capability and robustness. Therefore, further analysis and validation were conducted exclusively using the ANN model to ensure high reliability and generalization in scenario simulations and process optimization. The ANN model demonstrates the highest R^2 (0.991), the lowest MSE, RMSE, and MAE, and the highest cross-validation R^2 (0.981), confirming superior predictive performance and generalization compared to both linear and nonlinear regression models. Consequently, the ANN model was selected for further development, detailed analysis, and scenario simulation in this study.

Performance evaluation of the ANN model accuracy

The ANNs have been utilized in adsorption research to investigate fluoride removal efficiency using Al-SGAC. It should be noted that the model predicts only the **%** of fluoride removal and does not provide predictions for adsorption capacity (mg/g) or equilibrium concentration (C_e), because

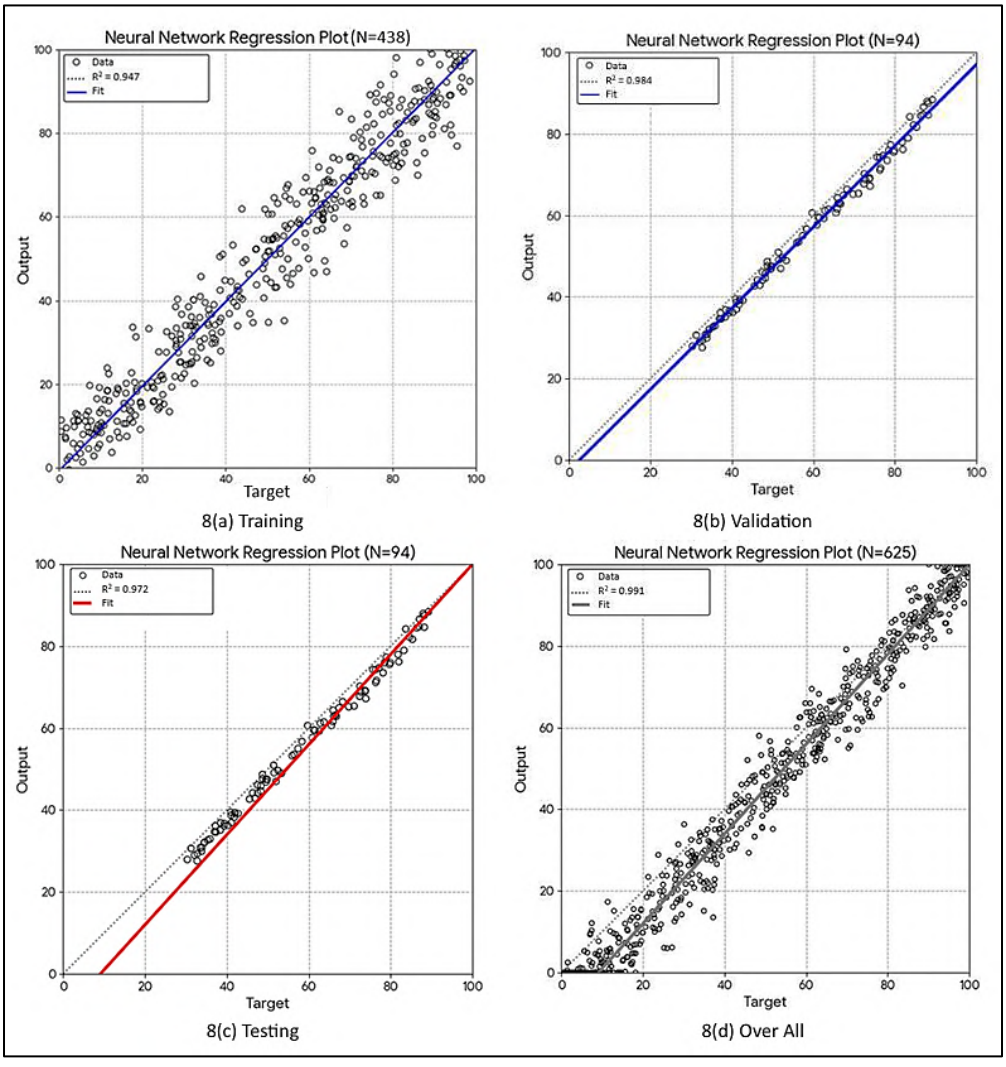

Fig. 10: ANN regression analysis comparing predicted and observed fluoride removal for training, test, validation, and combined datasets, indicating high correlation and reliable predictive performance of the model.

the training dataset was generated using removal % as the response variable rather than absolute adsorption values. The Levenberg-Marquardt algorithm, a standard technique for minimizing MSE in nonlinear models, was used for training. Data division occurred randomly during training, enhancing model generalization. MATLAB software supported the analysis of both individual and interactive adsorption phenomena and facilitated process parameter optimization (Addar *et al.,* 2023). Table 4 compares experimental and ANN-predicted fluoride removal efficiencies for selected conditions rather than all 625 combinations. Predictions closely matched observations, with residual errors ranging from 0.2% to 6.3%, MSE between 0.0015 and 0.0032, RMSE between 0.0387 and 0.0566, MAE between 0.030 and 0.042, and high R^2 values, confirming strong reliability. The highest removal, 92.6% at 2.360 mm particle size, 8 g dosage, 300 rpm agitation, and 120 min contact time, was accurately predicted at 92.4%, confirming strong

Table 4: Experimental (observed) and ANN model (predicted) comparison on the removal of fluoride in groundwater using Al-SGAC

Particle size	Adsorption dosage	Agitation speed	Contact time	Observed removal (%)	Actual quantity removal, mg/L	Predicted removal (%) by ANN	Residuals mg/L	Chi-square (χ^2)
0.425	2	100	60	32.6	0.815	31.7	0.9	0.02555
0.600	2	100	60	44.1	1.103	37.8	6.3	1.05000
1.180	2	100	60	58.7	1.468	55.1	3.6	0.23521
2.360	2	100	60	70.8	1.770	69.4	1.4	0.02824
4.750	2	100	60	71.0	1.775	71.0	0.0	0.00000
2.360	4	100	60	73.2	1.830	68.7	4.5	0.29476
2.360	6	100	60	78.4	1.960	77.2	1.2	0.01865
2.360	8	100	60	81.7	2.043	80.9	0.8	0.00791
2.360	10	100	60	81.9	2.048	80.9	1.0	0.01236
2.360	8	200	60	83.7	2.093	83.2	0.5	0.00301
2.360	8	300	60	86.4	2.160	84.0	2.4	0.06857
2.360	8	400	60	82.3	2.058	83.2	0.9	0.00974
2.360	8	500	60	78.4	1.960	80.4	2.0	0.04975
2.360	8	300	80	88.1	2.203	87.8	0.3	0.00103
2.360	8	300	100	90.2	2.255	90.7	0.5	0.00276
2.360	8	300	120	92.6	2.315	92.4	0.2	0.00043
2.360	8	300	140	92.7	2.318	92.5	0.2	0.00043

reliability. The ANN maintained high accuracy across varying conditions and effectively captured nonlinear interactions, such as improved removal with longer contact time (Addar *et al.,* 2023). The model reduces the need for lengthy experimental trials while supporting dependable optimization and scenario modeling.

Validation of the ANN model with experimentation

Fluoride removal efficiencies were assessed under varying experimental conditions and compared with predictions from an ANN model. Key performance indicators such as the R^2, χ^2, MSE, RMSE, MAE, and cross-validation scores were used to evaluate predictive accuracy. Among all runs, Run 16 exhibited the highest fluoride removal, with an observed value of 92.6%, a predicted value of 92.4%, a residual of 0.2%, and a χ^2 of 0.00001, indicating close agreement between actual and predicted results. The linear regression equation, y = 1.0667x - 6.1563, was derived from the correlation between observed and predicted values. The equation explains 98.9% of the variability, with MAE below 5% and cross-validation R^2 = 0.981, confirming strong accuracy and consistency. Close alignment with the regression trend line further validates its predictive reliability (Reddy *et al.,* 2023). To further evaluate the statistical significance of the regression between observed and ANN-predicted fluoride removal efficiencies, an analysis of variance (ANOVA) was performed. Table 5 presents the ANOVA for the linear regression between observed and ANN-predicted fluoride removal efficiency. It can be noted from Table 5 that the high F-value and $p < 0.0001$ confirm that the regression model is statistically significant, with 98.9% of the variability explained by the ANN model, demonstrating strong predictive reliability and minimal unexplained variance. The low residual mean square further indicates that the deviation between experimental and predicted values is negligible, confirming the robustness of the developed ANN model. The study focuses on fluoride removal from groundwater using Al-SGAC, and the ANN model effectively optimizes and predicts adsorption performance.

Comparative analysis of experimental and ANN model on fluoride removal

ANN modelling outperformed conventional experimentation for evaluating fluoride

Table 5: ANOVA for observed and ANN-predicted fluoride removal

Source	Sum of squares (SS)	df	Mean square (MS)	F-value	p-value
Regression	4825.36	1	4825.36	1392.45	< 0.0001
Residual	55.42	16	3.46	—	—
Total	4880.78	17	—	—	—

adsorption by Al-SGAC, processing multidimensional inputs and capturing nonlinear interactions with minimal error. Predicted results closely matched observations, with 92.6% removal predicted at 92.4%, an R^2 approaching unity, and χ^2 values near zero, confirming strong reliability and reduced experimental effort. Integrating the bio-derived adsorbent with adaptive machine learning further enabled real-time optimization and efficient, sustainable process control (Addar *et al.,* 2023). This reduces reliance on fixed protocols and extensive laboratory trials while supporting rapid decision-making. The low-cost synthesis, high regeneration efficiency, and scalability of Al-SGAC make it suitable for decentralized and rural treatment systems. High predictive accuracy, minimal residuals, and strong statistical validation confirm reliable optimization and reduced uncertainty (Reddy *et al.,* 2023; Abdurahim *et al.,* 2024), demonstrating an efficient and sustainable strategy for water treatment design.

Material performance, regeneration stability, and practical implications of Al-SGAC for decentralized water treatment

Material performance and scalability

Aluminium-impregnated AC, particularly Al-SGAC, is emerging as a promising adsorbent for fluoride removal from groundwater and as a sustainable solution for efficient wastewater treatment. Comprehensive characterization using FTIR, SEM, EDX Spectroscopy, XRD, and BET surface area analysis confirmed structural stability, well-developed porosity, and effective adsorption behavior. Under optimized conditions, the material achieved 92.6% fluoride removal along with substantial elimination of coexisting contaminants, including Fe (93.8%), Mg (89.3%), Ca (84.2%), NO_3^- (84.1%), and TDS (85.6%), while maintaining near-neutral pH (7.12). Predictive modeling using ANN analysis demonstrated high accuracy, with a regression coefficient (R) of 0.9948 and a mean error of 2.87%, supporting reliable process scale-up. The present investigation was conducted at laboratory scale, and no detailed cost analysis, pilot-scale validation, or full-scale implementation study was performed; therefore, future work should incorporate economic assessment and continuous-flow pilot trials to confirm operational feasibility and real-world scalability.

Regeneration and structural stability

Furthermore, the adsorbent exhibited strong regeneration capability, maintaining 84.2% desorption efficiency after five cycles with 0.1 M HCl. Microscopic and structural analyses confirmed preserved integrity after reuse, with BET surface area decreasing from 780 to 615 m^2/g and XRD analysis showing an increase in amorphous content from 74.8% to 81.1%, indicating effective occupation of active sites without structural degradation. Collectively, these properties demonstrate durability, reduced replacement frequency, and lower operational costs, underscoring the material's suitability for sustainable and decentralized water treatment applications.

Practical implications for decentralized water treatment

These findings show that Al-SGAC is a practical, affordable, and reusable adsorbent for decentralized wastewater and groundwater treatment, providing effective fluoride removal and reducing concentrations to the limits recommended by the World Health Organization (WHO). Produced from locally available biomass, it

supports low-cost, scalable synthesis suitable for rural and resource-limited settings. Its rapid kinetics, wide pH applicability, and easy regeneration enable simple integration into existing systems while maintaining performance. Overall, its efficiency, low cost, and reusability make Al-SGAC a sustainable option for safe drinking water applications.

Recommendation

Successful implementation requires pilot-scale field validation, community participation, and regulatory monitoring. Field studies should confirm real-world performance across varying water qualities, while local involvement can improve acceptance and long-term sustainability. Routine monitoring of treated water is necessary to ensure health compliance and detect any potential leaching. Together, pilot testing, community engagement, and consistent quality checks support safe and effective deployment.

Future research directions

Future work should enhance adsorption capacity, durability, and sustainability through alternative biomass sources and improved modification methods. Detailed mechanistic studies are needed to clarify fluoride interactions with active sites, and performance should be assessed for removing other contaminants, such as heavy metals and organics. Life-cycle and environmental evaluations of production, regeneration, and disposal are also essential to optimize efficiency and broaden applicability for safe drinking water provision.

CONCLUSION

Al-SGAC prepared from SG biomass demonstrates promising applicability for fluoride removal from groundwater, supported by favorable surface characteristics, regeneration capacity, and the ability to reduce multiple coexisting contaminants. Material characterization confirmed the presence of hydroxyl and oxygenated functional groups, developed porosity, and structural stability that facilitate fluoride binding through surface interactions and ligand exchange mechanisms. Under optimized conditions, the adsorbent achieved a maximum fluoride removal efficiency of 92.6%, corresponding to an adsorption capacity of 0.29 mg/g with a relatively high dosage of 8 g/L, while simultaneously lowering concentrations of Ca, Mg, Fe, nitrate, total dissolved solids, and hardness, contributing to improved water quality within BIS limits. Regeneration experiments indicated sustained adsorption performance after repeated reuse cycles, suggesting acceptable durability and reduced material replacement frequency. Decreases in surface area and increased amorphous character after adsorption further support pore occupation and successful contaminant interaction without major structural damage. Statistical and predictive analyses showed progressive improvement from linear to nonlinear regression and further enhancement using the ANN model, which demonstrated strong agreement between predicted and experimental outcomes and supports its use for process optimization and operational planning. It should be noted that the model predicts only the percentage of fluoride removal and does not provide adsorption capacity or equilibrium concentration, as the dataset was generated using removal percentages. The performance of the model for scaling up or field deployment has not been demonstrated, making claims of scalability premature without column studies or pilot-scale data. The use of a locally available biomass precursor and simple preparation method indicates potential for cost-conscious and decentralized treatment applications, though detailed economic and life-cycle analyses are required. Findings are currently limited to laboratory-scale evaluation, and pilot-scale or column studies are necessary to assess scalability, long-term stability, and operational feasibility

under field conditions. Taken together, the results indicate that Al-SGAC provides a feasible and adaptable option for fluoride mitigation with scope for further refinement and validation.

AUTHOR CONTRIBUTIONS

M. Perarul Selvan conceptualized the study, conducted the experiments, performed data analysis, and prepared the original manuscript draft. D. Sivakumar supervised the research design, validated the methodology, and critically reviewed and edited the manuscript. V. Kumar provided technical expertise, assisted in the interpretation of results, and contributed to manuscript revision. S. Chandran supported statistical analysis, modeling, and final manuscript review. All authors read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, 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
ABC	Activated Bamboo Carbon
AC	Activated Carbon
AHAC	Aluminium Hydroxide–Coated Activated Carbon
Al	Aluminium
$Al(OH)_3$	Aluminium hydroxide
$AlCl_3$	Aluminium chloride
Al–SGAC	Aluminium-impregnated *Sesbania grandiflora* Activated Carbon
ANN	Artificial Neural Network

APHA	American Public Health Association
BAC	Bamboo Activated Carbon
BC	Bamboo Carbon
BET	Brunauer–Emmett–Teller (surface area analysis)
BIS	Bureau of Indian Standards
Ca	Calcium
CAC	Catha edulis–derived Activated Carbon
Cl	Chloride
cm^3/g	Cubic centimetres per gram
CSAC	Canola Stalk Activated Carbon
EDX	Energy Dispersive X-ray
Fe	Iron
FTIR	Fourier Transform Infrared Spectroscopy
g	Grams
g/L	Grams per litre
HCl	Hydrochloric acid
hr	Hours
ISLP	Indian Sandalwood Leaf Powder
K	Potassium
KBr	Potassium bromide
M	Molarity
m^2/g	Square metres per gram
MAE	Mean absolute error
MATLAB	Matrix Laboratory
MBAC	Magnetite Bamboo Activated Carbon
Mg	Magnesium
mg	Milligrams
mg/g	Milligrams per gram
mg/L	Milligrams per litre
min	Minutes
mL	Millilitres
mm	Millimetres
MSE	Mean Squared Error
Na	Sodium
nm	Nanometres
NO_3^-	Nitrate
OAC	Oak Activated Carbon
PAAC	*Populus alba* Activated Carbon
pH	Potential of Hydrogen
pH_pzc	The point of zero charge
PSAC	Palm Shell Activated Carbon
PS–$AlCl_3$	Pinus sawdust modified with $AlCl_3$
R^2	Coefficient of determination
RMSE	Root mean squared error
rpm	Revolutions per minute
SEM	Scanning Electron Microscope
SG	*Sesbania grandiflora*
SGAC	*Sesbania grandiflora* Activated Carbon
SO_4^{2-}	Sulfate
SPSS	Statistical Package for the Social Sciences
TDS	Total Dissolved Solids
TH	Total Hardness
V	Volt
WHAC	Water Hyacinth Activated Carbon
WHO	World Health Organization
XPS	X-ray Photoelectron Spectroscopy
XRD	X-Ray Diffraction
$\Delta G°$	Gibbs free energy change
$\Delta H°$	Enthalpy change
$\Delta S°$	Entropy change
ϑ	Theta
χ^2	Chi-square

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ORIGINAL RESEARCH ARTICLE

Impacts of mangrove land use change on carbon stocks in coastal ecosystems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Mangrove ecosystems are critical blue carbon reservoirs, yet carbon dynamics in intensively used coastal landscapes remain poorly understood. Along the northern coast of Java, aquaculture expansion, rehabilitation, and community-based management coexist within the same coastal mosaic. The objective of this study is to analyze the effects of land-use trajectory influences ecosystem carbon stocks and carbon partitioning across recovered, semi-natural, and degraded mangrove systems.

METHODS: The total carbon stocks of the ecosystem, which encompass aboveground biomass, belowground biomass, and soil organic carbon to a depth of 150 centimeters, were measured at representative locations. Differences among land-use treatments were tested using non-parametric statistics (Kruskal–Wallis and Dunn's tests), and Spearman correlation analysis was applied to assess relationships between years since land-use change and carbon stocks. Community interviews were utilized to frame management practices and the historical context of land use.

FINDINGS: Total ecosystem carbon stocks ranged from 121.63 ± 33.91 to 217.86 ± 161.27 megagrams of carbon per hectare, with the highest values observed in semi-natural mangrove systems and the lowest in long-term degraded sites. The statistical analyses revealed that total carbon stocks did not differ significantly among recovered, semi-natural, and degraded mangroves. Instead, land-use trajectories strongly influenced carbon partitioning. Soil carbon dominated ecosystem carbon storage, contributing 71.8–93.5 percent of total carbon, while biomass carbon accounted for only 6.5–29 percent. Vertical soil profiles demonstrated that the lower soil layers (50–150 centimeters) possessed the largest carbon stocks, implying that carbon storage is controlled by long-term sedimentary processes. Correlation analyses showed weak relationships between total carbon stocks and years since land-use change, highlighting strong legacy effects in subsurface carbon pools.

CONCLUSION: These results demonstrate that mangrove carbon storage in working coastal landscapes is controlled by sediment properties, hydrological connectivity, and long-term disturbance history, rather than land-use classification alone. The lasting presence of deep soil carbon pools elucidates the reason behind the relatively stable carbon stocks in ecosystems, particularly in aquaculture-dominated areas where there is considerable variation in vegetation structure. Effective blue carbon management should therefore prioritize protecting existing soil carbon and maintaining hydrological connectivity, particularly in semi-natural systems with long-term sediment stability. This study provides empirical evidence supporting process-based mangrove management and more nuanced coastal land-use policies in rapidly developing tropical coastlines.

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INTRODUCTION

Mangrove ecosystems are intertidal forests uniquely situated in coastal zones where tidal inundation, salinity gradients, and sediment dynamics strongly shape ecosystem structure and function. Mangroves, as a coastal ecosystem, are essential for preserving shoreline stability by dissipating wave energy, minimizing erosion, and shielding coastal regions from storm surges. These functions are increasingly acknowledged as part of nature-based solutions for coastal protection (van Hespen *et al*., 2023; Lovelock *et al*., 2024). Mangroves are also globally recognized as one of the most carbon-rich ecosystems in coastal environments, storing large amounts of carbon in both aboveground biomass and deep, waterlogged soils, a characteristic that forms the basis of the blue carbon concept (Donato *et al*., 2011; Sanderman *et al*., 2018). Furthermore, mangrove ecosystems are not only significant for carbon storage but also for their ability to regulate greenhouse gas fluxes. Alterations in land use can lead to changes in hydrological and biogeochemical conditions, which in turn can impact greenhouse gas emissions. Aquaculture-associated systems may enhance methane emissions under prolonged anoxic conditions and increase nitrous oxide emissions under nutrient enrichment, highlighting potential trade-offs in climate mitigation (Rosentreter *et al*., 2018). Despite their ecological importance, mangrove ecosystems have experienced substantial loss and degradation worldwide. Over the course of the past fifty to sixty years, approximately 20–35 percent (%) of global mangrove coverage has either been lost or significantly degraded, with Southeast Asia noted as a major hotspot for the mangrove decline (Goldberg *et al*., 2020). Using multi-decadal delineation data, Chaiklang *et al*. (2024) documented that mangrove area in Thailand declined sharply from approximately 367,900 hectares (ha) in 1961 to 160,000 ha by 1996, largely driven by aquaculture expansion and coastal development, before increasing again to 277,923 ha by 2020 following conservation and restoration initiatives. This trajectory illustrates that mangrove landscapes often undergo alternating phases of degradation and recovery rather than irreversible loss, emphasizing that land-use outcomes are strongly shaped by management responses over time. An important conceptual dilemma arises from the common framing of mangrove land-use changes in existing literature. Coastal aquaculture development is frequently portrayed as a direct and uniform conversion of mangrove forests into aquaculture ponds. While this binary framing captures one dominant pathway of mangrove loss, it oversimplifies the complexity of many coastal landscapes. In real-world scenarios, mangroves might be partially maintained within aquaculture systems, rehabilitated following degradation, or persist as fragmented stands along channels and embankments. These diverse land-use approaches demonstrate the variations in governance, hydrological changes, and local management techniques, potentially leading to different ecological consequences even within largely similar aquaculture environments (Richards and Friess, 2016; Friess *et al*., 2019). This oversimplification is particularly problematic when evaluating mangrove carbon stocks. Mangrove carbon storage, including both biomass and soil carbon pools, is highly sensitive to canopy condition, disturbance intensity, and changes in soil properties such as sediment texture, salinity, nutrient availability, and redox conditions, which are often modified by hydrological alteration and land-use change. In addition, vegetation characteristics such as species composition, age structure, and stand density further mediate carbon storage by influencing aboveground biomass development and belowground root systems (Simard *et al.,* 2019). Comprehensive ecosystem evaluations indicate that mangrove soils frequently sequester the majority of ecosystem carbon and can preserve carbon for centuries in stable, anoxic environments. These

conditions are likely affected by hydrological connectivity, which encompasses tidal exchange, freshwater input, and sedimentation processes that regulate oxygen availability and carbon preservation (Donato *et al*., 2011; Sanderman *et al*., 2018). Conversely, land-use changes that disturb soils, such as pond construction and drainage, can result in substantial carbon losses. Field-based studies in Southeast Asia and Indonesia demonstrate that conversion to aquaculture ponds generally reduces ecosystem carbon stocks, particularly through losses of soil carbon, while rehabilitated or naturally regenerating sites can retain higher carbon stocks depending on sediment properties and post-conversion management (Elwin *et al*., 2019; Sasmito *et al*., 2019). Evidence from Indonesia further emphasizes the significance of land-use management in influencing mangrove carbon dynamics. Sasmito *et al*. (2019) showed that mangrove carbon stocks vary markedly across landscapes with different disturbance histories and hydrogeomorphic settings. Their study reveals that carbon results in coastal areas primarily focused on aquaculture are inconsistent, as variations in land-use intensity and management practices affect both the rates of carbon loss and accumulation. Abandoned or partially restored ponds may still retain substantial soil carbon, whereas intensively managed ponds and heavily disturbed sites tend to experience more rapid carbon depletion. These results underscore that mangrove carbon dynamics cannot be comprehensively understood through simple forest-versus-aquaculture classifications; rather, they represent a range of land-use practices and management histories. In this study, mangrove systems were explicitly categorized into three land-use trajectories: recovered, semi-natural, and degraded, representing contrasting management histories and levels of anthropogenic influence within the same coastal landscape. Notwithstanding the progress made in blue carbon research, there is a scarcity of studies that directly compare various coastal mangrove land-use treatments within a unified analytical framework, especially in areas characterized by significant coastal development intensity. This knowledge gap is especially relevant along the northern coast of Java, Indonesia, where mangroves coexist with extensive aquaculture, coastal settlements, and infrastructure, and where land-use pressure has been sustained for decades. Understanding how different forms of coastal mangrove land use influence carbon stocks in such working landscapes is critical for improving the evidence base linking land-use decisions to carbon storage outcomes. Consequently, this study evaluates the impact of recovered, semi-natural, and long-term degraded systems on ecosystem carbon stocks along the northern coast of Java. By integrating vegetation structure and soil carbon measurements across sites representing contrasting land-use conditions, this study provides a comparative evaluation of how different land-use treatments influence both aboveground and belowground carbon pools. The study conceptually enhances the overly simplistic narratives surrounding mangrove conversion by recording carbon responses across a spectrum of land-use conditions. From a management and policy perspective, the findings offer evidence to support more nuanced coastal land-use planning in regions where aquaculture and mangrove ecosystems are tightly interlinked. The aims of this study are to diagnose how land-use trajectory influences ecosystem carbon stocks and carbon partitioning across recovered, semi-natural, and degraded mangrove systems. This study has been conducted in the Tenjo Ayu, Tanjung Pasir, Tanjung Tiga and Patimban in Indonesia in 2025.

MATERIALS AND METHODS

Site description

The study was conducted in the northern coast of Java in Banten Province and West Java Province, Indonesia, located between 5.97°–6.24° south (S) latitude and 106.38°–107.89° east (E) longitude

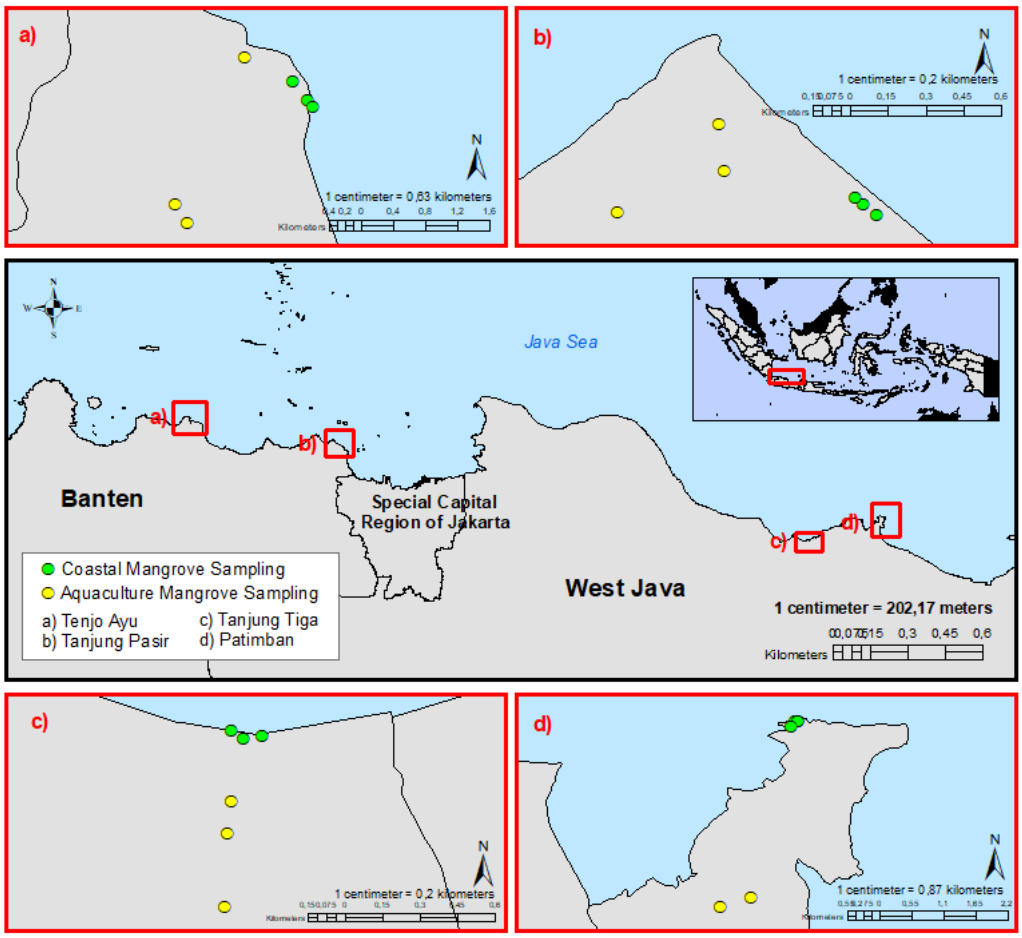

Fig. 1: Geographical location of the study area along with the sampling sites: a) Tenjo Ayu; b) Tanjung Pasir; c) Tanjung Tiga; and d) Patimban in Indonesia

(Fig. 1). The area has experienced significant changes in land-use, with the expansion of aquaculture and urban development posing pressures on mangrove ecosystems. These modifications render the region an optimal setting for analyzing the effects of land-use practices on mangrove carbon stocks. These sites included mangrove ecosystems and adjacent aquaculture ponds, with field data collected in June 2025. Data and samples were collected from two distinct environments, namely mangroves within aquaculture ponds and intact mangroves along the coastline. Sampling was carried out at four locations along the northern coast of Java, each representing distinct mangrove land-use conditions. These locations were selected to encompass a variety of mangrove management techniques, spanning from degraded ecosystems to restored regions, to evaluate the impact of these practices on carbon sequestration capabilities; consequently, the sites were categorized into three broad classifications: semi-natural (intact), recovered, and degraded mangroves. In Tenjo Ayu, Banten Province, mangroves grow naturally around community-owned aquaculture ponds, with *Avicennia sp*. as the dominant species. The area is characterized by significant fragmentation due to deforestation driven by local economic pressures, and mangrove density is generally low due to degradation caused

by pond activity. The sediments are predominantly muddy sand. The sampling sites at Tenjo Ayu are designated as Tenjo Ayu Pesisir (TAP) for the coastal area and Tenjo Ayu Tambak (TAT) for the aquaculture area. The coastal mangrove system is experiencing ongoing stress, evidenced by its low regeneration rates and insufficient rehabilitation efforts, thereby justifying its identification as a degraded mangrove system. Tanjung Pasir, located in Banten Province, represents a mangrove system heavily impacted by reclamation and urban development. Despite the presence of diverse mangrove species, including *Rhizophora sp*. and *Avicennia sp*., the overall mangrove cover has declined significantly due to land conversion for coastal development. This area is characterized by sediments that are mainly silty mud, and access to certain zones was limited, which restricted the ability to conduct direct field measurements. The sampling sites are classified as Tanjung Pasir Pesisir (TPP) for the coastal area and Tanjung Pasir Tambak (TPT) for the aquaculture area. While mangrove vegetation is still present, it is fragmented, and the system is heavily influenced by external factors such as reclamation and urban expansion. Although fragmented, the persistence of natural mangrove stands, and tidal influence allows this site to represent a semi-natural mangrove condition rather than a fully degraded system. Tanjung Tiga in West Java Province represents a more stable mangrove ecosystem with minimal anthropogenic disturbance. Mangroves in this area are in natural growth, with relatively little human intervention. The vegetation is dominated by *Avicennia sp*., and the area develops on fine muddy substrates. Compared to other regions, Tanjung Tiga exhibits moderate to high mangrove density. The sampling sites are classified as Tanjung Tiga Pesisir (TTP) for the coastal area and Tanjung Tiga Tambak (TTT) for the pond area. This site acts as a resource for relatively untouched mangrove ecosystems, offering significant insights into the natural growth of mangroves and their potential for carbon sequestration with minimal human interference. Consequently, this site is classified as a semi-natural mangrove system. Patimban, located along the West Java coastline, has undergone extensive mangrove rehabilitation between 2008 and 2013. The site represents a transition from rehabilitated to naturally regenerating mangrove ecosystems. The mangrove restoration initiatives in Patimban have been bolstered by both governmental and local efforts, yet the failure to implement sustained management strategies creates obstacles for the ecosystem's long-term viability. The sampling sites at Patimban are designated as Patimban Pesisir (PTP) for the coastal area and Patimban Tambak (PTT) for the pond area. The sediments in this area shift from muddy to sandy, with the mangrove vegetation showing significant recovery despite challenges in ongoing management. This combination of previous restoration activities and ongoing natural regeneration supports the classification of Patimban as a recovered mangrove system. These four sites illustrate a spectrum of mangrove conditions, ranging from heavily degraded aquaculture systems to recovering ecosystems. The sites vary in terms of mangrove density, land-use practices, and environmental pressures, allowing for an in-depth analysis of how these factors impact carbon sequestration. The geomorphic variation from depositional flats in Tanjung Tiga to eroded coastlines in Tenjo Ayu and Patimban provides valuable insight into the environmental controls on carbon storage and ecosystem health (Table 1). To minimize subjectivity and enhance comparability, land-use categories were established through a blend of field observations and semi-quantitative indicators, including vegetation density individual per hectare (ind/ha), fragmentation degree, signs of disturbance, and the duration since restoration or significant land-use change. Degraded sites were characterized by relatively low vegetation density, high fragmentation, and ongoing anthropogenic disturbance. Semi-natural sites retained moderate to high vegetation density,

Table 1: Mangrove site conditions

Site	Province	Dominant species	Sediment Type	Land use	Ecological status
Tenjo Ayu	Banten	*Avicennia sp*.	Muddy sand	Pond, Fragmented	Degraded
Tanjung Pasir	Banten	*Rhizophora sp*. and *Avicennia sp*.	Silty mud, sand	Pond, Urbanization	Semi-natural (5–6 years post-empowerment intervention)
Tanjung Tiga	West Java	*Avicennia sp*.	Muddy sediments	Pond, Natural	Semi-natural
Patimban	West Java	*Avicennia sp*.	Muddy to sandy	Pond, Restored	Recovered (13-year-old post-rehabilitation)

partial structural integrity, and continued tidal influence despite external pressures. The identification of recovered sites was conducted using documented rehabilitation history and visible vegetation regrowth, even though structural and soil characteristics may not yet fully reflect natural systems. These criteria were applied consistently across all sites to support classification along a gradient of mangrove condition rather than as strictly discrete categories.

Mangrove vegetation and biomass carbon stock assessment

Community structure assessment was carried out using a transect-based sampling approach, with three replicate plots established in coastal mangrove areas and three in adjacent aquaculture (pond) systems at each site (six plots per site). Within each plot, sampling points were arranged along transects with intervals of >50 m and plots of 28 × 28 meters (m) to capture local spatial variability. The purpose of this design was to depict the differences between coastal mangroves and aquaculture-related mangroves, while ensuring consistency across different sites. This approach is in accordance with mangrove carbon assessment techniques that emphasize depth-resolved measurements over broad spatial replication (Kauffman *et al*., 2020). While the number of replicate plots per site was limited, this design reflects a trade-off between spatial replication and the need for depth-resolved soil carbon measurements to 150 cm, which are logistically intensive. It is acknowledged that enhancing replication would augment statistical power and more effectively capture fine-scale spatial heterogeneity; thus, it is recommended that forthcoming studies utilize larger sample sizes in comparable land-use contexts. Within each plot, all mangrove trees were identified to species level, and their diameter at breast height (DBH) was measured at 1.3 m above the ground. In accordance with the methodologies established by Costa *et al*. (2019), the community structure was examined utilizing the Shannon–Wiener Diversity Index (H'), incorporating parameters such as species density (Di), relative density (RDi), species frequency (Fi), relative frequency (RFi), and the Importance Value Index (IVI) for each mangrove species at every site. The above-ground biomass (AGB) and below-ground biomass (BGB) of mangroves were estimated using non-destructive allometric equations based on the species. The above-ground carbon (AGC) was derived from the AGB of all trees in the plot, which included trunks, branches, and leaves. The below-ground carbon (BGC) was calculated from the BGB, representing the root mass of the mangrove species (Table 2).

Soil sampling and carbon analysis

To quantify the soil organic carbon (SOC) stocks, soil samples were collected from the center of each 10 × 10 meter plot using a soil auger with a diameter of 7 cm. Soil samples were collected at fixed depth intervals (0–15, 15–30, 30–50, 50–100 and 100–150 cm) to capture vertical variability in soil carbon stocks, adapting the approach used in mangrove soil carbon studies where similar depth horizons were sampled (Sasmito *et al*., 2020). Soil sampling was executed to a depth of 150 cm to

Table 2: Biomass equations per species

Site	Biomass	Equations
Avicennia sp.	AGB - Dharmawan and Siregar (2008)	$0.1848DBH^{2.3524}$
	AGC - Kauffman and Donato (2012)	AGB x 0.46
	BGB - Dharmawan and Siregar (2008)	$0.1682DBH^{1.7939}$
	BGC	BGB x 0.39
Rhizophora sp.	AGB - Clough and Scott (1989)	$0.105DBH^{2.68}$
	AGC	AGB x 0.46
	BGB - Comley and McGuinness (2005)	$0.261DBH^{1.86}$
	BGC	BGB x 0.39

ensure that both surface and deep soil carbon pools accounted for, as it is well-established that deeper layers hold a considerable share of mangrove carbon (Donato *et al.,* 2011). Coarse fragments, including stones and woody debris, were removed prior to analysis to ensure that bulk density and soil organic carbon measurements represented fine sediment only. All samples were oven-dried at 60 °C, and bulk density was determined in gram per cubic centimetre (g/cm^3) for each depth interval. Soil organic carbon content was analysed using the Walkley–Black method at the Marine Technology Cooperation Research Center (MTCRC), Indonesia, a method widely applied in mangrove and coastal carbon studies despite its known limitation of underestimating total organic carbon (Tinh *et al.,* 2020). The Walkley–Black method was used to estimate soil organic carbon, acknowledging that it may underestimate total organic carbon due to incomplete oxidation. This study did not apply any correction factor, since the method was uniformly across all samples to allow for relative comparison among sites. Therefore, the reported values should be interpreted as conservative estimates of soil carbon. SOC stocks in megagrams Carbon per hectare (Mg C/ha) were calculated for each depth interval by integrating carbon concentration, bulk density, and layer thickness, and subsequently summed across all depth intervals to obtain total soil carbon stocks up to 150 cm, as described in Eq. 1 (Dincă *et al.,* 2015):

$$SOC\ stock = BD \times C \times Depth \times 10 \quad (1)$$

Statistical analysis

Differences in ecosystem carbon stocks among mangrove sites representing recovered, semi-natural, and degraded land-use trajectories were analysed using non-parametric statistical approaches due to non-normal data distributions, as confirmed by the Shapiro–Wilk test. The Kruskal–Walli's test was employed to analyze variations in total ecosystem carbon and specific carbon pools, namely aboveground, belowground, and depth-resolved soil organic carbon. Subsequently, Dunn's post-hoc test with Bonferroni correction where appropriate. To evaluate temporal and legacy effects of land-use change, Spearman's rank correlation analysis was employed to investigate monotonic relationships between the number of years since the predominant land-use change and ecosystem carbon stocks across biomass and soil depth intervals. Additional correlation analyses were conducted to explore associations between vegetation attributes (e.g., tree density and biomass-derived carbon) and total ecosystem carbon stock. All analyses were performed at a 95% confidence level ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Characteristics of mangroves in study sites

Mangrove vegetation was present in both coastal and aquaculture-associated areas, but showed clear variation in density, species composition, and spatial continuity, forming a gradient rather than a strict division between intact and aquaculture-influenced systems (Fig. 2).

The overall stand density exhibited considerable fluctuations and lacked a consistent trend among various site types. Based on ecological standards, densities below 1000 individual per hectare are categorized as low or degraded (Jayadi *et al.,* 2024). In coastal sites, densities ranged from about 272.61 ± 234.86 individual per hectare at TPP to 648.14 ± 268.21 individual per hectare at TAP, with moderate values at PTP and TTP. In aquaculture-associated areas, densities ranged from 287.06 ± 89.16 individual per hectare at TTT to over 730 individual per hectare at PTT and TPT, in some cases exceeding nearby coastal areas, suggesting that traditional aquaculture does not always reduce mangrove structural density where vegetation is retained or rehabilitated. Throughout all locations, mangrove forests were primarily composed of *Avicennia marina*, especially in regions characterized by significant hydrological fluctuations, extensive salinity variations, and increased turbidity, including Tenjo Ayu and Patimban. These conditions favor *Avicennia marina* due to its tolerance to salinity fluctuations and unstable substrates, as well as its physiological flexibility under stress (Jacotot *et al.,* 2018). In contrast, *Rhizophora* spp. were more localized and associated with stable, marine-influenced environments such as Tanjung Pasir, where salinity was higher and turbidity lower, supporting prop-root systems. This distribution pattern aligns with prior documented associations between mangrove species and environmental circumstances (Alongi, 2014; Friess *et al.,* 2019; Sasmito *et al.,* 2019).

Biomass carbon partitioning under different mangrove land-use treatments

Total biomass per hectare showed strong site-to-site variability across coastal and aquaculture-associated ecosystems (Fig. 3). In all sites, AGB constituted the dominant component of total biomass, accounting for approximately 70–85% of the observed biomass, while BGB contributed a smaller but consistent share (15–30%). The relative proportions of AGB and BGB remained fairly stable across all locations, with averages of 80% and 20%, respectively. This observation is consistent with the biomass distribution of mangroves in other estuaries of Indonesia (Harefa et al., 2023). Among coastal sites, PTP recorded the highest total biomass = 103.88 ± 2.43 Mg/ha, followed by TAP (86.24 ± 4.19 Mg/ha) and TTP (86.71 ± 6.68 Mg/ha), whereas TPP showed markedly lower biomass (17.5 ± 10.63 Mg/ha). Within aquaculture-associated sites, TPT (95.39 ± 16.15 Mg/ha) and TTT (82.84 ± 17.46 Mg/ha) exhibited high biomass values comparable to or exceeding several coastal sites, while PTT showed moderate biomass (56.09 ± 3.2 Mg/ha) and TAT remained low (14.41 ± 6.26 Mg/ha). Correlation analysis confirmed that biomass was positively associated with stem density ($r = 0.84$, $p < 0.01$). Importantly, sites with comparable ecosystem classification often exhibited contrasting biomass levels, while aquaculture-associated sites sometimes supported biomass equal to or exceeding that of coastal sites. This illustrates that the classification of coastal versus aquaculture by itself fails to sufficiently account for the observed patterns in biomass. Instead, biomass distribution reflects site-specific conditions and land-use trajectories, reinforcing the need to interpret biomass outcomes at the site level rather than through generalized land-use labels.

Total ecosystem carbon stocks under different mangrove land-use treatments

Total ecosystem carbon stocks, encompassing AGC, BGC, and SOC, displayed significant spatial variability throughout the examined mangrove systems; however, there was no consistent distinction between coastal mangroves and those linked to aquaculture ponds. Across all stations, total carbon stocks ranged from approximately 97.65 ± 20.40 Mg C/ha at TAT to 331.90 ± 59.74 Mg C/ha at TPT, reflecting strong site-specific controls rather than a simple land-use effect (Fig. 4). This wide range underscores that mangrove carbon storage in intensively modified coastal landscapes is shaped by local environmental and management conditions, rather than by land-use classification alone.

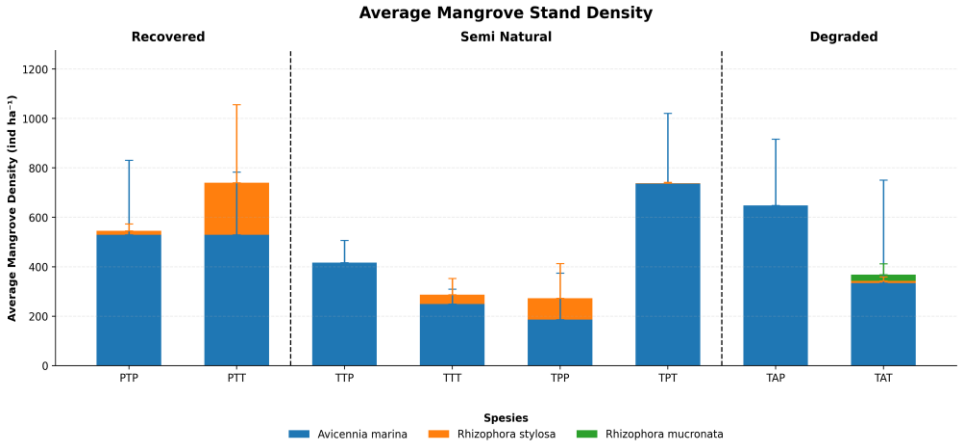

Fig. 2: Mangrove density in intact forest (PTP, TAP, TPP, TTP) and aquaculture areas (PTT, TAT, TPT, TTT) across different land-use categories, namely recovered, semi-natural, and degraded conditions

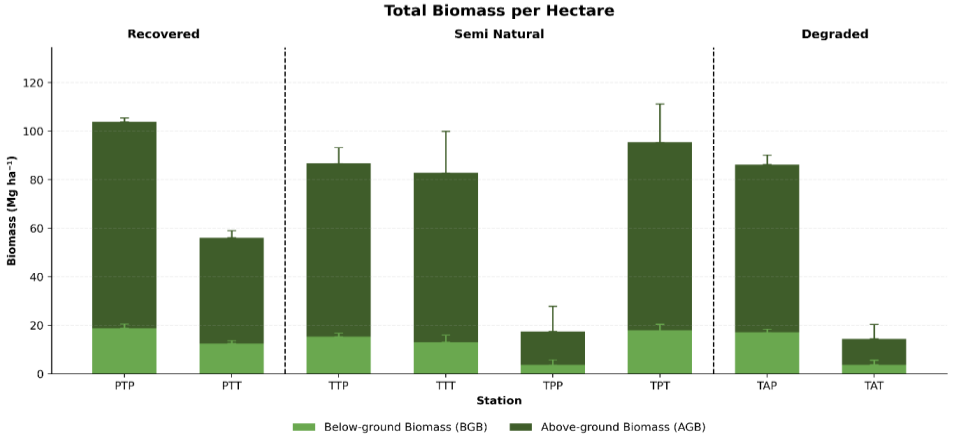

Fig. 3: Total Biomass per hectare of mangrove in intact forest (PTP, TAP, TPP, TTP) and aquaculture areas (PTT, TAT, TPT, TTT) across different land-use categories, namely recovered, semi-natural, and degraded conditions

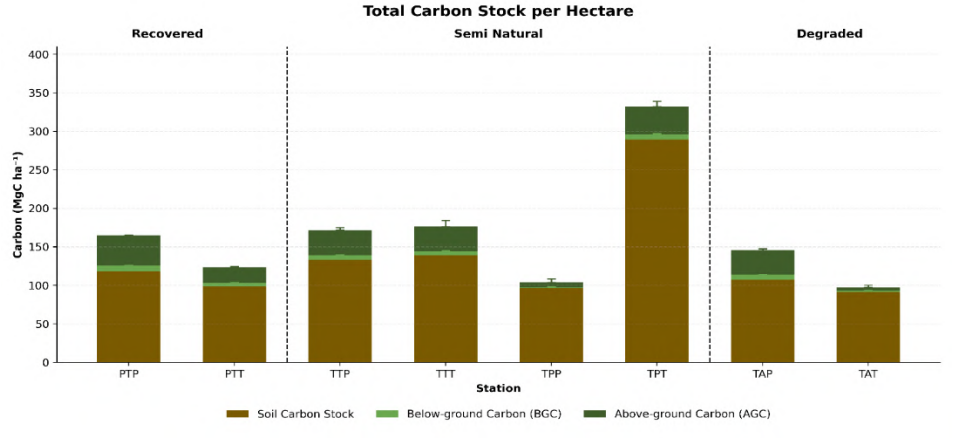

Fig. 4: Total carbon per hectare of mangrove in intact forest (PTP, TAP, TPP, TTP) and aquaculture areas (PTT, TAT, TPT, TTT) across different land-use categories, namely recovered, semi-natural, and degraded conditions

When carbon from all components was integrated, soil carbon consistently dominated total ecosystem carbon stocks, contributing approximately 71.8–93.5%, while biomass (AGC + BGC) accounted for 6.5–29%, consistent with global mangrove patterns (Bulmer *et al.,* 2016). Total carbon stocks were strongly correlated with SOC ($r = 0.92$, $p < 0.001$), whereas the relationship with biomass was weaker ($r = 0.54$, $p < 0.05$), indicating that vegetation alone cannot explain carbon variability. Analysis using non-parametric methods revealed no significant differences observed between mangroves found in coastal areas and those linked to aquaculture (Kruskal–Wallis test, $p = 0.7728$). However, carbon partitioning varied among sites, with some coastal areas showing relatively balanced contributions (~25–30% biomass), while others stored more than 90% of carbon in soils, indicating that vegetation degradation primarily reduces biomass while soil carbon remains dominant. The prominence of soil carbon signifies its capacity as a sustainable carbon sink in conditions characterized by anaerobic and fine-textured sediments that hinder decomposition (Ouyang *et al.,* 2017). This resilience is corroborated by studies that reveal soil carbon remains intact despite the influences of aquaculture. For instance, in Thailand, abandoned shrimp ponds retained soil carbon comparable to natural mangroves (Elwin *et al.,* 2019). Furthermore, in Ecuador, it was observed that ~80% of carbon persisted in subsurface sediments, even in the face of a total carbon loss of up to 70% (Merecí-Guamán *et al.,* 2021). Site-specific variation further highlights the role of sediment and hydrological conditions; for example, TPT showed high total carbon (331.90 ± 59.74 Mg C/ha) dominated by soil carbon (289.27 ± 59.28 Mg C/ha; ~87%), whereas TAT had the lowest total carbon (97.65 ± 20.40 Mg C/ha), likely due to more aerated sediments. Overall, these results indicate that carbon dynamics are primarily controlled below ground, and total ecosystem carbon alone is insufficient to explain carbon stability in mangrove systems.

Vertical distribution of soil organic carbon across mangrove systems

To further resolve the mechanisms underlying total ecosystem carbon storage, SOC was analyzed along vertical depth profiles to a maximum depth of 150 cm, subdivided into five intervals (0–15, 15–30, 30–50, 50–100, and 100–150 cm). This depth-based stratification method was created to account for both organic contributions from the surface and the deeper, enduring carbon accumulation that reflects sedimentary processes and historical ecosystem conditions. Across all sites, SOC exhibited pronounced vertical heterogeneity, indicating that carbon storage in mangrove soils is strongly depth-dependent rather than uniformly distributed throughout the soil profile (Fig. 5). Partitioning the drivers of SOC storage shows that bulk density exerts stronger control than carbon concentration, as %C declines with depth while bulk density increases, resulting in higher SOC stocks in deeper layers. This suggests that SOC buildup is predominantly driven by sediment mass rather than merely by carbon enrichment. The effect is especially evident in aquaculture-associated sites, where compacted subsurface sediments—formed through pond construction and drainage—exhibit higher bulk density. Notwithstanding the reduced %C, these layers preserve substantial SOC stocks owing to the augmented sediment mass, especially at depths of 50–100 cm, underscoring the significant influence of physical sediment characteristics on long-term carbon storage. SOCCorrelation analysis supports this pattern: bulk density was negatively correlated with %C ($r = -0.43$, $p > 0.29$), while SOC stocks showed a weak, non-significant relationship with bulk density ($r = -0.24$, $p > 0.56$),

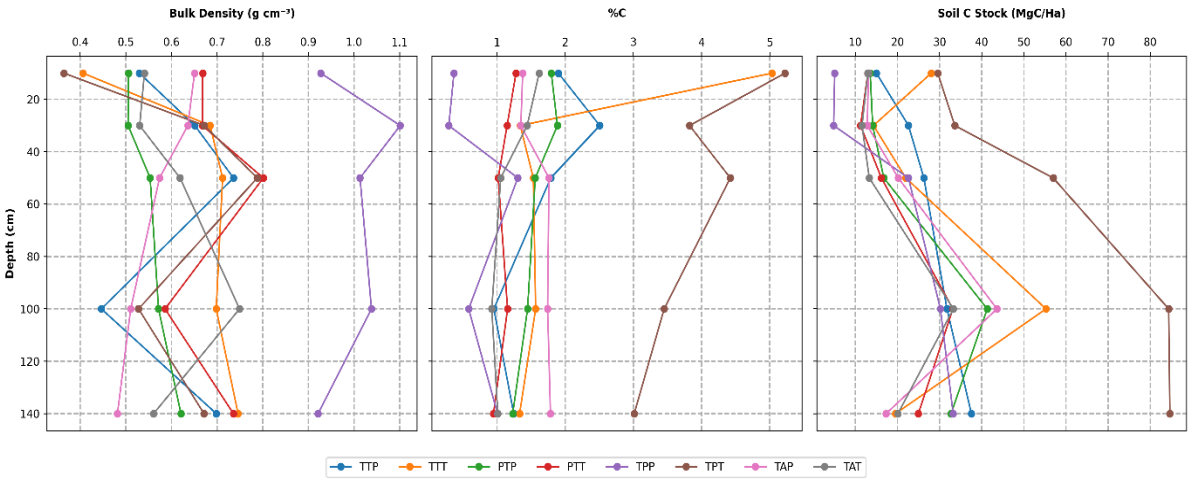

Fig. 5: Vertical distribution of soil properties along the soil profile: (a) Bulk Density, (b) Percent Carbon Content (%C), and (c) Soil Carbon Stock (Mg C /ha)

indicating a compensatory effect rather than limitation. SOC stocks were positively related to vegetation density ($r = 0.42$, $p > 0.30$), emphasizing the importance of organic inputs. Statistical evaluations additionally substantiated depth as an essential element, revealing significant variations in SOC across various layers ($\chi^2 = 39.889$, $p < 0.001$), and deeper layers (50–100 cm and >100 cm) storing significantly more carbon than surface soils. Although surface layers contain fresher organic matter, their lower bulk density and thinner profiles limit total carbon storage, demonstrating that surface measurements alone underestimate the full carbon storage capacity of mangrove soils. The dominance of SOC in the 50–100 cm depth interval is evident when expressed as cumulative stock (Fig. 6), showing that carbon storage is governed more by sediment mass and long-term stabilization than by surface carbon concentration. Although surface layers (0–30 cm) exhibit an increased %C from recent litter and root inputs; however, their contribution is restricted by reduced bulk density and thinner horizons. In contrast, the 50–100 cm layer consistently contributes the largest share of SOC due to greater compaction, thicker sediment accumulation, and persistent anoxic conditions that reduce decomposition. These patterns are presumably affected by the interplay of physical and biogeochemical processes, in which diminished oxygen availability in deeper soil layers limits decomposition rates and promote long-term carbon stabilization (Alongi, 2014; Kristensen *et al*., 2008). This layer incorporates carbon over extended periods and is largely insulated from surface disruptions, which accounts for the similarity in total ecosystem carbon stocks between coastal and aquaculture systems, even with variations in vegetation structure. Depth patterns were generally consistent across sites, though some variation occurred. Coastal sites with intact vegetation (e.g., PTP, TTP) showed higher SOC in surface and mid-layers due to continuous organic input, whereas aquaculture-associated sites often had lower SOC but retained high carbon stocks at depth. This vertical decoupling indicates that deep SOC pools persist despite surface disturbance and represent the most stable component of carbon storage. Consequently, reliance on surface soils or biomass alone underestimates total carbon storage and misrepresents ecosystem resilience. This underscores the necessity to concentrate on subsurface processes and controlling environmental factors, including sediment characteristics and hydrology.

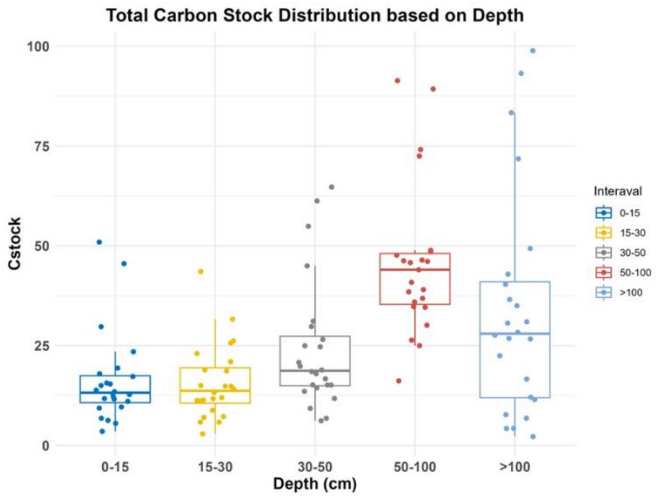

Fig. 6: Distribution of soil carbon stock per depth

Controls on carbon storage: effects of land-use treatment, sediment characteristics, and hydrological proxies

The Kruskal–Wallis test showed no significant differences in total ecosystem carbon stocks among degraded, recovered, and semi-natural mangrove systems (χ^2 = 5.10, df = 2, p = 0.078). Pairwise comparisons using Dunn's test with Bonferroni correction further confirmed the absence of statistically significant differences between categories, although a marginal trend was observed between degraded and semi-natural systems (adjusted p = 0.099). The effect size was small (η^2 = 0.027), suggesting that the variation in total carbon stock among different land-use categories was restricted. The comprehensive results of the statistical analyses are summarized in Table 3.

The absence of major differences in overall ecosystem carbon stocks among land-use categories does not imply that these categories lack ecological relevance. Rather, it highlights an important limitation of total carbon as a sole indicator, as large and persistent soil carbon pools—particularly in deeper layers—can mask differences associated with vegetation structure, disturbance intensity, and land-use history. This is particularly significant in mangrove ecosystems, where deep soil carbon serves as a long-term legacy reservoir that is relatively unaffected by recent land use changes. Consequently, while categorical distinctions such as recovered, semi-natural, and degraded systems capture meaningful differences in ecological condition and management trajectory, these differences are more clearly reflected in carbon partitioning, biomass structure, and vertical carbon distribution than in total ecosystem carbon stocks alone. This conclusion highlights the importance of conducting process-oriented evaluations that incorporate subsurface carbon dynamics in the assessment of land-use change impacts within coastal mangrove ecosystems. Mean total carbon stock reached 144.22 ± 29.32 Mg C/ha in the recovered site, 196.04 ± 96.47 Mg C/ha in semi-natural systems, and 121.63 ± 33.91 Mg C/ha in degraded conditions, with overlapping values explaining the absence of statistical significance. Aboveground biomass declined from 29.62 ± 13.49 Mg C/ha (recovered) to 26.76 ± 13.66 Mg C/ha (semi-natural) and 18.38 ± 19.04 Mg C/ha (degraded), while deeper soil carbon showed the opposite trend. Correlation analysis indicated no significant relationship between time since land-use change and total carbon (ρ = 0.21, p = 0.79) or

Table 3: Results of Kruskal–Wallis and Dunn's post-hoc tests for differences in ecosystem carbon stocks across mangrove land-use categories

Analysis	Comparison	Test statistic	df	p-value	Adjusted p-value	Interpretation
Kruskal–Wallis	All categories (degraded, recovered, semi-natural)	$\chi^2 = 5.10$	2	0.078	–	Not significant
Dunn test (Bonferroni)	Degraded vs Recovered	Z = -0.61	–	0.542	1	Not significant
Dunn test (Bonferroni)	Degraded vs Semi-natural	Z = -2.13	–	0.033	0.1	Marginal (trend)
Dunn test (Bonferroni)	Recovered vs Semi-natural	Z = -1.43	–	0.154	0.461	Not significant
Effect size	All categories	$\eta^2 = 0.027$	–	–	–	Small effect

biomass (ρ = 0.11, p = 0.89), although deeper SOC (100–150 cm) showed a stronger but non-significant association (ρ = 0.74), suggesting that deep soil carbon reflects long-term processes rather than recent changes. Site-level patterns further highlight the role of environmental history and management. Tanjung Pasir exhibited high total carbon (217.86 ± 161.27 Mg C/ha), likely reflecting long-term sediment stability and legacy carbon accumulation rather than recent interventions, consistent with findings that deep soil carbon can persist despite land-use change (Donato *et al.,* 2011). In contrast, the ~13-year-old restored site at Patimban stored lower carbon (144.22 ± 29.32 Mg C/ha), indicating that biomass recovery has not yet translated into substantial soil carbon accumulation, a pattern commonly reported in restoration chrono sequences. The results reveal that the recovery process of mangroves is characterized by asynchronous carbon dynamics, where aboveground biomass can regenerate relatively swiftly, while soil carbon—especially in deeper layers—takes much longer to recover. This suggests that the most critical phase of ecosystem recovery is the re-establishment of hydrological connectivity and sediment processes that enable long-term soil carbon accumulation, rather than the initial phase of vegetation regrowth alone. Vegetation characteristics, including species composition and stand structure, may contribute to differences in carbon resilience by influencing biomass recovery and belowground carbon inputs, although these mechanisms were not explicitly quantified in this study. Tanjung Tiga showed intermediate carbon (174.21 ± 3.02 Mg C/ha) with relatively high biomass (32.49 ± 0.50 Mg C/ha) but moderate soil carbon, while the degraded Tenjo Ayu site had the lowest carbon stock (121.63 ± 33.91 Mg C/ha), reflecting losses in both biomass and soil pools under prolonged disturbance. The disparities in carbon storage are probably due to sediment and hydrological conditions. Fine-textured, compact, and anoxic sediments promote higher SOC storage (Harefa *et al.,* 2025), consistent with evidence that sediment properties dominate mangrove carbon dynamics (Donato *et al.,* 2011). Hydrological connectivity probably governs carbon retention by managing sediment input and redox conditions, which interact with sediment properties to affect carbon storage. Sediment composition affects nutrient availability and redox dynamics, while salinity and nutrient conditions further regulate decomposition and carbon stabilization processes. Although hydrological connectivity was not directly measured in this study, its influence is inferred based on observed site conditions and is consistent with regional patterns reported for Indonesian mangrove systems, where tidal exchange and sediment dynamics strongly regulate carbon storage (Sasmito *et al.,* 2020). Locations exhibiting significant tidal exchange due to suitable tidal frequency, duration of inundation, and water flow can facilitate sediment deposition and sustain anoxic conditions that promote carbon preservation (Wang *et al.,* 2025; Guo *et al.,* 2024). However, excessive water exchange or disturbance may enhance oxygenation, sediment resuspension, and carbon export, potentially increasing carbon loss (Alongi, 2014; Lovelock *et al*., 2017; Adame and Lovelock, 2011; Sasmito *et al*., 2020). These patterns may reflect differences across the study sites: Tanjung Pasir likely benefits from sustained tidal connectivity, Tenjo Ayu

exhibits reduced deep SOC associated with restricted water exchange, and Patimban shows biomass recovery but slower soil carbon accumulation (Kang *et al.,* 2025). Nevertheless, an overabundance of water exchange or disruption could improve oxygen levels, lead to sediment resuspension, and facilitate carbon export, which may result in a heightened carbon loss. In addition to biophysical factors, differences in carbon storage across sites may also reflect variations in local management practices and community engagement. Sites with sustained community involvement and better-managed hydrological conditions may support more stable carbon retention, whereas areas with limited management or unclear tenure systems may be more vulnerable to degradation and carbon loss. While these factors were not assessed in quantitative terms, insights from field observations and local interviews imply that governance and management have an indirect yet significant influence on long-term carbon outcomes. Overall, these findings suggest that hydrological connectivity and sediment characteristics, rather than land-use category alone, play an important role of mangrove carbon storage, particularly in deep soil pools (Guo *et al.,* 2024; Kauffman *et al.,* 2020).

Implications for mangrove carbon management and coastal land-use policy

This study indicates that in managed coastal landscapes, the carbon storage of mangroves is primarily influenced by soil carbon pools, which are developed through prolonged sedimentary and hydrological processes rather than short-term vegetation dynamics. Soil carbon contributes more than 70–90% of total mangrove carbon stocks globally, meaning that approaches focused only on mangrove extent or aboveground biomass risk misrepresenting carbon permanence and vulnerability (Kauffman *et al.,* 2020; Sanderman *et al.,* 2018). Consequently, blue carbon strategies that emphasize tree cover gains without addressing subsurface processes may overestimate mitigation benefits and underestimate long-term emissions risks. The effectiveness of silvofishery systems is conditional. Semi-natural systems such as Tanjung Pasir (217.86 ± 161.27 Mg C/ha) and Tanjung Tiga (174.21 ± 3.02 Mg C/ha) can maintain high carbon stocks where tidal connectivity and sediment stability persist, consistent with findings from Southeast Asia showing that mangrove-integrated aquaculture retains substantial ecosystem carbon, particularly in soils (Perwitasari *et al.,* 2020; Royna *et al.,* 2024; Bosma *et al.,* 2012; Phung *et al.,* 2023). In contrast, degraded systems such as Tenjo Ayu (121.63 ± 33.91 Mg C/ha) demonstrate that silvofishery alone is insufficient when hydrology is disrupted and sediments are compacted, leading to carbon loss (Lovelock *et al.,* 2017). Recovered systems like Patimban (144.22 ± 29.32 Mg C/ha) demonstrate that biomass recovery may happen at a quicker rate than the accumulation of soil carbon, suggesting that carbon recovery is not yet complete. Governance and local management strongly influence carbon outcomes. Community-based management at Tanjung Pasir, including maintaining tidal access and limiting tree removal, aligns with high carbon storage and reflects broader evidence that participatory governance improves ecosystem sustainability (Datta *et al.,* 2012; Romañach *et al.,* 2018). Conversely, inadequate institutional support and the persistent expansion of ponds in Tenjo Ayu are associated with diminished carbon stocks and ongoing degradation, aligning with trends of ineffective governance that contribute to to ecosystem decline (Romañach *et al.,* 2018; Aditya *et al.,* 2021). International examples from Vietnam and Ecuador further demonstrate that policies emphasizing mangrove retention, hydrological integrity, and secure tenure are more effective than area-based planting targets alone (Thao and Cong, 2023; López-Rodríguez, 2020). Should the existing land-use patterns continue, it is probable that degraded mangrove ecosystems will face ongoing carbon depletion, especially from deep soil reservoirs that take a considerable amount of time to recuperate after being disturbed (Goldberg *et al.,* 2020). Effective management should therefore prioritize protecting existing soil carbon, maintaining

hydrological connectivity, and minimizing sediment disturbance. Restoration must be process-based—focusing on hydrology and sediment dynamics rather than planting alone—as failure to restore these processes often results in poor outcomes and limited carbon gains (Lewis, 2005; Romañach *et al.,* 2018). In summary, maintaining mangrove carbon stocks necessitates the incorporation of ecological processes, governance, and community-based management into coastal development planning.

CONCLUSION

This study demonstrates that mangrove ecosystems in intensively managed coastal landscapes are characterized by high spatial variability and cannot be adequately described using a simple dichotomy between intact and aquaculture-associated systems. The continuum of mangrove structure, composition, and carbon storage is instead shaped by local environmental factors, hydrological patterns, and the history of land-use. Mangrove stands across all sites exhibited relatively low densities, yet biomass and structural attributes varied widely, with some aquaculture-associated areas supporting biomass comparable to or exceeding that of coastal sites. The results imply that the effect of land-use classification on overall ecosystem carbon stocks is not distinctly discernible with the existing sampling design, likely due to substantial spatial variability and the dominance of long-lasting soil carbon pools. Total ecosystem carbon stocks also showed substantial variability, ranging from 97.65 ± 20.40 Mg C/ha to 331.90 ± 59.74 Mg C/ha, with no statistically detectable differences between coastal and aquaculture-associated systems under the current sampling design. Across all sites, soil organic carbon overwhelmingly dominated total carbon storage, contributing between 71.8% and 93.5%, while biomass accounted for a comparatively minor proportion. This emphasizes that the dynamics of carbon in mangroves are mainly influenced by belowground activities instead of solely by aboveground vegetation. The weak relationship between biomass and total carbon further reinforces that vegetation metrics cannot fully capture carbon ecosystem storage, particularly in modified landscapes where soil carbon pools remain relatively intact despite variations in biomass. The analysis of the vertical distribution of soil carbon indicated a marked dependency on depth, where deeper soil layers played a disproportionately large role in total carbon storage. Although surface soils contained higher organic carbon concentrations, their overall contribution was limited by lower bulk density and shallower depth. In contrast, deeper layers, particularly within the 50–100 cm interval, consistently stored the largest share of carbon due to higher sediment mass, compaction, and persistent anoxic conditions that reduce decomposition. This depth-related pattern reveals that the processes of sedimentation are the main drivers of long-term carbon accumulation, as opposed to recent organic inputs, and highlights that deep carbon soil is the most stable and key component of carbon storage within mangroves. Although deep soil carbon pools represent the most stable and dominant component of mangrove carbon storage, they can become vulnerable under conditions of erosion, hydrological alteration, or intensive land-use, which may expose previously protected carbon to decomposition and loss. Consequently, assessments based solely on surface soils or vegetation significantly underestimate total carbon stocks and ecosystem resilience. Variations in carbon storage across different sites were probably influenced by sediment properties, hydrological connections, and management history rather than by land-use category. Sites with fine-textured, compact, and anoxic sediments supported higher carbon stocks, while hydrological connectivity played a critical role in maintaining sediment deposition and limiting carbon loss. Systems with sustained tidal exchange exhibited higher and more stable carbon storage, whereas hydrological isolation and prolonged disturbance were associated with reduced carbon stocks. The systems that were recovered demonstrated signs of biomass recovery; however, there was minimal accumulation of soil carbon. This suggests that

subsurface carbon pools react more gradually to restoration efforts. In contrast, long-term stable systems retained substantial legacy carbon in deeper sediments, while degraded systems exhibited declines in both biomass and soil carbon under continued disturbance. These findings underscore the need to shift mangrove carbon management from a vegetation-centric perspective toward a process-based approach that prioritizes soil carbon conservation, hydrological integrity, and sediment dynamics. Management strategies ought to prioritize the preservation of current carbon-rich soils, the maintenance of tidal connectivity, and the reduction of sediment disturbance, especially in areas impacted by aquaculture development. Restoration efforts should be designed to address hydrological and sedimentary processes prior to or alongside planting, with realistic expectations regarding the timescales of carbon recovery. Overall, sustaining mangrove carbon stocks in working coastal landscapes requires integrating ecological processes with adaptive management and long-term planning, ensuring that both surface and subsurface components of the ecosystem are effectively conserved. These findings further emphasize that efficient governance and community-driven management are crucial for preserving hydrological integrity and safeguarding soil carbon in mangrove ecosystems experiencing land-use transformation. Although not explicitly assessed in this study, future climate-driven changes, including sea-level rise, increased storm intensity, and rising temperatures, are likely to influence mangrove carbon dynamics by altering hydrological connectivity, sediment deposition, and decomposition processes. These adjustments may also have further implications for the stability of soil carbon reservoirs, especially in mangrove environments that have already experienced the effects of land-use changes, where disruptions in hydrology and sediment disturbances can increase the risk associated with stored carbon. Future changes in sea level, storm intensity, and temperature may further alter hydrological regimes and sediment dynamics, with potential implications for carbon stability, particularly in systems already affected by land-use change. These results should be interpreted with caution, as limited replication and high variability may reduce statistical power and constrain the detection of differences among land-use categories.

AUTHOR CONTRIBUTION

D.G.K. Ketaren developed the study framework and prepared the initial draft of the manuscript. F. Sidik supervised the overall research project and provided critical review of the manuscript. I.M. Radjawane contributed through research supervision and literature review, while H. Latief supported the study through supervision and literature review activities. S.W. Trenggono provided critical comments to improve the manuscript. M.I. Akbar was involved in field sampling and data collection during the research. J.A.L. Raja contributed by providing essential data to support the study. M.A. Farkhan assisted in conducting laboratory analyses. S. Maharani contributed to data analysis, editing, and interpretation of the results. K. Kasim supported the development of the conceptual framework and contributed to the literature review. All authors reviewed and approved the final version of the manuscript prior to publication.

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CONFLICT OF INTEREST

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

ABBREVIATIONS

>	Greater than
<	Less than
%	Percent
%C	Percent carbon
°	Degree
°C	Degree Celsius
S	South
E	East
A.	Avicennia
AGB	Above-ground biomass
AGC	Above-ground carbon
BD	Bulk Density
BGB	Below-ground biomass
BGC	Below-ground carbon
C	Carbon
cm	Centimeter
DBH	Diameter at Breast Height
Di	Species density
Fi	Species frequency
Fig.	Figure
ha	Hectare
IVI	Importance value index
m	Meter
Mg	Megagram
Mg/ha	Megagrams per hectare
Mg C/ha	Megagrams of carbon per hectare
MTCRC	Marine Technology Cooperation Research Center
NTU	Nephelometric turbidity unit
p	Significance value (p-value)
ppt	Parts per thousand
PTP	Patimban coastal
PTT	Patimban pond
r	Correlation coefficient
R.	Rhizopora
RDi	Relative density
RFi	Relative frequency
SOC	Soil organic carbon
sp.	Species
TAP	Tenjo Ayu Coastal
TAT	Tenjo Ayi Pond
TPP	Tanjung Pasir Coastal
TPT	Tanjung Pasir Pond
TTP	Tanjung Tiga Coastal
TTT	Tanjung Tiga Pond
χ^2	Chi-square statistic

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ORIGINAL RESEARCH ARTICLE

Factors influencing methane emissions in rice paddies using alternate wetting and drying method

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ABSTRACT

BACKGROUND AND OBJECTIVES: Addressing global food security, rice is one of the fundamental food sources, particularly in Southeast Asia where traditional flooded rice cultivation is a major methane source. Conventional techniques encourage anaerobic breakdown in saturated soils, resulting in methane emissions, where effective water management being a significant determinant. The study objectives were to investigate rice cultivation under different alternate wetting and drying water management practices, while measuring methane concentration using the closed chamber method.

METHODS: This study investigated methane emissions from irrigated rice under five water management treatments, with the control being continuous flooding (Treatment 1), maintained at 5 centimeters. The alternate wetting and drying methods exhibited differences in the initial water depth with. Treatment 2 followed the Thailand standards with 5 centimeters water depth, while Treatment 3, 4, and 5 applied alternate wetting and drying depths of 1, 10, and 20 centimeters, respectively. The study was carried out in the rice cultivation season utilizing lysimeter systems. The methane flux was measured weekly together with other environmental parameters.

FINDINGS: Rice treatments showed differences in water use and methane emissions. The application of alternate wetting and drying at 1 and 5 centimeters has led to a reduction in irrigation water usage by over 40 percent. Rice growth generally increased through the growth stages, with no significant differences. methane emissions varied. Treatment 5 and 1 produced the highest methane fluxes (19.88 ± 1.02 and 17.45 ± 10.67 milligram per square meters per hour, followed by Treatment 4, while 2 and 3 showed the lowest emissions (7.37 ± 3.29 and 3.06 ± 2.35 milligram per square meters per hour). During the heading stage, methane emissions were at their peak, as plant biomass, root exudates, and aerenchyma had fully matured. Under alternate wetting and drying conditions, higher dissolved oxygen and oxidation-reduction potential were also seen.

CONCLUSION: Water level is the controlling factor for methane emissions in rice paddies. During the heading stage, methane emissions were at their peak, as plant biomass, root exudates, and aerenchyma had fully matured. While frequent wetting drying cycles promoted oxygen diffusion and methane oxidation. The study revealed that employing the alternate wetting and drying technique is a viable approach to managing water resources, leading to improved water-use strategy and a reduction in methane emissions during rice farming.

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INTRODUCTION

Global warming and climate change are major problems caused by the increase in greenhouse gas (GHG) emissions. The agricultural industry has been identified as a major factor in global GHG emissions, especially in developing countries such as Thailand, where rice farming serves as one of the main contributors. In 2023, Thailand emitted approximately 91.63 million tons of carbon dioxide equivalent. Thailand is an agricultural country with a rice cultivation area of approximately 50 million hectares (Mha) with 19 percent (%) of the total land area (Office of Agricultural Economics, 2021) and is also one of the world's major rice exporters (FAO, 2021). At present, the increasing demand for rice consumption due to the growing global population has led to increased rice production (*Oryza sativa L.*), which consequently results in higher methane (CH_4) emissions (Lakshani *et al.*, 2023). In standard agricultural practices, it is noted that the majority of Thai farmers frequently utilize continuous flooding (CF) for rice cultivation, which has been proven to boost production as a result of the anaerobic conditions fostered by flooding. Water management is one of the key factors influencing CH_4 emissions in rice paddies (Lakshani *et al.*, 2023). Extended periods of flooding result in anaerobic soil conditions, facilitating the decomposition of organic matter by anaerobic microorganisms. This procedure generates substrates that are later transformed into methane (CH_4), which can be emitted into the atmosphere from rice paddies through diffusion, ebullition (bubble release), and plant-mediated transport via the aerenchyma tissues of rice plants particularly during the tillering and flowering stage of rice growth (Wang *et al.*, 2021).Plant-mediated transport through the aerenchyma is generally the dominant pathway of CH_4 emission in rice systems, (Rajendran *et al.*, 2024a). Although CF promotes rice growth effectively, it is a major factor contributing to CH_4 emissions. Currently, an alternative water management technique referred to as alternate wetting and drying (AWD) has become increasingly popular. AWD consists of the periodic flooding and drying of the soil, which facilitates the diffusion of oxygen (O_2) into the soil and establishes aerobic conditions, consequently decreasing CH_4 production (Xiao *et al.*, 2025). This growing method does not only reduce CH_4 emissions but also improves water-use efficiency without negatively affecting rice yield (Loaiza *et al.*,2024). The findings of this study can suggest improving rice cultivation practices by emphasizing efficient water management, maintaining yield while reducing CH_4 emissions. With emphasis on water management strategies that mitigate CH_4 emissions while maintaining rice productivity. In this regard, the AWD is recognized for its ability to lower CH_4 emissions from rice fields, although its effectiveness often influenced by factors such as water-management intensity (drying duration), soil conditions, rice growth stage, and local climate. Consequently, the objective is to enhance the AWD from a broad mitigation approach into a management strategy that is specific to water depth by determining the circumstances in which AWD continues to be effective or loses its CH_4 mitigation advantage. This study focused on CH_4 emission from rice paddies as it is regarded as the dominant greenhouse gas pathway. Consequently, CH_4 was identified as the key element in analyzing how AWD water depth and drying frequency influenced reduced soil conditions and CH_4 emission. This study investigates whether the mitigation of CH_4 is contingent not only upon wetting–drying cycles but also on variables including water depth, drying duration, and soil aeration intensity. By linking water-level dynamics with dissolve oxygen (DO), oxidation and reduction potential (ORP), rice growth, and CH_4 fluxes, together with physical and biological factors, this study aims to identify a potential hydrological threshold for AWD treatments that can enhance soil aeration and suppress CH_4 emissions at the King's Royally Initiated Laem Phak

Bia Environmental Research and Development Project (LERD), Phetchaburi Province, Thailand, in 2025.

MATERIALS AND METHODS

Study site

This study was conducted at (LERD) Project, Phetchaburi Province, located on the western coast of Thailand (coordinates 13.0490919°N, 100.0883058°E). The area has a tropical monsoon climate with distinct wet and dry seasons (Thai Meteorological Department, 2025) (Fig. 1). The experiment was conducted during Thailand's rainy season, which coincides with the rice growing season, between July and November 2025, at the plot scale, with rice grown within a lysimeter system.

Experimental design

This experiment focused on cultivating rice based on the AWD principle, incorporating different water levels. The adjustments to the water levels spanned the rice growth period, which lasted from 10 to 80 days post-planting. Treatment 1 (T1) was used as a control following the traditional CF water management system, maintaining a constant water level of 5 centimeters (cm) above the soil surface. Treatment 2 (T2) was the standard Thailand AWD wet-and-dry management system, using a water level of 5 cm and allowing the soil to dry to 15 cm below the surface (Royal Irrigation Department, 2015). Treatments 3 (T3) to Treatment 5 (T5) used the same AWD principle as T2 but with different water level adjustments: T3: 1 cm, Treatment (T4): 10 cm, and Treatment (T5): 20 cm, respectively. Overall, there were three replications implemented for every treatment, amounting to 15 experimental units. Prior to 80 days, approximately 60 days of the AWD cycle, 50% of the total experimental period, the rice has now entered the heading stage, the water level was adjusted and maintained at 5 cm in all experimental treatments, while 15 days before harvest, the water was drained from all experimental units (Fig. 2). The designated water intended to illustrate a systematic gradient in water management conditions, where, according to the Royal Irrigation Department (2016) identified a depth of 5 cm as the standard for the conventional AWD method. The 1 cm treatment represented a shallow-ponding, near-saturated soil condition as this was based on the rice is depended on the water-saturated or flooded soil, a condition that optimizes nutrient availability (Kima *et al.,* 2014) , while 10 cm and 20 cm were included as progressively deeper water levels to test whether increasing depth affects the anaerobic conditions and alters CH_4 emissions. This gradient facilitated the assessment of both agronomic significance and potential threshold responses in CH_4 production across various water management strategies (Molla *et al.,* 2021). The rice variety used in this experiment was the Chainat 1 rice variety, where this variety was most popular rice variety grown in Phetchaburi province, especially in irrigated areas. The soil employed in the experiment was obtained from irrigated rice paddies in Phetchaburi Province and dried. A lysimeter system was used for rice cultivation to manage all environmental conditions, with each lysimeter having dimensions of 80 cm in height and 80 cm in diameter. The lysimeter structure consisted of three layers: a 10 cm bottom layer of gravel and sand, a middle layer of planting soil 40 cm thick, and a top water layer (Fig. 3). In the assessment of water levels, each experimental unit was comprised of a 70 cm tall polyvinyl chloride (PVC) pipe, which was fitted with holes drilled at 5 cm intervals around its circumference (Fig. 3b). In the rice planting structure, five sub plots of rice seedlings were planted in each lysimeter, with three seedlings per plot, spacing 15 cm apart and 10 cm from the edge of the pond to ensure the rice plants received adequate light and other factors from the lysimeter. Before planting in the lysimeters, seedlings were cultivated in a seedling nursery for 10 days. The seedling cultivation process followed the RRDD, (2015) (Fig. 3a).

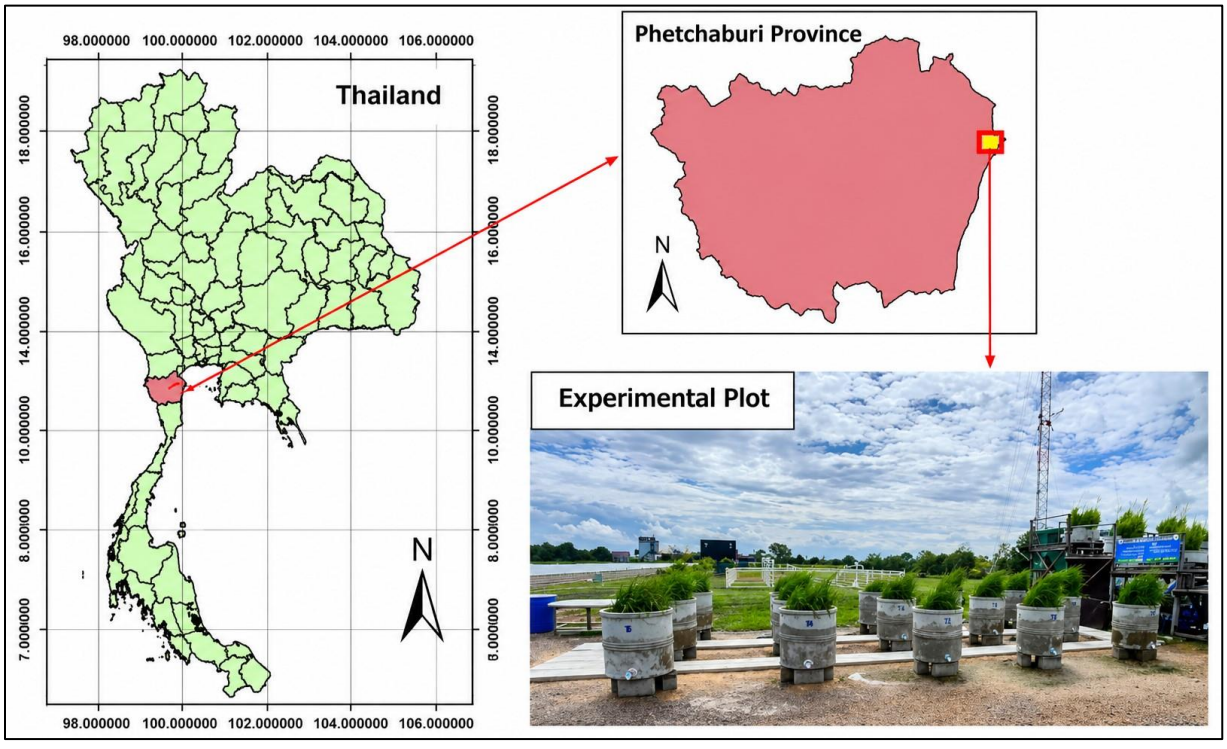

Fig. 1: Geographical location of the study area in Phetchaburi Province, Thailand

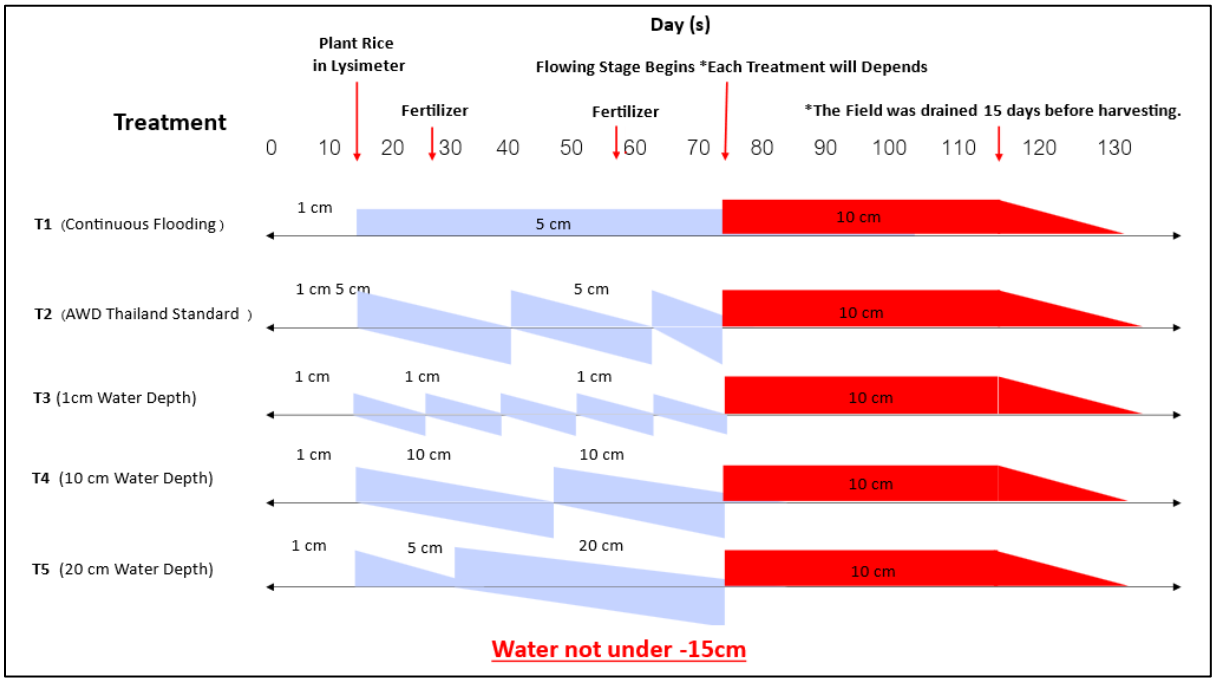

Fig. 2: Water-level management under continuous flooding and alternate wetting and drying treatments during the rice-growing period

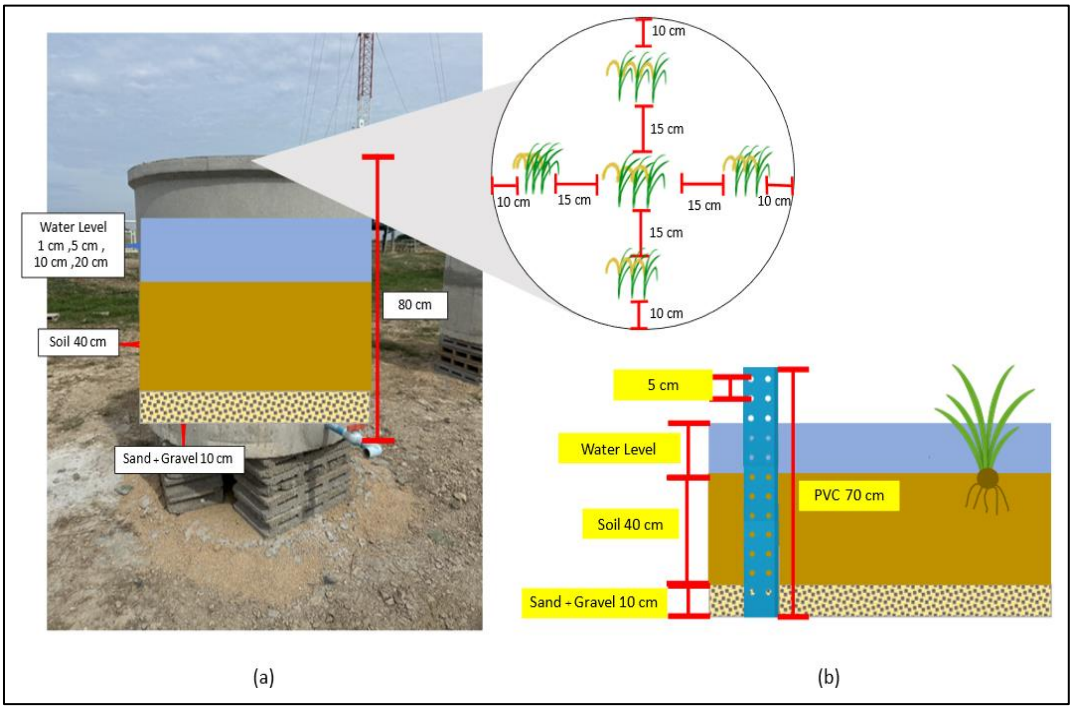

Fig. 3: Water and planting system

In accordance with the standard rice growing practices in Thailand, chemical fertilizers were administered to all treatments as a control. The first application took place 15 days after transplanting, using a 16-16-8 formula at a rate of 9.43 grams for each experimental unit. The second application was during the heading stage (approximately 60 days old), using a 46-0-0 formula at a rate of 9.43 grams per experimental unit. (RRDD, 2015) (Fig. 3). The water table in each lysimeter was measured daily throughout the experiment to monitor water depth dynamics, visible cracking and determining of irrigation timing for each treatment. Daily precipitation and evaporation rates were documented and utilized to analyze variations in water level within the lysimeter system. All lysimeters were situated within a designated experimental zone of approximately 50 meter (m) × 50 m (Fig. 1), rainfall input was assumed to be similar across all treatments as this experiment was conducted during Thailand's regular growing season. With respect to water loss or seepage, the lysimeters were constructed of concrete and further sealed with a waterproof coating.

Methane Sampling and Analysis

In measurement of the CH_4 concentrations gas samples were taken every 7 days for an 18-week rice growing period of rice cultivation. The closed chamber method (Chamber Acrylic 80 x 80 cm) (Fig. 4) was utilized for measurements, along with a gas chromatography (GC) model 55i calibrated every 2 months during the study (Thermo Fisher Scientific Inc., USA). The chamber remained sealed for a duration of 10 minutes (min), during which gas samples were collected every 1 min for a total of 15 min for each experimental unit. The CH_4 flux was then calculated (Eq. 1). Gas measurements were taken between 10:00 and 14:30 (Bunquin *et al.,* 2024). The obtained values were calculated CH_4 flux emissions, using Eq. 1 NIAESM (2015):

$$Flux\ CH_4 = \rho CH_4 \times \frac{V}{A} \times \frac{dC}{dt} \times \frac{273}{273+T} \quad (1)$$



Fig. 4: Closed chamber method applied for methane measurements in the lysimeter

where:

Flux CH_4 = CH_4 flux emission in milligram per square meter per hour ($mg/m^2/h$)

ρ = density of CH_4 gas at standard conditions with 0.716 kilograms per cubic meter (kg/m^3)

V = Chamber volume (m^3)

A = Cover surface (m^2)

dC/dt = Rate of change in CH_4 concentration inside the chamber in Parts Per Million per Hour (ppm/h)

T = Chamber temperature in degrees Celsius (°C)

The closed chamber method was selected based on its practical and widely accepted method for measuring CH_4 emissions in rice paddies. This study subsequently utilized the Methodological guidelines for paddy rice, which recommended that weekly sampling occur between 10:00 and 14:00, as this timeframe would yield emission data that is comparable to other studies (NIAESM, 2015). However, the frequency of weekly measurements may emission actual trend peak, studies have shown that this sampling frequency can estimate growing-season CH_4 emissions at about 93–106% of higher-frequency measurements. Consequently, it was determined that weekly sampling would be adequate to yield a reliable estimate of the average total CH_4 emissions (NIAESM, 2015).

Water quality and growth monitoring

Water quality monitoring was performed in conjunction with gas concentration and plant growth monitoring to assess environmental factors affecting CH_4 formation in rice paddy systems. Water quality assessment was performed at depths of 5, 15, and 25 cm beneath the soil surface, measuring the following parameters: 1) Potential of hydrogen (pH), 2) DO, and 3) ORP with analysis conducted according to the American Public Health Association (APHA, 2017) standards. The growth monitoring of rice plants is conducted in accordance with the guidelines established by the International Rice Research Institute (IRRI, 2013), utilizing various parameters for assessment including: 1) Height, 2) Number of tillers, and 3) Stem circumference.

Other data measurements

This study further compiled meteorological parameters for analysis alongside CH_4 emission data to gain insights into the environmental factors affecting CH_4 emissions from rice paddy systems. The collected parameters included air

temperature, photosynthetically active radiation (PAR), Relative humidity, rainfall, and evaporation.

Data Analysis

Data collected from CH_4 flux measurements, water quality assessments, observations of rice growth, yield evaluations, water usage metrics, and other pertinent environmental factors were examined to identify differences across different water management treatments. One-way analysis of variance (ANOVA) was used to test treatment effects at a significance level of $p < 0.05$. When significant differences were detected, Duncan's Multiple Range Test (DMRT) was applied for post hoc comparison among treatments.

RESULTS AND DISCUSSION

Water use irrigation

The amount of irrigation water utilized in each experimental unit (Fig. 5) exhibited notable variations among the five treatments. It was found that T5 and T1 had the significantly highest total water usage, at 798.52 ±39.21 liters (L) and 800.81 ±77.65 L, respectively, while T3 had the lowest total water usage, averaging 486.63 ±38.56 L, representing a water saving of more than 40% compared to T5. For T2 and T4, the average total water usage was 653.84 ±28.54 L and 641.83 ±30.49 L, respectively. This experiment was carried out during Thailand's traditional growing season, which spans from July to November (Prabnakorn *et al*., 2021), while considering the water balance between rain and evaporation. During this period, the climatic conditions, especially temperature and rainfall, adhered to the typical seasonal pattern, with an average evaporation rate at 5.17 milliliters (mm) per day while to total accumulate rainfall was 50.4 millimeters (mm). In application of the lysimeter experiment, all rice planting was conducted under controlled conditions, allowing treatment effects and relative differences in CH_4 emissions to be compared under uniform soil, crop, and water management conditions (Sagar *et al.,* 2022). Nonetheless, the primary constraint is that the implementation of AWD in actual paddy fields exhibits significantly more heterogeneity, characterized by increased variability in soil composition, plant density, root distribution, water flow, and irrigation methods managed by farmers. These factors can influence soil aeration, redox dynamics, methanogenic activity, and CH_4 oxidation, thereby altering the magnitude of CH_4 emissions under field conditions. Furthermore, conducting a future field-scale experiment would yield a more relevant and comprehensive evaluation, as this method would also enhance the practical applicability of the AWD method for farmers in their rice fields.

Growth

Over an 18-week timeframe, the growth of rice demonstrated that alterations in tillering, height, and circumference tended to rise steadily in alignment with the growth phases of the rice plant (Fig. 6 and Fig. 7). These growth pattern can be divided into four stages: 1) Seedling stage (Weeks 1–4), 2) Tillering Stage (Weeks 5–9), and 3) Heading stage (Weeks 10–14) and 4) Harvesting (Weeks 15-18) (Hosseiniyan Khatibi *et al.,* 2025). During the seedling stage (Weeks 1–4), tillering and circumference of rice plants showed slow growth (Fig. 7b and 7c), with tillering growth rates ranging from 1.13 to 2.03 tillers per week and circumference of 0.07-0.2 centimeters per week (cm/week). However, the most significant change at this stage was the height, which increased continuously in all experimental units with no significant differences ($p > 0.05$), with relative growth rates ranging from 10.55 to 11.12 cm/week. However, T5 showed the highest growth rate, at 12.31 ± 0.36 cm/week. Consequently, this was the primary element that resulted in the rice plants rising above the water surface. It is essential to clarify that in the seedling phase, height is fostered as the initial establishment stage after transplanting

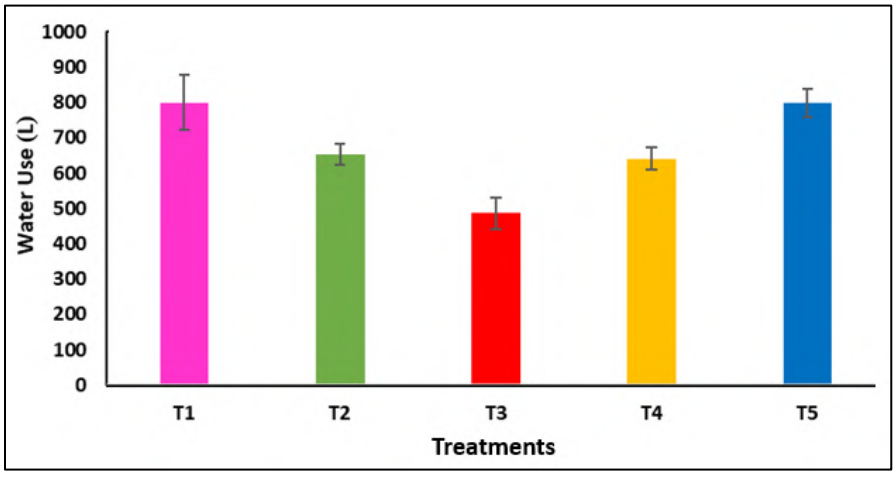

Fig. 5: Total irrigation water uses for five water management treatments (18-weeks period)

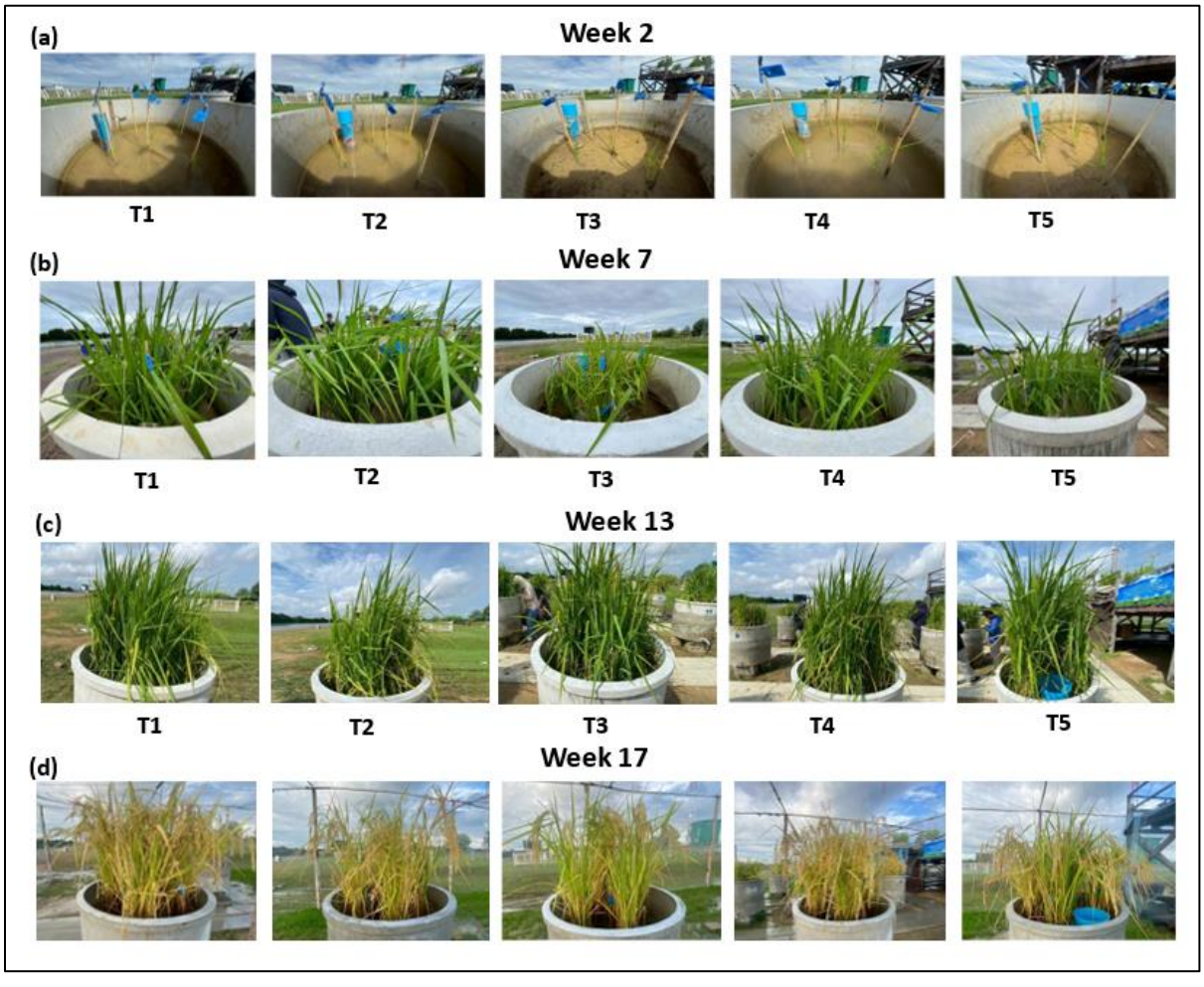

Fig. 6: Time-lapse photographs showing rice growth under different water treatments (T1–T5)
(a) Seedling stage, (b) Tillering stage and (c) Heading stage (d) Harvesting stage

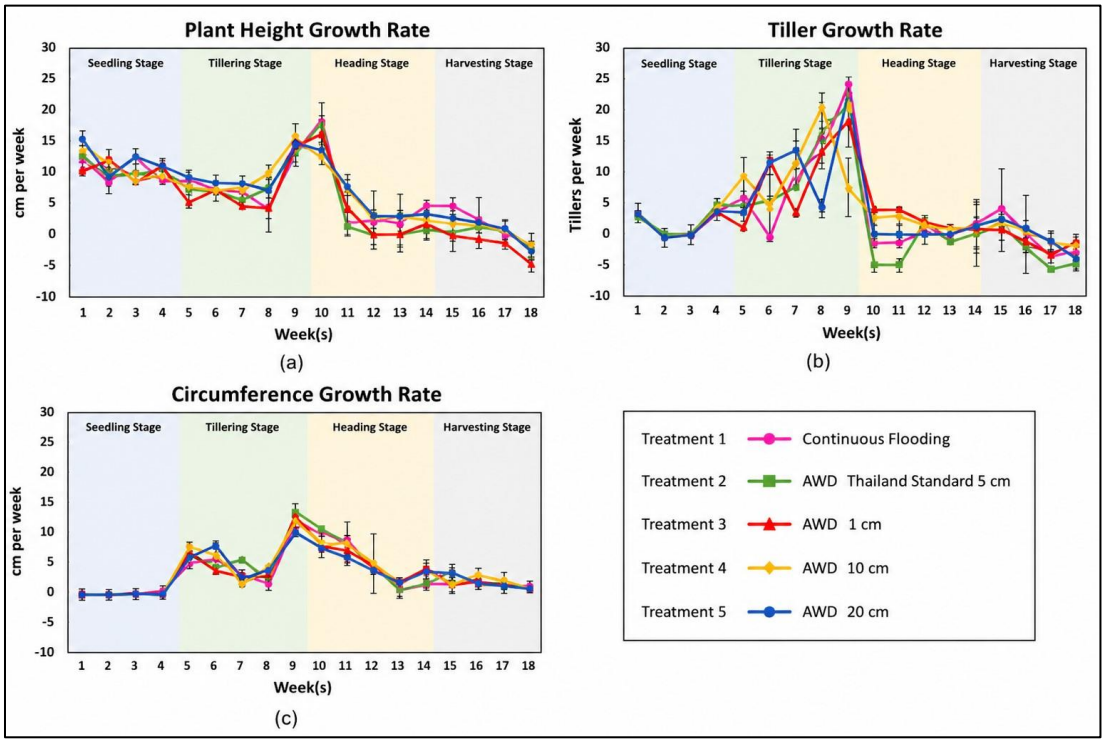

Fig. 7: Rice growth stages in all treatment lysimeter (18-weeks period)

(Kato *et al.*, 2019). During this period, the root system begins to develop and acclimatize to the environment inside the lysimeter, reflecting the physiological and foundational growth of the rice plant prior to progressing into the subsequent tillering stage (Verma *et al.*, 2022). During the tillering stage (Weeks 5–9), rice plants exhibited rapid growth, particularly in tiller number and stem circumference, which continuously expanded. During this stage, average tillering rates ranged from 10.04 to11.81 tillers per week, circumference increased by 5.59 to 6.86 cm/week, and height increased by 7.08 to 8.54 cm/week, indicating increased rice biomass accumulation. Despite the consistent increase in plant height, the evaluation of tillering and the expansion of stem circumference among all treatments indicated no significant variations ($p > 0.05$). The increase in tiller number was positively associated with stem thickening. As tillers proliferate, the plant requires greater mechanical support and enhanced vascular capacity, leading to increased stem circumference. Concurrently, root system expansion is stimulated to support higher nutrient, and water uptake demands, particularly under dense canopy conditions. This synchronized development both above and below ground aligns with prior studies, which indicates that the level of tillering is significantly related to the proliferation of roots and the strengthening of plant structures (Bouman *et al.*, 2007; Linquist *et al.*, 2015). The heading stage (Weeks 10–13), tiller growth rate stabilized. At this stage, tillering rate ranges from -2.1 to 1.75 tillers/week, circumference -2.08 to 0.57 cm/week, and height at 3.91 to 6.93 cm/week. Stem circumference and tillering stabilized around week 10 (Fig. 7) transferred assimilates from vegetative tissues to the panicle for grain formation (Verma *et al.*, 2022; Lakshani *et al.*, 2023). Statistical analysis revealed that all treatments exhibited no statistically significant differences ($p > 0.05$). Observations from the field additionally revealed the emergence of panicles along with the accumulation of grains (Gu *et al.*,

2022). It was also observed that CH_4 emissions reached their peak during this stage, which can be attributed to biomass accumulation patterns that increased the amount of organic matter derived from leaves and mature or submerged rice stems, providing an additional carbon substrate for methanogenesis (Wang *et al*., 2021; Somboon *et al*., 2024). These variations were especially noticeable at elevated water levels, which were associated with heightened CH_4 emissions. The minor decline in rice growth metrics can be elucidated by the process of tiller senescence and the reallocation of resources, wherein the plant eliminates weaker tillers to preserve and enhance the primary structure (Yuan *et al*., 2024). In the harvesting stage (Weeks 14–18), the water from all treatments was drained and the soil was allowed to dry, resulting in decreased CH_4 concentrations across all treatments. Rice productivity exceeded national standards in all treatments, with average yields of 5,812 ± 881.82 in T1, 6,392.31 ± 559.05 in T2, 5,238.05 ± 535.63 in T3, 6,687.30 ± 613.50 in T4, and 6,171.31 ± 367.99 kilograms per hectare (kg/ha) in T5, respectively. With respect to the growth, all soil employed in the 15 treatment lysimeters was preserved under uniform biological, chemical, and physical conditions (Table 1), with no significant were detected among treatments ($p > 0.05$). Soil texture, organic carbon content, pH, and bulk density play critical roles in regulating CH_4 production and oxidation through their control over soil redox dynamics, substrate availability, and microbial habitat. In paddy soils, elevated levels of soil organic carbon facilitate methanogenesis by providing labile carbon substrates for methanogenic archaea, particularly under anaerobic conditions. Conversely, AWD promotes periodic aeration, increasing O_2 diffusion and enhancing methanotrophic activity, which suppresses CH_4 emissions. Furthermore, when examining CH4 dynamics in rice paddies, the properties of the soil are a crucial controlling element that affects the balance between CH_4 production and oxidation. In this study, all lysimeters had a clay texture, which is important because clay soils generally promote higher CH_4 emissions under flooded conditions due to their fine particles, greater water retention, slower O_2 diffusion, and stronger reducing conditions (Nikolaisen *et al.,* 2023). The recommended texture for rice paddies consists of clay-to-clay loam textures in irrigated lowland paddy soils (Yanai *et al*., 2020). In addition, the soil organic carbon is often one of the strongest direct drivers of CH_4 production because it provides the usable carbon substrates required for methanogenesis (Shen *et al.,* 2024). During the later growth stages, root exudates, root turnover, decaying weak stems and roots, together with other organic decays inputs further enhance CH_4 production. Furthermore, the initial carbon content also supports rice growth of these experiment ranges in 0.85 to 1.00 % Organic Carbon (OC). Thus, before reaching 18 weeks, a minor increase in OC was noted, ranging from 0.82 to 1.06% (Luo *et al.,* 2022; Wang *et al.,* 2024). The soil pH also plays an important role in shaping microbial community structure and substrate availability, with the recommended pH range for paddy soils is around 5.5–6.5 (IRRI, 2013) as the experiment kept the initial condition following the recommendation (Fig. 8). The nearly neutral conditions usually benefit nutrient accessibility for the growth of rice, while simultaneously promoting increased methanogenic activity under anaerobic conditions (Xia *et al.,* 2024). As thus the shift in the soil pH was seen moving from 6.65–6.84 under the initial conditions to 7.13–7.34 at the harvesting stage suggest more neutral condition This change may be attributed to prolonged flooding and anaerobic decomposition processes, increasing the carbonate and bicarbonate accumulation, promoting conditions in paddy soils. Consequently, this may significantly boost microbial activity levels and establish a more conducive environment for methanogenic microorganisms, particularly in treatments where water saturation was sustained for extended durations (Table 1) (Conrad, 2020).

Table 1: Soil physicochemical properties at initial and post-harvest condition in the experimental lysimeter

Parameter	Initial					F-test	Post- harvest					F-test
	T1	T2	T3	T4	T5		T1	T2	T3	T4	T5	
pH	6.65 ±0.34	7.09 ±0.23	6.44 ±0.30	6.84 ±0.20	6.49 ±0.55	ns	7.24 ±0.27	7.26 ±0.03	7.13 ±0.15	7.20 ±0.04	7.34 ±0.17	ns
% OC	0.89 ±0.10	0.84 ±0.13	0.85 ±0.29	0.97 ±0.05	0.97 ±0.10	ns	0.820 ±0.12	0.988 ±0.18	0.871 ±0.14	1.061 ±0.17	0.99 ±0.02	ns
Texture	Clay	Clay	Clay	Clay	Clay	ns	Clay	Clay	Clay	Clay	Clay	ns

Note: Statistical variances at a level of 95% confidence, ns = No significant differences at 95% confidence level

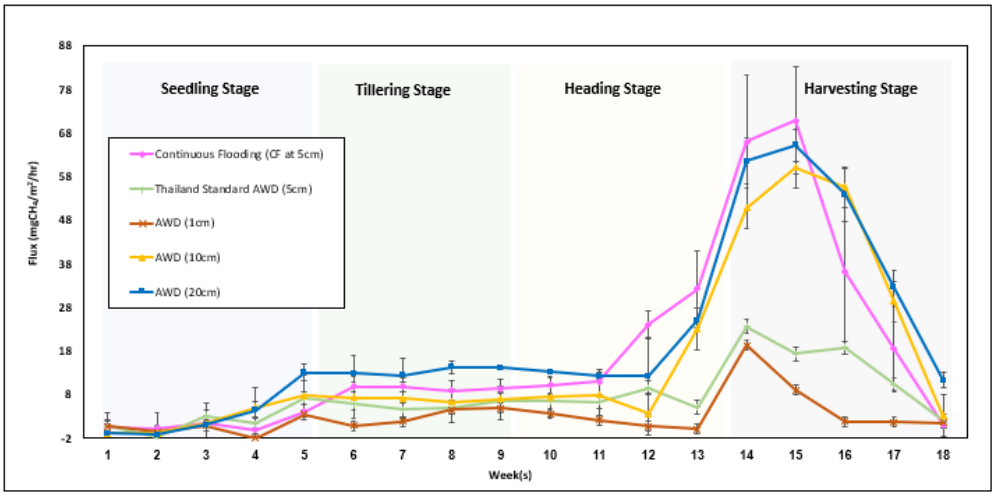

Fig. 8: Methane emission patterns over 18 weeks under different water management regimes

In addition, to support the conditions of the AWD water management. The post-harvest nitrogen levels were noted to have caused a transition in the rice paddies system shifted toward a more oxidized condition especially with the AWD treatments T2 and T3. This is evidenced by a reduced total Kjeldahl nitrogen to total nitrogen ratio (TKN:TN) of 0.83± 0.04 and 0.88± 0.01, in contrast to 0.92± 0.02, 0.91± 0.05 and 0.93± 0.02 in the CF, T4 and T5 treatments respectively. This also aligned with the with higher nitrate (NO_3^-) concentrations in T3 having the concentration of 0.06± 0.02 to 0.05± 0.02 mg/L while T4 concentration were 0.01± 0.01 mg/L as the CF ad T5 were non detected. The aforementioned ratio was bolstered by the continuous process of wetting and drying, which enhances soil aeration and contributing to elevated rates of nitrification into NO_3^-. In contrast, under continuous flooding, the soil remains more anaerobic, nitrification is suppressed, and organic nitrogen remains the dominant available nitrogen form (Islam *et al.,* 2018). The bulk density of the soil is also considered physical control on AWD effectiveness, because higher bulk density reduces macroporosity and slows gas exchange. The recommended bulk density for rice paddy soils is approximately 1.2–1.3 grams per cubic centimeter (g/cm^3), while values above 1.4 g/cm^3 may indicate compaction and reduced suitability for root development; such conditions can preserve anaerobic microsites and weaken CH_4 oxidation (Huo *et al.,* 2022). For the initial conditions of this experiment, the bulk density ranges from 1.0-1.2 ± 0.14 g/cm^3. In addition, associated microbial activity is central to AWD performance: during flooded periods, methanogens recover and produce CH_4, whereas during dry-down periods, O_2 suppresses methanogenesis and favors methanotrophs (Ume *et al.,* 2025). The increase in anaerobic bacteria was observed to rise from 3.47

x 10^4 at the initial condition to 5.71 x 10^4 after the first week of flooding. Nevertheless, when different water management treatments were applied, it was found that the increase in anaerobic colony-forming units (CFU) varied, with the CF treatment showing the highest anerobic bacteria count of 5.71 x 10^5 CFU to 1.44-2.72x 10^5 CFU/g. In such, the continuous flooding maintained stronger anaerobic conditions favoring methanogenic groups. Conversely, the repeated wetting and drying cycles of the AWD enables higher aerobic conditions, reducing anaerobic microbial abundance and limiting CH_4 production potential (Zhu *et al.,* 2026). The evaluation of the trade-off involving CH_4 reduction, water savings, and rice productivity was conducted through the examination of rice yield and water-use efficiency (WUE) (Table 2). The result suggested that there were no significant differences among the yield production with all treatment reaching above the national standard (4,375 kg/ha). However, when calculating water use efficiency (WUE) it was noted that according to the DMRT analysis, it was that T1 (CF) and T5 exhibited a decrease in WUE due to their higher water consumption within the treatment.

Methane emission in relation to different AWD management

The emissions of CH_4 flux from rice cultivation during the 18-week period indicated that the patterns of water management had a significant impact on the quantity of CH_4 flux released, as the emissions differed across various water management types ($p < 0.05$). The average total CH_4 flux emissions indicated that treatments T1 and T5 had the highest emission values at 17.45 ± 10.67 and 19.88 ± 1.02 milligrams per square meter per hour (mg/m²/h), respectively. Subsequently, T4 recorded values of 15.65 ±9.92, T3 at 7.37 ±3.29, and T2 at 3.06 ±2.35 mg/m²/h, with T2 exhibiting the least emissions across the entire growing season. The stage-based pattern showed that CH_4 emissions were lowest during the seedling stage (Fig. 9), increased during tillering, peaked during heading, and subsequently decreased again during the late harvesting stage. This indicates that the heading period contributed most strongly to seasonal CH_4 release. During the initial seedling and tillering stages, CH_4 emissions remained relatively constant across all treatments, with emission slopes ranging from −0.69 to 1.92. However, during the heading stage, the CF, T4, and T5 treatments showed a substantial increase in emission slope, with the CF treatment showing the highest slope of 7.85, while the slopes of the AWD treatments, particularly T2 and T3, remained low. Ultimately, during the harvesting stage, the slopes shifted to negative values, implying that CH_4 emissions diminished following the drainage of water (Table 3). Separating CH_4 emissions across growth stages (Table 4), it was observed that during the initial seedling stage, the rhizosphere system of the rice plant is still in the growth phase, and the amount of organic matter serving as a carbon source for methanogenic microorganisms remains low (Hosseiniyan Khatibi *et al*., 2025). At this stage, CH_4 emissions were very low ranging only between 0.00–1.13 mg/m²/h with no significant differences were observed across all treatments. This illustrates the preliminary flooding conditions during which the DO availability in all treatments was maintained above 5.0 milligrams per liter (mg/L). Suggesting that CH_4 production was still limited during the early stage because both methanogenic substrate supply and plant-mediated CH_4 transport were not yet fully developed. During the tillering stage (Weeks 5–9), CH_4 flux emissions increased, while values across all treatments remained relatively consistent. Plots with higher water levels showed slightly higher CH_4 emission rates, ranging from 4.19 to 9.83 mg/m²/h. In spite of the lack of significant differences in CH_4 production among the treatments, a trend was observed where increased water levels correlated with greater emissions. This reflects enhanced anaerobic conditions within the soil, particularly in the high-water-level treatments (T1 and T5), which exhibited the highest CH_4 flux values, followed by T4, T2, and T3, respectively (Fig. 5).

Table 2: Yield and water use efficiency

Parameters	Units	T1	T2	T3	T4	T5	F-test
Rice yield	kg/ha	5,812.90 ± 881.82	6,392.31 ± 559.05	5,238.06 ± 535.64	6,687.30 ± 613.50	6,171.31 ± 367.99	ns
Rice water use efficiency (WUE)	kg/m^3	10,331.08 ± 861.81^b	15,597.94 ±1,950.97 ^{a}	17,887.48 ± 3154.30 ^{a}	16,653.62 ± 110.99 ^{a}	10,549.08 ± 71.01^b	*

Note: *Statistical variances at a level of 95% confidence, ns = No significant differences at 95% confidence level. a-c is high to low value of statistical from DMRT.

Table 3: CH_4 Emission slope at different stages under the linear equation

Treatment(s)	Seedling stage weeks 1-4	Tillering stage weeks 5-9	Heading stage weeks 10-13	Harvesting stage week 14-18
T1 (CF)	-0.08	0.94	7.95	-18.21
T2	0.69	-0.18	-0.09	-5.01
T3	-0.69	0.67	-1.17	-4.25
T4	1.98	-0.24	4.25	-12.59
T5	1.82	0.38	3.53	-13.29

Table 4: Average methane emission at different stages

Growth stages	Units	T1 (CF)	T2	T3	T4	T5
Seedling stage (weeks 1-4)	mg/m^2/h	0.55 ± 0.29^a	0.90 ± 0.99^a	−0.20 ± 0.68^a	1.19 ± 1.39^a	0.91 ± 1.29^a
Tillering stage (weeks 5-9)		8.42 ± 1.19^b	5.19 ± 0.53^c	3.12 ± 1.75^d	7.15 ± 0.24^b	13.38 ± 0.42^a
Heading stage (weeks 10-13)		19.35 ± 5.36^a	6.85 ± 0.94^{c,d}	1.67 ± 0.76^d	10.52 ± 4.30^{b,c}	15.74 ± 3.12^{a,b}
Harvesting stage (week 14-18)		38.46 ± 15.01^a	14.42 ± 4.19^b	6.72 ± 3.84^b	39.82 ± 11.80^a	44.86 ± 11.30^a

Note: Statistical variances at a level of 95% confidence, ns = No significant differences at 95% confidence level. a-d is high to low value of statistical from DMRT.

The differences in CH_4 flux across treatments are associated with the changes in water levels during this timeframe, where T1 and T5 underwent extended waterlogging, leading to persistent anaerobic soil conditions that promote the activity of methanogens, the main contributors to methanogenesis (Shen *et al.,* 2024). In contrast, the AWD treatments (T2–T4) showed fluctuating water levels (Fig. 7), with intermittent drying periods that suppress methanogen activity and delay the methanogenesis process, causing the total CH_4 flux in the AWD treatments to be significantly lower than under continuously waterlogged conditions throughout the growing season (Li *et al.*, 2025). The DO dynamics during the AWD period also reflects this pattern. The rewetting cycles differed among treatments, with T2 at a 7-day cycle, T3 at 4 days, T4 at 12 days, and T5 at 19 days. The relatively high CH_4 emissions observed in T5 were likely caused by the high and excessive initial water depth, which prolonged the time required for the water level to drop below the soil surface. Consequently, the soil was inundated and lacked oxygen for extended durations, averaging 19 days, which led to conditions similar to persistent flooding. This suggests that the effectiveness of AWD depends on reaching sufficient drying intensity and duration to interrupt aerobic process leading to higher methanogenesis process. These cycles are associated with the number of days the water level fell below 0 cm, signifying times when the soil was uncovered and capable of exchanging oxygen (O_2) with the atmosphere. The total number of days below 0 cm was 41 days for T2, 72 days for T3, 25 days for T4, and 20 days for T5. This resulted in corresponding differences in average DO and ORP values during Weeks 3–11. The average DO values were T1: 5.02, T2: 4.96, T3: 6.32, T4: 5.31, and T5: 5.63 mg/ L. Similarly, ORP values were T1: 166.6, T2: 175.8, T3: 207.1, T4: 190.2, and T5: 176.4 millivolt (mV), indicating more oxidized conditions in the AWD treatments, particularly T3. During the heading stage, all treatments were maintained at a constant water level of 5 cm, as this approach is a standard practice among Thai farmers (Chidthaisong *et al*., 2018) to promote the establishment of rice grains for optimal rice yields.

In comparison between growth stages and CH_4 fluxes, this stage of rice growth showed the highest CH_4 emissions, with rates of 19.35 ± 5.36 in T1, 6.85 ± 0.94 in T2, 1.67 ± 0.76 in T3, 10.52 ± 4.30 in T4, and 15.73 ± 3.12 mg/m²/h in T5. This situation can be elucidated by the extended and more profound flooding experienced in the earlier stages (tillering), where the water addition frequency was the lowest in T5 (19 days), followed by T4 (12 days). Conversely, T3 and T2 demonstrated the greatest irrigation frequency at 4 and 7 days, respectively. T1 was maintained at a constant 5 cm water level. Although all treatments were standardized to the same 5 cm water depth during heading, the CH_4 response still reflected the effect of earlier water management, where soils exposed to longer anaerobic conditions during the previous stage remained more favorable for methanogenesis. The DO and ORP conditions throughout the various growth stages also exhibited this pattern. During the seedling stage, DO was relatively high in all treatments, ranging from 5.57 mg/L in T1 to 7.17 mg/L in T5, while ORP ranged from 163.37 mV in T1 to 201.71 mV in T5, indicating generally oxidized conditions at the early stage. At this stage, the average CH_4 emissions were limited across all treatments, with values of 0.55 ±0.29, 0.90 ±0.99, −0.20 ±0.68, 1.19 ±1.39, and 0.91 ±1.29 mg/m²/h¹ in T1,2,3,4, and 5, respectively. However, during the tillering stage, a decline in DO was observed in T1,4, and 5, with values of 2.31, 2.36, and 2.98 mg/L, respectively, compared with the higher DO values observed in T2 and 3, at 3.49 and 3.73 mg/L, respectively. A comparable trend was noted for ORP, with T1, T4, and T5 exhibiting lower values of 172.60, 166.98, and 165.98 mV, respectively, in contrast to T2 and T3, which recorded ORP values of 177.76 and 198.93 mV, respectively. This corresponded to higher average CH_4 emissions in T1, 4 and 5, with values of 8.42 ±1.19, 7.15 ±0.24, and 13.38 ±0.42 mg/m²/ h, respectively, compared with lower values in T2 and 3 of 5.19 ±0.53 and 3.12 ± 1.75 mg/m²/h, respectively. During the heading stage, because of prolonged flooding under different water management regimes, T1 and 5 had the lowest DO and ORP values, with DO values of 2.68 and 3.38 mg/L and ORP values of 56.74 and 77.47 mV, respectively, indicating more reduced soil and water conditions. Conversely, T2 and 3 maintained higher levels, with DO values of 4.02 and 3.40 mg/L and ORP values of 118.12 and 140.23 mV, respectively. The average CH_4 emissions were also higher in T1 and T5, with values of 19.35 ± 5.36 and 15.74 ± 3.12 mg/m²/h, respectively, while T4 also showed a relatively high value of 10.52 ± 4.30 mg/m²/h. In contrast, average CH_4 emissions remained lower in T2 and 3, with values of 6.85 ±0.94 and 1.67 ±0.76 mg/m²/h, respectively. Lastly, during the harvesting stage, DO was relatively lower in T1, 4, and 5, with values of 2.54, 3.01, and 3.28 mg/L, respectively, whereas T2 and T3 still maintained higher DO values of 4.01 and 3.63 mg/L, respectively. ORP also decreased in T1, 4, and T5, with values of −104.71, −116.33, and −114.17 mV, respectively, indicating strongly reduced conditions. In comparison, T2 showed the least negative ORP value of −31.27 mV, followed by T3 at −80.55 mV, suggesting that the more frequent wetting–drying cycles helped maintain relatively more oxidized conditions. The average CH_4 emissions were highest in T1, 4, and 5, with values of 38.46 ±15.01, 39.82 ±11.80, and 44.86 ±11.30 mg/m²/h, respectively, while T2 and T3 had much lower emissions of 14.42 ±4.19 and 6.72 ±3.84 mg/m²/h, respectively. While the methanogenic threshold of approximately −150 mV (Das *et al.*, 2018), the lower ORP values observed in T1, T4, and T5 indicate reduced conditions compared with T2 and T3. In contrast, CH_4 oxidation is generally linked to oxygenated microsites and the oxic to anoxic interface (Lee *et al.*, 2015). Consequently, the comparatively elevated ORP values observed in T2 and T3 indicated that AWD preserved more oxidized soil conditions, which facilitated CH_4 oxidation. In explanation, the AWD water management are likely to alter the balance between methanogenic and methanotrophic processes by changing soil O_2 availability as seen in their redox status. Prolonged flooding limited O_2 diffusion and favored methanogenesis, whereas drying periods

increased DO and ORP (Table 5 and Fig. 9), suppressing CH_4 production and enhancing CH_4 oxidation as seen with the average CH_4 emission. Furthermore, when comparing the DO and ORP values with T2 and T3, the restricted O2 availability in T1 (CF), T4, and T5 significantly encouraged anaerobic driven by lower wetting and drying frequency, thereby effectively preconditioning the soil for higher CH_4 emissions in later growth stages. As a result, T5, T4, and T1 exhibited the highest CH_4 emissions during this period. In all the AWD systems (T2 to T5), changes in water level are the key drivers of fluctuating CH_4 emissions depending on the irrigation cycle (Yakubu *et al*., 2019). The total number of days that the water level remained beneath 0 cm reflects times when the soil was exposed to the atmosphere, with T2 at 41 days, T3 at 72 days, T4 at 25 days, and T5 at 20 days. Subsequent to the commencement of a new irrigation cycle, CH_4 flux emissions experienced a decrease 2 to 5 days later, due to the soil being in an aerobic condition beforehand. This phenomenon was most pronounced in T3, where water level changes were most frequent, resulting in alternating wet and dry periods. It promotes increased soil oxygenation and CH_4 oxidation, resulting in the lowest overall CH_4 flux among all experimental treatments (Rajendran *et al.,* 2024b). Conversely, elevated and stable water levels foster extended anaerobic conditions within the soil, reducing alterations in soil conditions and consequently enhancing CH_4 emissions (Fig.7). This shows that the frequency and duration of wetting and drying directly affect CH_4 release, with prolonged waterlogging being the primary factor promoting CH_4 generation and release in rice paddy systems (Xuan *et al*., 2025). Another crucial aspect is the frequency of water addition, as demonstrated by T2 and T3 where the reduced conditions are maintained for shorter durations. T2 has a cycle of 7 days, T3 has 4 days, T4 has 12 days, and T5 has 19 days. This suggests a diminished potential for microbial CH_4 production potential due to more frequent wetting–drying cycles associated with AWD. This resulted in intermittent drainage allowing greater O_2 diffusion into the soil. Furthermore, the buildup of labile carbon substrates rises concurrently with the development of tillers, as there is an increase in root exudates and the decomposition of organic matter (Zheng *et al*., 2018). While the root exudation was not directly quantified in this study, its influence on CH_4 emissions was interpreted from rice growth stage, water regime, and the CH_4 emission patterns. Studies by Chen *et al* (2019). have shown that rice root morphology, physiological activity, O_2 release, and rhizosphere organic acid composition strongly regulate the CH_4 emission fluxes, with tittering and heading stage contributing approximately 39.0–49.7% of total seasonal CH_4 emissions. The findings of this study indicates that the heightened CH_4 emissions recorded in T1 and T5 were likely a result of the combined influences of enhanced root-derived carbon availability and sustained flooding leading to a reduced soil condition. In contrast, the lower CH_4 emissions emitted from T2 and 3 is suggested to be affected by the frequent wetting–drying cycles, which increased O_2 diffusion into the rhizosphere limiting the production of carbon into CH_4 (Xiao *et al.,* 2025). This is in agreement with the elevated activity of methanogens that enhances the breakdown of organic materials in conditions lacking O_2, thereby resulting in greater CH_4 output. At the same time, methanotroph community activity also responds dynamically (Liu *et al*., 2016). CH_4 emissions are further explained by plant-mediated transport, where the development of aerenchyma tissue (gas transport channels) (Jia *et al*., 2022) provides an efficient pathway for CH_4 movement from the soil to the atmosphere, accounting for approximately 60–90% of CH_4 transport in rice systems (Linquist *et al.,* 2015; FAO, 2021; Zhu *et al*., 2025). Consequently, the significant rise in CH_4 emissions observed during the heading stage was probably influenced by the synergistic impact of advantageous anaerobic soil conditions, enhanced substrate availability, and more developed plant-mediated gas transport. Lastly, in the harvesting stage, as all water was drained, leaving the soil

Table 5: Dissolved oxygen and oxidation–reduction potential under different water management treatments

Stages	DO (mg/L)					ORP (mV)				
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
Seedling	5.57	6.18	6.02	6.35	7.17	163.37	167.9	194.32	189.8	201.71
stage	±0.78^{b}	±0.92^{a,b}	±0.72^{a,b}	±0.29^{a,b}	±0.80^{a,b}	±8.75^{b}	±8.91^{a,b}	±19.63^{a,b}	±28.45^{a,b}	±21.51^{a}
Tillering	2.31	3.49	3.73	2.36	2.98	172.60±1	177.76±1	198.93±2	166.98±4	165.98
stage	±0.35^{c}	±0.44^{a,b}	±0.33^{a}	±0.22^{c}	±0.31^{b}	9.60^{a}	7.76^{a}	5.61^{a}	1.80^{a}	±11.59^{a}
Heading	2.68	4.02	3.40	3.55	3.38	56.74±28.	118.12±2	140.23±1.	121.25±2	77.47
stage	±0.71^{b}	±0.48^{a}	±0.27^{a,b}	±0.36^{a,b}	±0.31^{a,b}	28^{b}	0.59^{a}	27^{a}	3.41^{a}	±13.37^{b}
Harvesting	2.54	4.01	3.63	3.01	3.28	-104.71	-31.27	-80.55	-116.33	-114.17
stage	±0.10^{d}	±0.15^{a}	±0.20^{b}	±0.23^{c}	±0.18^{c}	±50.31^{b}	±45.38^{a}	±23.02^{a,b}	±1.88^{b}	±1.50^{b}

Note: Statistical variances at a level of 95% confidence, ns = No significant differences at 95% confidence level. a-d is high to low value of statistical from DMRT.

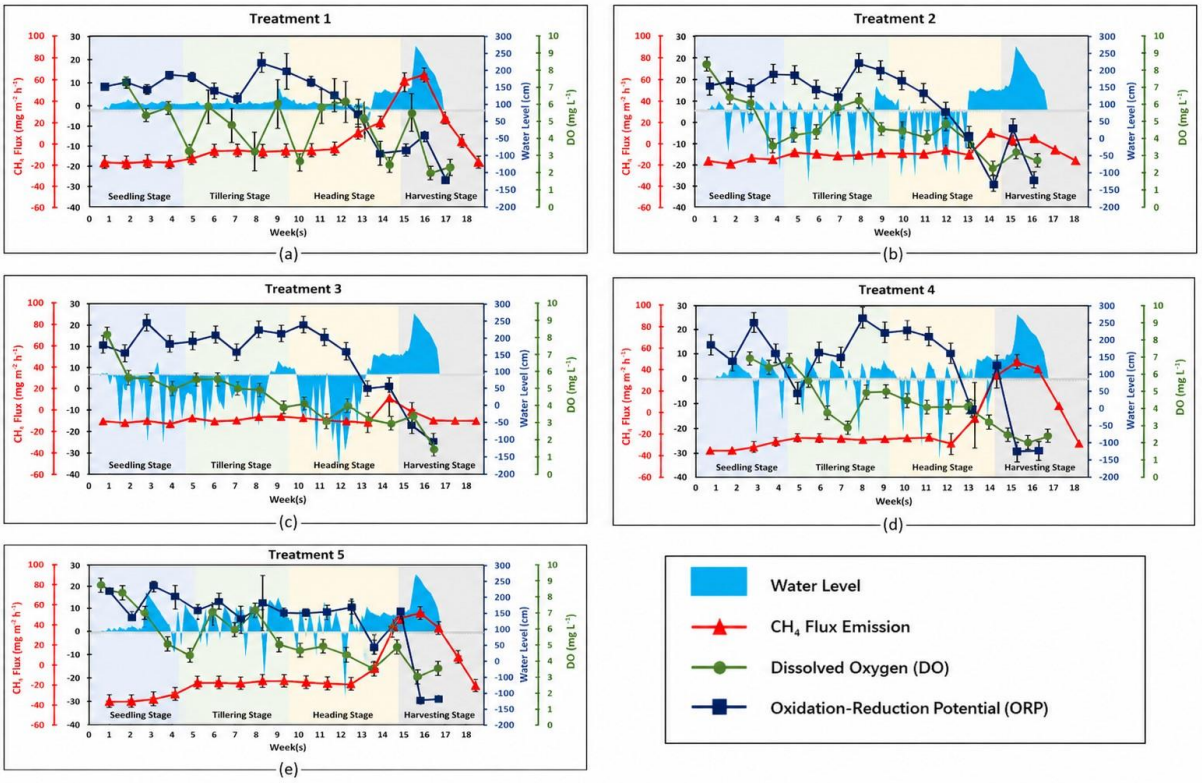

Fig. 9: The relationship between water level and methane emission

exposed to the air, CH_4 emissions decreased across all treatments, reflecting the dominance of aerobic conditions. In comparing among the treatments to the CF (T1), CH_4 were reduced by approximately 82% in T2 and 58% in T3 compared with the CF treatment. In the treatments with a higher water table, the reduction diminished to around 10% in T4, while T5 exhibited an increase of approximately 14%. The results for CH_4 emissions under the standardized water management method are consistent with those reported by Islam *et al.* (2018) for rice fields in Bangladesh, where the AWD method reduced emissions by 49–70%. Similarly, in paddy fields in Prachin Buri, Thailand, emission reductions were reported to be within 40–50% (Chidthaisong *et al.*, 2018). In the process of broadening this study, a field-level AWD guideline can be established by concentrating on the management of shallow water and the visual monitoring of field water

depth. The results showed that shallow AWD treatments, particularly T2 and T3, reduced CH_4 emissions and irrigation water use while maintaining rice growth and yield. The application of applying the shallow flooding of approximately 1–5 cm, allow the water level to decline to about 15 cm below the soil surface, and then re-irrigate to a shallow ponded level rather than maintaining prolonged deep flooding. To ensure safety, it is important to limit deep flooding to below 10 cm, as effective decision-making at the farmer level must also factor in the water depth in the field, the duration of dry days, crop growth stage, and rainfall forecast.

CONCLUSION

In future global food security and rice cultivation methods will play an increasingly important role in addressing global greenhouse gas emissions. With the continuous increase in the global population, the demand for rice production is anticipated to grow, especially throughout Southeast Asia. Studies have suggested that rice paddies are one of the largest agricultural sources of CH_4. Where ideas on improving cultivation practices will be essential for balancing food security with climate change mitigation. Consequently, sustainable rice production systems should prioritize not only the maintenance of yield but also the minimization of environmental impacts. The findings in this study have suggested that when compared to the traditional CF method, the T2 and T3 treatments with an applied water depth of 5 and 1 cm, have shown an average reduction of over 65% of the total CH_4 emission, while maintaining good rice growth. The reduction in CH4 emission demonstrates that water management can substantially decrease CH_4 formation, especially when under AWD conditions. The results from the study demonstrated that plant growth was on par with the control CF system, implying that productivity was not detrimentally influenced. This demonstrates that controlling water levels with AWD periods improves soil aerobicity, inhibiting CH_4 production during rice growth. As such application enables the frequency of the wetting and drying periods to allow the O_2 to transfer from the free atmosphere into the paddy soils leading to higher O_2 availability thus suppressing the emission of CH_4. Concurrently, the height, number of tillers, and stem circumference of rice grown in the AWD system were not significantly different from those in the CF system. The highest CH_4 emission was observed during the rice heading stage, when water levels of all the traditional CF and all AWD treatments underwent prolonged flooding and were adjusted for yield formation. During Weeks 13–16, CH_4 emissions increased the rise observed in the late season usually coincides with the reproductive period of rice growth, characterized by heightened root exudation and an increased availability of fresh organic substrates for microbial decomposition. At this stage, the developed rice structure and expanded aerenchyma tissues promoted greater CH_4 transport from the soil to the atmosphere. Also, higher CH_4 emissions were observed in the control CF treatment (peaking) and in higher water-level treatments, as the major factor contributing was through the frequency of wetting and drying cycles. The persistent or elevated water levels (T4 and T5) lead to flooding, which hinders O_2 diffusion into the soil and sustains significantly reduced conditions that have been prolonged since the tillering stage. These anaerobic environments promote CH_4-producing microbes and allow CH_4 to accumulate before being released through water, soil diffusion, or plant-mediated transport. Conversely, it was seen that the effects of the AWD method created more aerobic soil conditions, promoting respiration pathways, limiting methanogenesis. Under these circumstances, aerobic microorganisms utilized the O_2-dependent respiration pathway to break down organic matter instead of the anaerobic pathways that result in CH_4 production. As a result, organic matter is more likely to be released as carbon dioxide rather than CH_4. In addition, this study only measured for CH_4 while the nitrous oxide (N_2O) emissions were not measured, as for

future studies the inclusion of N_2O should be integrated for global warming potential. In all, the AWD irrigation management, particularly T2 and T3, holds significant promise for decreasing CH_4 emissions and preserving water while ensuring rice growth is not hindered. These treatments represent practical water management strategies that farmers can adopt with minimal structural changes to existing rice systems. Their combined environmental and agronomic advantages they offer render them excellent candidates for climate-smart agriculture initiatives, given that the soil utilized in this study was sourced from a tropical climate under controlled lysimeter conditions. This practice can be adapted to various agro-climatic regions; however, careful implementation and necessary adjustments are required variation under field-scale conditions. In contrast, the traditional CF method produced higher CH_4 emissions and consumed more irrigation water. Thus, this study suggests that the AWD method, particularly T2 and 3 could be recommended for rice practices in Thailand to support as a base factor in the calculation of the carbon credit accounting. The factor can be utilized for the creation of local CH_4 mitigation strategies for rice cultivation in Thailand. However, field-scale validation and simultaneous CH_4 and N_2O measurements are still required before these results can be directly applied to national emission factors or carbon credit systems.

AUTHOR CONTRIBUTIONS

J. Boonphue performed literature review, experimental design, material preparation, data collection, analysis, interpretation, and manuscript preparation. P. Maskulrath performed data collection, experimental design, interpretation, and manuscript preparation. O. Phewnil performed experimental design and data collection and interpretation. W. Wararam performed data collection, analysis, and interpretation. K. Duangmal performed experimental design and manuscript editing. T. Pattamapitoon performed material preparation, data collection and analysis and manuscript preparation. Tasuku Kato performed study conception and experimental design. Warisara Tundam performed data collection and analysis and manuscript preparation. U. Nachaiboon performed data collection, experimental design. P. Wichittrakarn performed material preparation, data collection. K. Chunkao performed experimental design and manuscript preparation

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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, 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
ANOVA	Analysis of variance
AWD	Alternate wetting and drying
CF	Continuous flooding
CFU	Colony forming unit
CH_4	Methane
cm	Centimeter
cm/week	Centimeter per week
DMRT	Duncan's Multiple Range Test
DO	Dissolved oxygen
g/cm^3	Grams per cubic centimeter
GC	Gas chromatography
GHG	Greenhouse gas
kg/ha	Kilograms per hectare
kg/m^3	Kilograms per Cubic Meter
L	Liter
LERD	Laem Phak Bia Environmental Research and Development Project
m	Meter
m^2	Squared meter
m^3	Cubic meter
mg/L	Milligram per liter
$mg/m^2/h$	Milligram per square meter per hour
Mha	Million hectares
min	Minute
mm	Millimeter
mV	Millivolt
N_2O	Nitrous oxide
NO_3^-	Nitrate
O_2	Oxygen
OC	Organic carbon
ORP	Oxidation-reduction potential
PAR	Photosynthetically active radiation
pH	Potential of hydrogen
ppm/h	Parts per million per hour
PVC	Polyvinyl chloride
T1	Treatment 1 (Continuous flow: CF
T2	Treatment 2 (AWD 5cm)
T3	Treatment 3 (AWD 1cm)
T4	Treatment 4 (AWD 10cm)
T5	Treatment 5 (AWD 20cm)
Tilters/week	Tilters per week
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
WUE	Water use efficiency

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ORIGINAL RESEARCH ARTICLE

Dynamics of microplastics along landfill leachate pathways and treatment processes

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ABSTRACT

BACKGROUND AND OBJECTIVES: Landfill leachate has been identified as a pathway for microplastic release into aquatic environments; however, its role as a dynamic transformation system remains poorly understood. The objectives of the study were to analyze the variations in microplastic abundance and polymer composition at various stages of a landfill leachate system, in addition to comparing the present conditions with prior observations.

METHODS: Surface water samples were collected from four key points, including before effluent, leachate pond, leachate drain, and after effluent. The protocols previously established were followed for the sampling design, extraction, and identification procedures to maintain comparability. Microplastics were quantified in particles per cubic meter and characterized by polymer composition. These techniques were corroborated by Fourier transform infrared analysis, which revealed approximately 32 percent of the particles were accounted for, achieved a recovery efficiency of 99.5 to 99.9 percent, and exhibited no contamination in procedural blanks.

FINDINGS: Microplastic abundance increased across all stages, with moderate increments observed in upstream and downstream sections and higher increases within the leachate pond and drain. Relative to past observations, the current analysis demonstrates sustained amplification within the system. Polymer composition remained dominated by polyethylene and polypropylene, while additional polymer types emerged in the leachate pond and drain, indicating increased diversity. Multiple polymers remained following the discharge of effluent, indicating that removal was not fully achieved. These patterns are further supported by the dominance of fragment-type particles and shifts toward smaller size classes along the leachate pathway, suggesting progressive fragmentation inferred from size distribution. An evaluation grounded in relative concentration suggests that the system exhibits non-conservative behavior, characterized by negative removal efficiency in the transition from upstream and downstream sections.

CONCLUSION: The landfill leachate system does not behave as a simple transport pathway but instead exhibits characteristics of a transformation-active environment, based on observed spatial patterns and polymer evidence. The rise in abundance and the diversification of polymers suggest that the existing leachate management systems are not very efficient. These results underscore the necessity for enhanced treatment strategies, which encompass targeted methods for microplastic removal approaches, and integration of microplastic monitoring into leachate management systems to mitigate environmental risks downstream.

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38	4	1

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INTRODUCTION

Small-sized plastic debris, particularly microplastics, has emerged as a pervasive pollutant across aquatic, terrestrial, and atmospheric environments (Horton *et al*., 2017; Horton and dixon 2018; Wright and Kelly, 2017). Their diminutive size increases bioavailability and promotes the movement of harmful materials, such as persistent organic pollutants and heavy metals (Alimba and Faggio, 2019; Bouwmeester *et al*., 2015). While numerous studies have documented microplastic occurrences in marine and freshwater systems (Cordova *et al*., 2025; Nakano *et al*., 2025), the understanding of land-based sources, especially landfill systems, remains limited (Cordova *et al*., 2019; Cordova *et al*., 2020). Landfills are commonly acknowledged as one of the main storage sites for plastic waste, especially in developing nations where the systems for managing waste are often inadequate (Abdel-Shafy and Mansour, 2018; Damanhuri *et al*., 2014). Under landfill conditions, including mechanical pressure, temperature fluctuations, and microbial activity, plastics undergo fragmentation processes that generate smaller particles (He *et al*., 2019; Su *et al*., 2019). Subsequently, these particles may be conveyed through leachate systems into adjacent aquatic environments. Previous research has demonstrated that landfill leachate acts as a direct pathway for micro- and mesoblastic entering river systems, with significant increases observed after discharge points (Nurhasanah *et al*., 2021). In that study, it was observed that microplastics increased by as much as three times, while mesoblastic rose by up to nine times due to leachate input, emphasizing the importance of leachate as a point source (Nurhasanah *et al*., 2021). However, the leachate system has primarily been treated as a passive conduit, with limited attention to potential system where transformation, mixing, and redistribution processes occurring within the system. This perspective introduces a critical gap. The leachate pathway consists of multiple interconnected stages, including retention ponds, drainage channels, and effluent discharge points, each with distinct physical and chemical conditions. These circumstances may encourage fragmentation, selective retention, and re-release of microplastics, which could potentially change both their abundance and polymer composition (Alimi *et al*., 2018; Muhtadi *et al*., 2025). Despite the growing evidence regarding the presence of microplastics in landfill leachate, there are still several significant gaps that persist. Previous studies have largely treated leachate systems as point-source pathways, with limited attention to compartment-scale processes occurring within the system (Nurhasanah *et al*., 2024; Omeyer *et al*., 2023; Omeyer *et al*., 2022; Purba *et al*., 2021; Vriend *et al*., 2021). In addition, temporal evolution of microplastic dynamics under consistent methodological frameworks remains poorly documented (Anshar *et al*., 2026). Furthermore, the systematic investigation into the combination of physical indicators (including size and shape) and chemical indicators (specifically polymer composition) for inferring transformation processes remains unexplored. While dominant polymers such as polyethylene and polypropylene are commonly reported in landfill-derived microplastics (Nurhasanah *et al*., 2021), the emergence of less common polymer types within leachate systems may indicate secondary inputs, advanced degradation, or mixing processes. Comprehending these dynamics is crucial for recognizing the mechanisms that regulate microplastic behavior microplastics in landfill settings. Previous studies have primarily treated leachate systems as point-source pathways (Nurhasanah *et al*., 2021), with limited attention to compartment-scale processes occurring within the system (Nurhasanah *et al*., 2025). In addition,

temporal evolution of microplastic dynamics under consistent methodological frameworks remains poorly documented (Nurhasanah *et al*., 2024; Omeyer *et al*., 2023; Omeyer *et al*., 2022; Purba *et al*., 2021; Vriend *et al*., 2021). Furthermore, the integration of physical (size, shape) and chemical (polymer composition) indicators to infer transformation processes has not been systematically explored (Omeyer *et al*., 2023; Omeyer *et al*., 2022). Microplastic sources in landfill systems are primarily associated with municipal plastic waste, particularly packaging materials such as polyethylene, polypropylene, and polystyrene (Nurhasanah *et al*., 2021). Besides direct inputs, secondary microplastics are generated through fragmentation processes under landfill conditions (Cordova *et al*., 2019; Cordova *et al*., 2020). Direct source tracing was not conducted; instead, source inference was based on polymer composition, morphology, and size distribution patterns. In this study, the inference of sources is facilitated by employing polymer composition, particle morphology, and size distribution as combined indicators of origin and transformation. It is hypothesized that microplastic abundance and polymer diversity vary along the leachate pathway, influenced by transport, retention, and transformation-related processes within the system. Landfill leachate has been previously identified as a channel and a possible environment for the transformation of microplastics; however, quantitative evidence illustrating the evolution of transformation processes through different treatment compartments is still lacking. Existing studies have largely focused on point-source contributions or end-of-pipe discharge, with less attention given to intra-system dynamics and temporal shifts. Comparable observations in river environments have emphasized the importance of compartment-specific dynamics and secondary contamination pathways, while variations in polymer composition further demonstrate the usefulness of polymer diversity as an indicator of environmental sources and transformation processes (Yanuhar *et al.,* 2025; Basri *et al.,* 2024). This study contributes to the existing comprehension by delivering i) a compartment-specific examination of microplastic behavior throughout the leachate pathway, ii) a temporal comparison between datasets collected under consistent methodological frameworks, and iii) integrated evidence linking abundance, size distribution, and polymer composition to infer transformation processes within specific treatment units. Rather than reinterpreting landfill leachate as a transformation system, this study delivers a compartment-specific and temporally consistent quantification of microplastic dynamics, underscoring the spatial and temporal differences in transformation-related processes within the system. This study aims to i) evaluate the spatial variation of microplastic abundance across different stages of a landfill leachate system, ii) assess changes in polymer composition along the pathway, and iii) compare current conditions with previous observations to identify temporal trends. This study has been carried out was conducted in the Galuga landfill area in Indonesia, with sampling campaigns performed in 2021 and 2025 to enable temporal comparison.

MATERIALS AND METHODS

Study area and sampling design

The study was conducted in a municipal solid waste landfill system characterized by an open dumping practice and a conventional leachate management pathway. The Galuga landfill (Fig. 1) spans an area of about 42.7 hectares (ha). It has been operated jointly by the local governments of Bogor City and Bogor Regency since 1992. The facility receives around 1,100 tons of waste per day, consisting of roughly 500 tons from Bogor City

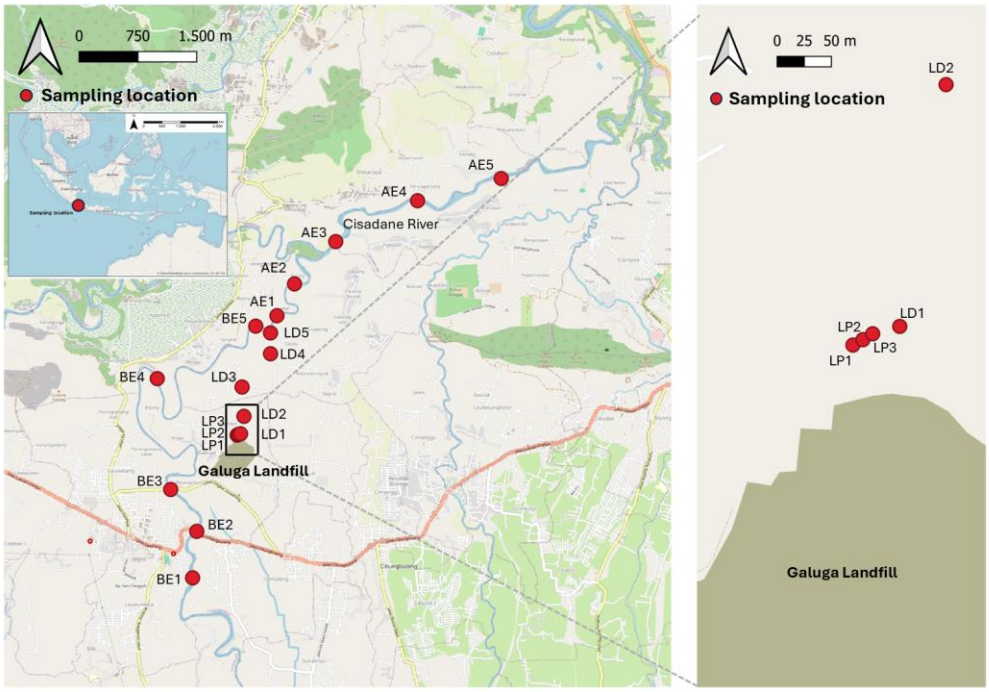

Fig. 1: Geographical location of the study and the sampling sites in Galuga Landfill area and Cisadane watershed in Indonesia

and 600 tons from Bogor Regency (Nurhasanah *et al*., 2025). The incoming waste stream is dominated by 76 percent (%) organic material, followed by plastic (19%), paper (4%), and other residual fractions (1%). Currently, waste management is conducted via an open dumping system, but there has been a proposal to move towards a controlled landfill method. The landfill has been operating for several decades and receives mixed domestic waste, creating conditions favorable for plastic accumulation and fragmentation processes. Leachate produced from the waste mass is conveyed through several management phases, which include a leachate pond and a drainage channel, prior to being released into an adjacent river system.

Field sampling

Sampling sites were chosen to illustrate the primary phases of the leachate pathway (Fig. 1), which includes i) five sampling locations in the upstream river segment prior to leachate introduction or before effluent (BE1-5), ii) three sampling points in the leachate pond (LP1-3), iii) five sampling points in the leachate drainage channel or leachate drain (LD1-5), and iv) five sampling points in the downstream river section after effluent discharge or after effluent (AE1-5). Each sampling category encompassed various stations positioned along the flow direction to account for spatial variability. The sampling framework followed the same design and spatial configuration as previously established to ensure temporal comparability (Nurhasanah *et al*., 2021; Nurhasanah *et al*., 2025). This design facilitated the evaluation of spatial variation in microplastic abundance across the leachate pathway and enabled comparison between compartments. Surface water samples were collected at each station using sterile high-density polyethylene containers. At each sampling point, approximately 150 liters (L) of water were collected in triplicate

to ensure representativeness. The sampling volume and replication method were preserved in alignment with prior studies to facilitate a straightforward comparison of the findings. Due to the high turbidity and organic content of leachate, samples were immediately filtered in the field using a multi-level stainless-steel sieve system with mesh sizes of 5 millimeters (mm), 200 micrometers (µm), and 20 µm. The collected material was washed with double-distilled deionized water and transferred into clean glass containers, which were then sealed and stored at a temperature of 4±2 degrees Celsius (°C) temperature prior to laboratory analysis. The sampling design included 18 stations distributed across four compartments. Each station was sampled in triplicate, resulting in 15 replicate samples for the upstream section (BE), 9 for the leachate pond (LP), 15 for the leachate drain (LD), and 15 for the downstream section (AE). This design was used to capture spatial variability within each compartment while maintaining consistency with previous datasets (2021 and 2025), enabling robust temporal comparison. The sampling framework was formulated to strike a balance between spatial coverage and analytical consistency, which guarantees that the differences identified between compartments are a true reflection of system dynamics rather than sampling bias.

Laboratory analysis

Microplastic extraction followed a density separation and chemical digestion approach adapted from established protocols (Nurhasanah *et al.*, 2021; Nurhasanah *et al*., 2025; Cordova *et al*., 2019; Cordova *et al*., 2020). Filtered residues underwent an initial drying process at a regulated temperature, followed by mixing with a saturated zinc chloride ($ZnCl_2$), possessing a density of 1.6 gram per cubic centimeter (g/cm^3), to facilitate the separation of low-density plastic particles from inorganic materials. In order to boost recovery efficiency, the separation procedure was conducted multiple times. The supernatant containing suspected microplastics was then subjected to chemical digestion using Fenton's reagent, consisting of 50 milliliters (mL) hydrogen peroxide (H_2O_2), 30% Merck Millipore Emprove®) and 20 mL of 10 milligram per milliliter (mg/mL) ferrous sulfate solution ($Fe(II)SO_4$, Merck Millipore Emsure®), to remove organic matter. The digestion procedure was performed under regulated circumstances to avert the degradation of plastic particles. After digestion, the samples were filtered onto membrane filters (0.45 µm pore size) and dried prior to microscopic examination. Microplastic particles were first recognized using a stereomicroscope according to visual criteria, which included consistent coloration, lack of cellular structure, and irregular morphology, in accordance with established guidelines (Hidalgo-Ruz *et al*., 2012). Particles were categorized according to shape (fiber, fragment, foam, and granule) and size classes consistent with previous classification schemes. This identification was done using an Olympus CX31 optical microscope equipped with an IMX307 Sony Camera. Quantification was articulated as particle concentration per cubic meter ($particles/m^3$), facilitating comparisons among sampling sites and aligning with previous results. A subset of representative particles was identified for polymer identification, based on size classes and morphotypes, with the application of Fourier transform infrared (FTIR) spectroscopy. The attenuated total reflectance (ATR)-FTIR (Fourier Transform Infrared Spectroscopy) techniques (Agilent Cary 630 FTIR spectrometer fitted with a diamond ATR unit and operated through MicroLab Expert software) were applied depending on particle size. Spectral data were collected within the range of 4000-650 cm^{-1} and compared against reference libraries to determine polymer types. Selected particles were designed to illustrate the

predominant size classes and morphotypes identified throughout the various compartments. Only spectra with a matching quality above 70% were considered valid, ensuring reliability in polymer identification (Nurhasanah *et al.,* 2021; Nurhasanah *et al*., 2025; Cordova *et al*., 2019; Cordova *et al*., 2020). The analysis facilitated the evaluation of polymer diversity and contributed to the understanding of possible sources and processes related to transformation.

Quality assurance/quality control

Strict contamination control procedures were implemented throughout the study. Laboratory work was conducted using non-plastic equipment where possible, and all materials were rinsed with filtered deionized water prior to use. Personnel wore cotton laboratory clothing to reduce synthetic fiber contamination. Procedural blanks were incorporated into the analysis to track possible contamination, and no substantial contamination was detected. Prior to use, all chemical reagents were subjected to pre-filtration to eliminate background particles. The procedural blanks consistently indicated no contamination, showing 0 particles per sample. Therefore, no correction was applied to sample counts. Recovery efficiency tests using spiked samples indicated an average recovery rate of 99.5-99.9%, confirming the reliability of the extraction method. The analytical method is limited to particles ≥20 µm due to filtration constraints. Consequently, the total abundance of microplastics may be underestimated due to the exclusion of nano-plastics and ultra-fine particles. Approximately 32% of the total recovered particles were subjected to FTIR analysis. From this subset, a representative group of particles (n = 479) with high spectral matching quality (>70%) was selected and reported for polymer composition analysis. This method guaranteed that the identification of polymers accurately represents the predominant particle types, all the while ensuring analytical reliability. The proportion of FTIR-analyzed particles falls within commonly reported validation ranges in microplastic studies (Nurhasanah *et al.,* 2021; Nurhasanah *et al*., 2025; Cordova *et al*., 2019; Cordova *et al*., 2020). Airborne contamination was mitigated by executing sample processing within a controlled environment, and blank filters were subjected to exposure during the analysis to assess airborne contamination levels. Additionally, the analytical method may exhibit biases in visual identification, face challenges in detecting smaller particle sizes, and rely partially on representative FTIR validation. These limitations were minimized through strict quality assurance/quality control (QA/QC) procedures and high recovery efficiency.

Data analysis

Differences in microplastic abundance among sampling locations were evaluated using non-parametric statistical tests with statistical software PAST5 (version 5.22). A correlation analysis was conducted to investigate the relationships between the abundance of microplastics and mesoplastics. Temporal comparisons of the datasets from 2021 and 2025 were carried out using a consistent sampling framework and methodology to ensure comparability. Variability across replicates was expressed using standard deviation and interquartile ranges. Statistical significance was evaluated at $p < 0.05$.

RESULTS AND DISCUSSION

Micro and mesoblastic were consistently identified across all sampling sites, which included before effluent (BE), leachate pond (LP), leachate drain (LD), and after effluent (AE). This observation confirms that the leachate system

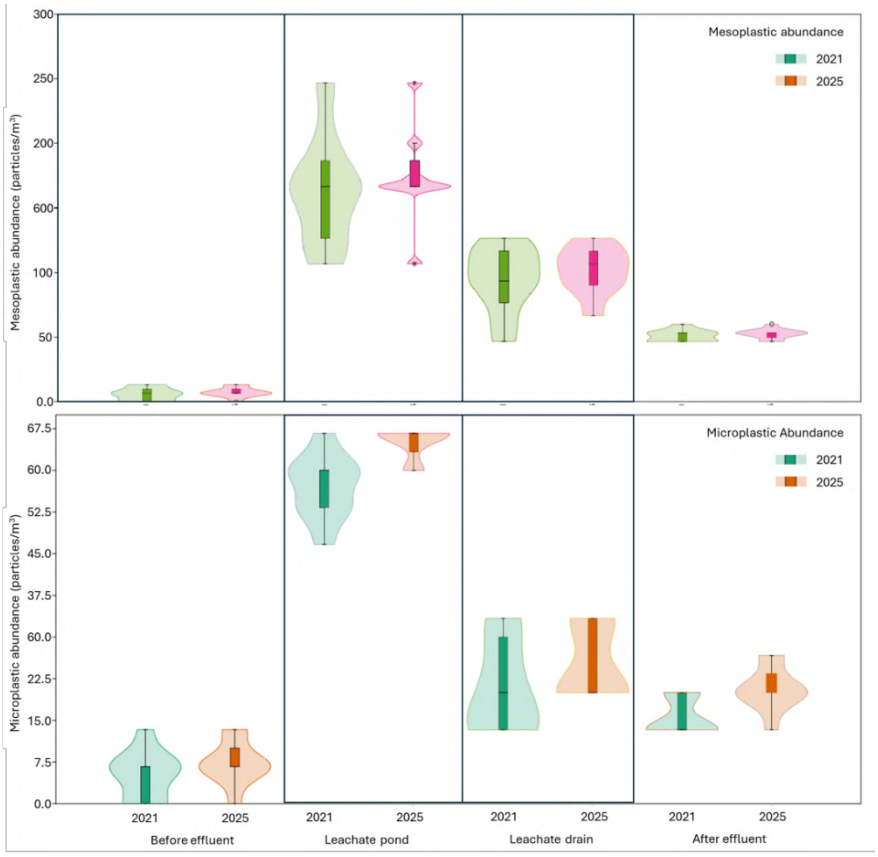

Fig. 2: Microplastics and mesoplastics abundance in the study area

operates as a conduit for the transport of small-sized plastics (Fig. 2). The abundance displayed a distinct spatial gradient along the leachate flow pathway, suggesting compartment-specific differences related to transport, retention, and transformation-related processes within the system. Fig. 2 illustrates the spatial variation and distribution range of microplastic and mesoplastic abundance across compartments, highlighting both central tendencies and variability among sampling points.

Abundance of dynamics across leachate system

At the BE, both micro- and mesoplastic abundances remained relatively low, with mean values of 5.19 ± 4.44 particles/m^3 and 5.93 ± 5.21 particles/m^3, respectively. This condition exemplifies a foundational state before the direct impact of leachate, indicating that plastic contributions are predominantly from diffuse environmental sources instead of point-source discharge. Similar baseline conditions have been reported in river systems with limited direct anthropogenic input (Hitchcock and Mitrovic, 2019). A marked increase in abundance was observed in the leachate pond (LP), where microplastics reached 65.19 ± 2.94 particles/m^3 and mesoplastics increased to 173.33 ± 36.67 particles/m^3. In comparison to the earlier dataset, this reflects an increase of roughly 8-12%, suggesting that the pond serves as a vital accumulation area with possible transformation-related activities. The elevated concentrations in this compartment can be attributed to intensive

mixing processes, high residence time, and the accumulation of suspended plastic debris. Such conditions may promote fragmentation and re-suspension of particles, as previously described in landfill leachate systems (He *et al*., 2019; Su *et al*., 2019; Nurhasanah *et al*., 2021). Further downstream, the leachate drain (LD) showed sustained elevated concentrations, with microplastic abundance measured to 25.19 ± 6.48 particles/m^3 and mesoplastic abundance reaching 101.48 ± 18.49 particles/m^3. The differences noted among compartments suggest a clear spatial variation, even though the patterns do not follow a strictly linear trajectory. This section represents a transitional zone where physical transport dominates, potentially accompanied by fragmentation processes influenced by hydraulic turbulence. The interplay of flow velocity and channelized transport increases the likelihood of particle collisions and disintegration, which may lead to the fragmentation of larger particles into smaller components (Klein *et al*., 2018; McCormick *et al*., 2017). At the downstream end, both micro- and mesoplastics remained detectable, with mean values of 20.74 ± 4.01 particles/m^3 and 52.59 ± 4.01 particles/m^3, respectively. Although lower than peak values in the pond, these concentrations indicate continued presence and potential residual leakage into the receiving aquatic system. This conclusion affirms that the leachate treatment and conveyance system fail to entirely retain plastic particles in the observed circumstances. This situation allows continuous discharge into the river system. Despite the overall upward trend observed, local discrepancies among compartments suggest that the dynamics of microplastics are not entirely linear, highlighting the impact of specific hydrodynamic conditions and retention mechanisms at each site. Comparable inefficiencies have been noted in landfill and wastewater management systems, where microplastics continue to exist even following treatment procedures (Mahon *et al*., 2017; van Praagh *et al*., 2018). Overall, the observed pattern demonstrates a structured pathway: baseline conditions at BE, accumulation and amplification in LP, transformation and transport in LD, and residual release at AE. This advancement bolsters the view that landfill leachate systems operate not just as channels for transportation but also as environments conducive to transformation processes that may happen prior to their discharge into the environment.

Temporal comparison with previous study

A comparison with the previous baseline study conducted at the same site reveals both continuity and evolution in the behavior of micro- and mesoplastics within the leachate system. The previous study indicated a three-fold rise in microplastics and a nine-fold rise in mesoplastics following the introduction of leachate input into the river (Nurhasanah *et al*., 2021). These findings highlighted the strong contribution of landfill leachate as a point source of plastic debris to aquatic environments. In the current study, the general upward trend continues to be stable; nevertheless, the extent and patterns of spatial distribution have altered. Instead of a sharp stepwise increase at the outlet, the data indicate a more distributed amplification along the system, particularly within the leachate pond and drain. Microplastic abundance increased from 24.63 ± 20.58 particles/m^3 (2021) to 29.07 ± 22.32 particles/m^3 (2025), while mesoplastics increased from 78.89 ± 63.70 particles/m^3 to 83.70 ± 65.46 particles/m^3. This incremental growth indicates that the accumulation of plastic has been persisted over time, possibly alongside processes of transformation (Cordova *et al*., 2022). More importantly, the spatial dynamics have become more complex. In the prior study, the leachate drain was pinpointed as the key area of increase,

whereas in the current dataset, the leachate pond stands out as the primary hotspot. This shift suggests that internal processes within the landfill system, such as prolonged retention and sludge accumulation, may play a more significant role than previously recognized. The conditions present in landfills, such as microbial activity, variations in temperature, and chemical reactions, can lead to the fragmentation of plastics and changes in their structure (He *et al*., 2019; Su *et al*., 2019; Nurhasanah *et al*., 2021). The persistence of high mesoplastic abundance alongside increasing microplastic fractions suggests a potential progressive fragmentation process. Rather than a simple reduction in particle size, the system may contribute to the generation of smaller particles from larger debris. This observation is consistent with the idea of secondary microplastic formation, in which mesoplastics serve as a reservoir for ongoing microplastic generation (Arthur *et al*., 2009; Song *et al*., 2017). Taken together, these results indicate that while the leachate system remains a significant source of plastic debris, its role has evolved from a primarily transport-driven system to a more dynamic transformation-driven system. This temporal shift emphasizes the necessity of regarding landfill leachate not just as a source, but also as a system in which processes associated with transformation might impact the properties and spread of plastic particles prior to environmental release.

Shape and size characteristics of micro- and mesoplastics

The composition of micro- and mesoplastics based on shape and size showed distinct spatial patterns across the leachate system, reflecting both source characteristics and potential in-situ transformation-related processes (Figs. 3 and 4). Overall, all four shape categories (fiber, fragment, granule, and foam) were identified in many sampling sites, although their relative proportions exhibited significant variation along the flow pathway. For microplastics (Fig. 3), fragments consistently dominated across all sampling sites, particularly in BE, where fragment proportions reached approximately 60-65%. Fibers were significantly lacking or present in minimal amounts at BE, indicating a minimal upstream input from sources related to textiles (De Falco *et al*., 2018; De Falco *et al*., 2019). This pattern suggests that the baseline condition is primarily influenced by secondary microplastics derived from the breakdown of larger debris rather than direct primary inputs (Hidalgo-Ruz *et al*., 2012; Cordova *et al*., 2019; Nurhasanah *et al*., 2021). In the LP pond, the variety of microplastic shapes achieved a greater balance, with fragments, fibers, granules, and foam each accounting for roughly 20-30%. This shift suggests the role of the pond as a mixing and retention zone, where heterogeneous plastic inputs accumulate and undergo physical redistribution. The presence of all shape types in relatively equal proportions suggests multiple concurrent processes, including input from landfill waste, mechanical mixing, and early-stage fragmentation. Analogous reports have emerged regarding landfill leachate systems, where extended retention time contributes to greater particle diversity (He *et al*., 2019; Su *et al*., 2019; Nurhasanah *et al*., 2021). As one moves further downstream in the LD, the dominance of fragments and fibers increased, making up about 70-80% in total, while the relative presence of granules and foam diminished. This pattern suggests that hydraulic transport and turbulence may influence the persistence of elongated and irregular particles, which are more resistant to settling. Simultaneously, granules are likely to fragment into smaller particles, which may contribute to the rising proportion of fragments. This study supports the interpretation from previous section that the drain may function as a transport-dominated corridor with possible

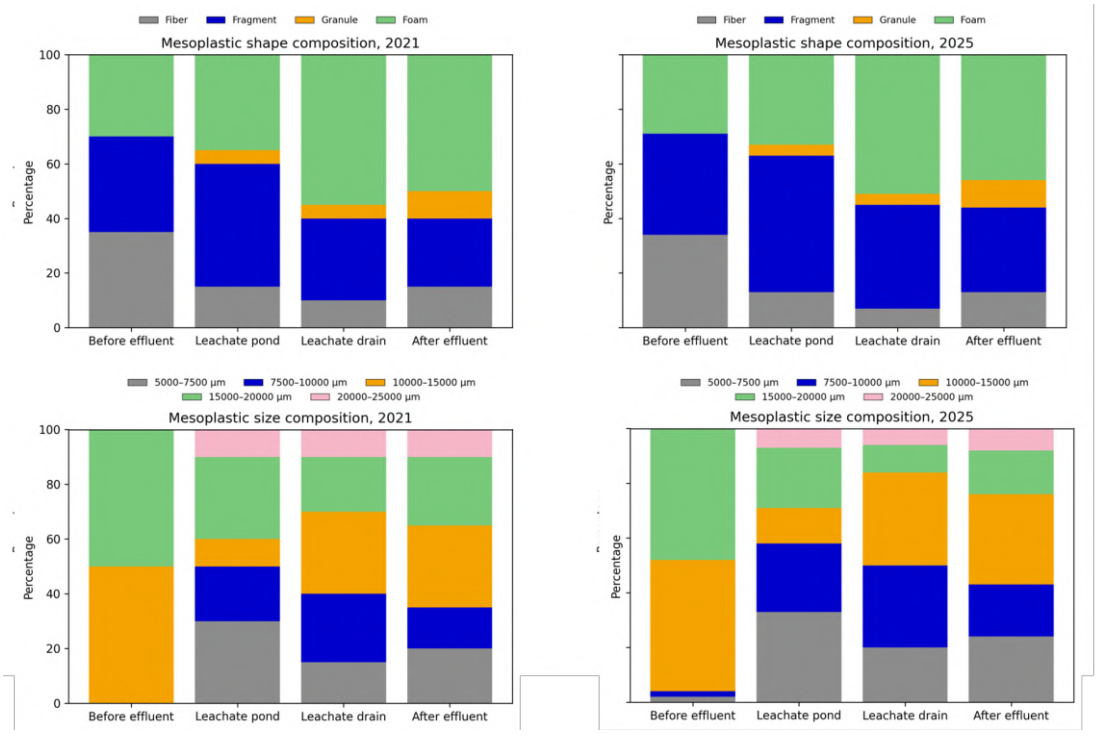

Fig. 3: Microplastic shape and size proportion in the sampling sites
(BE: before effluent, LP: leachate pond, LD: Leachate drain, AE: after effluent)

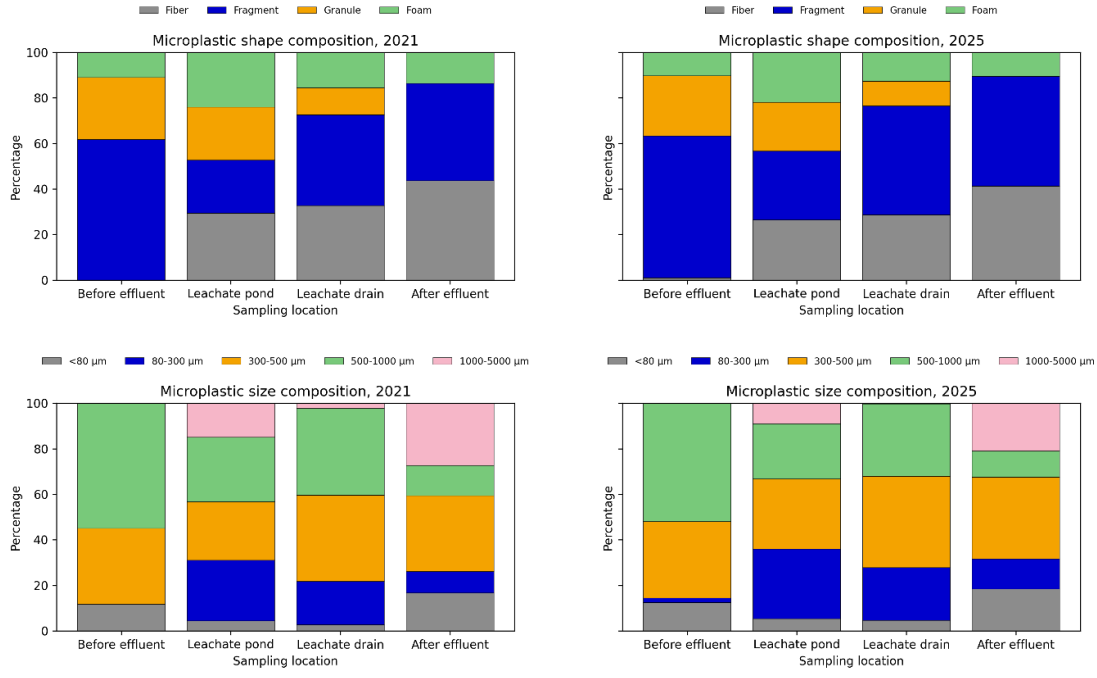

Fig. 4: Mesoplastic shape and size proportion in the sampling sites
(BE: before effluent, LP: leachate pond, LD: Leachate drain, AE: after effluent)

transformation-related processes influenced by hydrodynamic forces. At the AE site, fragments remained dominant, reaching nearly 90%, while granules were largely absent. The substantial decrease in granules at this phase points to the occurrence of advanced fragmentation processes, resulting in the breakdown of larger, more compact particles into smaller irregular forms. This observation is consistent with the increasing microplastic abundance downstream and supports the interpretation that the leachate system may facilitate progressive fragmentation processes, inferred from shifts in size distribution and shape composition along the pathway. For mesoplastics (Fig. 4), foam was the predominant shape across all sampling locations, accounting for approximately 35-55% of total particles. This dominance was already evident at BE and persisted through LP, LD, and AE. Foam materials, commonly sourced from packaging and insulation products, are distinguished by their low density and high buoyancy, which could elucidate for their persistence and broad distribution in aquatic systems (Andrady and Neal, 2009; Su *et al*., 2019). In addition to foam, fragment-type mesoplastics were also abundant, particularly in LP and LD, contributing approximately 30-40% of total particles. Compared to the previous study (Nurhasanah *et al*., 2021), the persistence of foam dominance suggests that the primary waste composition entering the landfill may have remained relatively consistent over time. Nonetheless, the elevated ratio of fragments in downstream sites implies an enhancement in mechanical breakdown activities. This aligns with the temporal shift identified in previous section, where the system shows stronger evidence of internal transformation dynamics. A distinct gradient in size distribution was noted, transitioning from larger to smaller particle classes along the leachate pathway (Figs. 3 and 4). For microplastics, the BE site was dominated by larger size fractions (300-500 µm and 500-1000 µm), indicating limited fragmentation prior to leachate influence. The absence or low proportion of smaller size classes (<80 µm and 80-300 µm) suggests that upstream inputs are relatively less processed. In LP, microplastic the size distribution of microplastics exhibited greater heterogeneous, characterized by enhanced contributions from intermediate size classes (80-300 µm and 300-500 µm). This illustrates the cumulative impacts of both accumulation and initial fragmentation within the pond ecosystem. The presence of multiple size classes supports the interpretation of the pond as a transitional zone where plastic debris may undergo progressive breakdown. In the LD, smaller size classes became more prominent, particularly 80-300 µm and 300-500 µm fractions, suggesting ongoing fragmentation during transport. The growth of smaller particles corresponds with mechanical stress caused by turbulence, potentially resulting in particle degradation (Klein *et al*., 2018; McCormick *et al*., 2016). At the AE, microplastics were dominated by smaller and intermediate size classes, particularly 300-500 µm and 1000-5000 µm. The ongoing existence of these fractions implies that a full decomposition into very fine particles (<80 µm) may necessitate an extended residence time or supplementary environmental processes, including photodegradation and biofouling (Andrady, 2011; Horton *et al*., 2017). For mesoplastics, larger size classes (10,000-15,000 µm and 15,000-20,000 µm) dominated at BE, indicating that upstream inputs consist primarily of relatively intact plastic debris originating from mixed municipal solid waste. In LP and LD, size distribution shifted toward a broader range, including smaller mesoplastic classes (5000-10,000 µm), reflecting progressive breakdown. At AE, the durability of mid-sized classes (10,000-15,000 µm) implies that fragmentation remains incomplete, which reinforces the coexistence of both meso- and microplastic fractions within the system.

Polymer composition and transformation

The analysis of the chemical composition of micro- and mesoplastics has shown a wide variety

of polymer types present within the leachate system, indicating the intricate nature of landfill inputs and potential transformation-related processes. More than twenty polymer types were identified, with clear dominance of polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Table 1). These polymers showed consistent increases from 2021 to 2025, indicating continued input and persistence within the system. Their dominance suggests that plastic debris entering the landfill is largely derived from single-use packaging materials (He *et al.*, 2019; Su *et al.*, 2019), consistent with previous studies in landfill environments (Nurhasanah *et al.*, 2021; Nurhasanah *et al.*, 2025). Spatially, polymer distribution exhibited distinct compartment-specific patterns. The upstream areas exhibited a lack of diversity, predominantly characterized by PE and PP, suggesting a minimal direct impact from landfill discharge. In contrast, the leachate pond displayed the highest polymer diversity and abundance, confirming its role as a major accumulation and mixing zone. Downstream in the leachate drain, polymer composition remained diverse but was increasingly dominated by more durable polymers, + suggesting selective retention and possible fragmentation of less stable materials (Andrady, 2011; Horton *et al.*, 2017). At the ultimate discharge location, there was a slight reduction in polymer diversity; nevertheless, essential polymers like PE, PP, and PS were still detected, suggesting that removal was not fully achieved and that environmental release persists. Temporal comparison between 2021 and 2025 further revealed an increase in both polymer abundance and diversity. In 2025, there was a notable increase in the prevalence of polymers like nylon, polyvinyl chloride (PVC), and oxidized polymers, indicating changes in waste inputs and potential transformation-related processes. The presence of oxidized polymers provides indirect evidence of possible chemical alteration within the system, likely associated with prolonged exposure to landfill conditions. Overall, the observed polymer patterns indicate that composition is determined not just by the source input but is also influenced by selective transport, retention, and transformation processes along the leachate pathway.

Relative concentration balance and removal efficiency across the leachate system

A quantitative evaluation of the microplastic mass balance throughout the leachate system demonstrates non-conservative behavior, highlighting the coexistence of accumulation, retention, and release processes within the system. Microplastic concentration increased markedly from 7.41 particles/m^3 at the upstream section to 65.19 particles/m^3 in the leachate pond, representing an approximately 780% increase. This enhancement indicates that the leachate pond functions not merely as a receiving compartment but also as a zone of particle accumulation and possible secondary formation processes. Subsequently, concentrations decreased to 25.19 particles/m^3 in the leachate drain and further to 20.74 particles/m^3 after effluent discharge. This reduction implies that there may be some degree of retention or sedimentation occurring, yet the sustained elevated concentrations observed downstream reveal that the removal process is not entirely effective. When evaluated from a system perspective, removal efficiency estimated between the upstream and downstream sections resulted in a negative value, indicating a net increase rather than removal of microplastics. This finding indicates that the leachate system may not function as an effective removal system under the observed conditions. However, instead contributes to the redistribution of microplastics prior to environmental release. Despite the observation of a general upward trend, the spatial distribution is not entirely linear. Variations

Table 1: Summary of polymer composition and spatial dominance across the leachate system (2021-2025)

Polymer Type	Total 2021	Total 2025	Change (%)	Dominant Zone	Interpretation
Polyethylene (PE)	17	22	29.41	LP-LD	Highly persistent, dominant packaging polymer
Polypropylene (PP)	15	19	26.67	LP-LD	Resistant polymer with strong transport potential
Polystyrene (PS)	12	18	50.00	LP	Accumulates in low-energy zones (pond)
Polyester	5	7	40.00	LP	Likely associated with textile and mixed waste
Nylon (6,9)	4	8	100.00	LP-LD	Indicates secondary inputs and transformation
Polyvinyl chloride (PVC)	3	9	200.00	LP	Increased presence suggests evolving waste input
Polybutadiene	1	9	800.00	LD	Likely fragmentation-derived polymer
Polyurethanes	3	5	66.67	LP-LD	Moderate persistence and degradation behavior
Polyethylene terephthalate (PET)	4	11	175.00	LP	Common packaging material with increasing input
Oxidized polymers	2	4	100.00	LD	Indicative of in-situ chemical transformation
Others (minor polymers)	<5 each	<5 each	0.00	Variable	Minor contributions, heterogeneous sources
Total identified polymers	91	141	54.95	LP dominant	Increasing diversity and complexity over time

between compartments indicate the influence of localized hydrodynamic conditions and retention processes. The leachate pond represents a primary accumulation hotspot, characterized by peak concentrations and the highest polymer diversity within the system. This indicates a generally low removal efficiency when assessing the concentrations upstream and downstream, suggesting a net increase in particle abundance across the system.

Treatment inefficiency, environmental release, and implication

Furthermore, the presence of both microplastics and mesoplastics at the AE sampling locations, despite their passage through the leachate management system, highlights the inadequacy of the treatment in completely eliminating these contaminants, leading to their ongoing discharge into the aquatic ecosystem. The mean abundance at AE reached 20.74 ± 4.01 particles/m^3 for microplastics and 52.59 ± 4.01 particles/m^3 for mesoplastics, indicating that a substantial fraction of plastic particles persists beyond the treatment stages. This observation emphasizes a shortcoming of the present leachate system, where the physical and chemical processes fail to adequately retain or remove plastic debris. While the leachate pond and drain may act as zones of accumulation and potential transformation-related processes, these compartments do not function as effective barriers for plastic containment. Instead, these units may facilitate fragmentation and redistribution, resulting in the downstream transport of smaller and more mobile particles. The ongoing issue of plastics in AE is notably troubling, as this site acts as the direct connection between the landfill system and the natural riverine environment. The release of microplastics and mesoplastics into the Cianter River and Cisadane watershed suggests that landfill leachate may act as a continuous point source of plastic pollution. Comparable findings have been documented in studies concerning wastewater and landfills, indicating that standard treatment methods are inadequate in entirely removing microplastics, which consequently enter surface waters (Mahon *et al*., 2017; van Praagh *et al*., 2018). In addition, the dominance of fragment-type microplastics and the presence of smaller size classes at AE indicate that particles released into the environment are already in a highly transformed state. These particles may remain suspended, be transported over long distances, and interact with biota due to their increased surface area and reactivity (Andrady, 2011; Horton

et al., 2017). This may enhance their environmental risk compared to larger debris. Several factors may account for the inefficiency of the leachate system in retaining plastics. First, the absence of dedicated filtration or separation units targeting micro-sized particles allows plastics to pass through the system. Second, hydraulic turbulence within the drain may resuspend previously settled particles, reintroducing them into the flow. Third, continuous fragmentation processes might lead to the creation of smaller particles within the system, counteracting any removal that could take place. These findings emphasize that landfill leachate management systems, particularly those based on conventional designs, are not equipped to address emerging pollutants such as microplastics. Without targeted intervention, such systems may unintentionally contribute to the propagation of plastic pollution in aquatic environments. The amalgamated outcomes from abundance dynamics, shape and size characteristics, and polymer composition together advocate for a conceptual shift in understanding of the role of landfill leachate systems. Instead of merely acting as passive conduits, these systems could serve as settings where processes related to transformation take place. This situation leads to changes in particle characteristics prior to environmental release. Within the landfill body, plastic waste is subjected to a range of stressors, including mechanical pressure, microbial activity, chemical reactions, and fluctuating environmental conditions. These elements could play a role in the disintegration of larger plastic objects into smaller particle sizes. As leachate forms and flows through the system, it mobilizes these particles and transports them into the leachate pond. The leachate pond functions as a vital processing zone, distinguished by extended residence time, intricate mixing dynamics, and accumulation of organic and inorganic materials. In this environment, plastic particles are exposed to prolonged interactions that may promote fragmentation and alteration of their physical properties. This is reflected in the increased diversity of observed shapes and sizes. As the leachate flows into the drainage system, hydraulic turbulence emerges as the primary process, which may increase particle collision and mechanical fragmentation. The results may contribute to a shift toward smaller particle sizes and fragment-dominated shapes. The drain thus serves as a transformation corridor, linking the accumulation processes in the pond with the release processes downstream. Finally, at the after-effluent phase, the system releases a blend of altered particles into the aquatic ecosystem. These particles are not only smaller and more abundant but may also exhibit signs of chemical alteration, as indicated by the presence of oxidized polymers. This may increase their environmental persistence and potential ecological impact. The framework of the leachate system, characterized as a transformation-active environment, offers a cohesive framework that links source, process, and outcome. It provides a possible explanation for the observed increase in microplastic abundance, the dominance of fragment shapes, the shift toward smaller size classes, and the persistence of specific polymer types across the system. This conceptual model has important implications for both research and management. From a scientific standpoint, it emphasizes the necessity of viewing landfill systems as dynamic ecosystems in which the transformation of plastic takes place actively. From a management perspective, it underscores the urgency of redesigning leachate treatment systems to include targeted removal technologies for microplastics, such as advanced filtration or sedimentation enhancements. To gain a deeper understanding of these patterns, the fundamental transformation processes within the leachate system are elaborated upon below.

Process interpretation and transformation mechanisms within the leachate system

Microplastic dynamics observed across the leachate pathway indicate that the system may function as an environment where multiple transformation-related processes occur simultaneously. A variety of physical, chemical, and biological mechanisms may impact these processes, with variations observed across compartments (Nurhasanah *et al.,* 2021; Nurhasanah *et al*., 2025). Physical processes, particularly hydraulic turbulence within the leachate drain, may play an important role in particle fragmentation (He *et al*., 2019; Su *et al*., 2019). The enhancement of flow velocity and the impact of particle collisions could encourage the fragmentation of larger plastic debris into smaller pieces, which in turn contributes to the noted transition toward smaller size classes downstream (He *et al*., 2019; Su *et al*., 2019). In contrast, the leachate pond may function as a low-energy environment with high residence time, facilitating particle accumulation, aggregation, and intermittent resuspension. The presence of oxidized polymers identified within the system may indicate chemical transformation. Oxidation processes, driven by prolonged exposure to leachate conditions, may weaken polymer structures and increase their susceptibility to fragmentation (Alimba and Faggio, 2019; Bouwmeester *et al*., 2015). This procedure may hold significant importance in the pond ecosystem, as extended retention heightens exposure to reactive conditions. Biological processes may also contribute to microplastic transformation. Under landfill conditions, microbial activity and organic matter interactions may influence degradation pathways (Alimi *et al*., 2018). Although anaerobic conditions may slow complete polymer degradation, they do not necessarily prevent mechanical fragmentation. Instead, plastics may persist while undergoing gradual size reduction over time (Alimi *et al*., 2018; Muhtadi *et al*., 2025). Furthermore, microplastics present in the leachate system engage with elevated levels of organic matter and dissolved substances (Alimba and Faggio, 2019; Bouwmeester *et al*., 2015). These interactions may promote aggregation, alter particle density, and increase the potential for contaminant adsorption (Alimba and Faggio, 2019). Consequently, microplastics can serve as vehicles for associated pollutants (for instance heavy metals and various contaminants), impacting their distribution and ecological consequences (Alimba and Faggio, 2019; Bouwmeester *et al*., 2015; Muhtadi *et al*., 2025). Based on these combined observations, the landfill leachate system can be conceptualized as a hybrid system that may function simultaneously as a source, retention zone, and transformation-active environment. The upstream section represents baseline conditions, the leachate pond may serve as a primary accumulation and processing compartment, and the drainage channel may act as a transport-dominated corridor with potential fragmentation-related processes. Ultimately, the system emits particles into the receiving environment, implying that processes associated with transformation could happen prior to environmental discharge instead of following it.

CONCLUSION

This study provides an integrated assessment of micro- and mesoplastic occurrence, characteristics, and transformation within a landfill leachate system. The results indicate that plastic particles are present across all stages of the leachate pathway, from upstream conditions to downstream discharge, suggesting that landfill leachate may act as a source of plastic pollution to aquatic environments. In accordance with the study objectives, the analysis reveals that both abundance and polymer composition vary across

compartments, reflecting spatial heterogeneity within the system. Spatial analysis reveals a structured pattern across the leachate pathway. The upstream segment denotes baseline conditions with a comparatively low abundance, while the leachate pond may function as a significant accumulation zone containing the highest levels of both microplastics and mesoplastics. The leachate drain may function as a transport-dominated corridor, where hydraulic conditions may contribute to particle redistribution and fragmentation-related processes. Additionally, the presence of plastic particles at the after-effluent stage suggests that the removal process is not fully effective, leading to their continued release into the river system. These findings are consistent with the study hypothesis that microplastic abundance and composition vary along the leachate pathway due to combined effects of transport, retention, and transformation-related processes, rather than following a strictly linear increase. The detected non-linear spatial arrangement, featuring localized peaks in the leachate pond and persistent concentrations downstream, underscores the significance of compartment-specific dynamics within the system. Temporal comparison with previous observations further indicates that system behavior has evolved from localized increases toward a more distributed pattern across compartments. This shift suggests that internal processes within the landfill system, such as retention, mixing, and prolonged exposure conditions, may increasingly influence plastic dynamics, rather than being controlled solely by external inputs. The characterization of plastic debris supports this interpretation. Microplastics are mainly characterized by their fragmented forms and reduced size classifications, particularly in downstream regions, which implies a continuous degradation of larger materials. Mesoplastics remain dominated by foam and fragment types but show a shift toward smaller size classes along the pathway. These patterns suggest a possible connection between mesoplastics and microplastics, indicating that larger debris could play a role in the gradual formation of smaller particles. Polymer composition analysis further reinforces these findings. Polyethylene, polypropylene, and polystyrene consistently dominate across sampling locations, reflecting their widespread use and persistence in the environment. The presence of oxidized polymers provides indirect evidence of possible chemical alteration within the system, particularly in compartments with longer residence time. The analogous polymer composition found in meso- and microplastics indicates that the formation of secondary microplastics may transpire within the leachate pathway. From a system perspective, landfill leachate may function not only as a transport pathway but also as a transformation-active environment, where physical, chemical, and biological processes influence particle characteristics prior to environmental release. These processes could enhance the mobility, persistence, and potential ecological interaction of plastic particles in aquatic environments. From a management perspective, the findings highlight a gap in current leachate treatment systems, which are not specifically designed to retain or remove microplastics. The ongoing existence of plastics in effluent implies that further treatment techniques, such as fine filtration, improved sedimentation, and optimized retention strategies, could be essential to decrease plastic emissions into water bodies. Integrating microplastic monitoring into routine leachate management frameworks may also improve early detection and mitigation of plastic leakage. Future studies ought to include flow-based measurements, sediment and sludge analysis, along with controlled experimental methods to

enhance the quantification of transformation mechanisms and to create a comprehensive system-scale evaluation. Such efforts will be essential to validate process-based interpretations and support the development of more effective management strategies for emerging plastic pollutants.

AUTHOR CONTRIBUTIONS

Nurhasanah, the corresponding authors contributed to result interpretation and manuscript preparation and finalization. Hasrianti, contributed to interpretation and manuscript preparation. L. Hakim contributed to result interpretation and manuscript preparation. E. Riani designed the field sampling, contributed to data analysis, and participated in result interpretation. M. R. Cordova, the primary contributor, conceived and designed the study, conducted laboratory analysis, performed data analysis, interpreted the results, prepared and finalized the 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, 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
µm	Micrometer or micron
AE	after effluent
ATR-FTIR	Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy
BE	Before effluent
cm	Centimeter
/cm	A reciprocal centimeter (or wavenumber)
$Fe(II)SO_4$	Iron(II) sulfate or ferrous sulfate
FTIR	Fourier Transform Infrared spectroscopy
g	gram
g/cm	gram per centimeter cubic
Ha	Hectare
H_2O_2	Hydrogen peroxide
kg	Kilogram
L	Liters
LD	leachate drain
LP	leachate pond
mg/mL	milligram per milliliter
mL	milliliter
mm	millimeters
particles/m^3	Particles per meter cubic
p-value	probability value
QA/QC	Quality assurance/quality control
$ZnCl_2$	Zinc chloride

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ORIGINAL RESEARCH ARTICLE

Policy awareness, occupational health risk and institutional support for informal waste pickers

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ABSTRACT

BACKGROUND AND OBJECTIVES: Informal waste pickers play a vital role within municipal solid waste management systems across many developing regions; they remain largely excluded from formal policy frameworks, occupational safety provisions, and social protection programs, resulting reduced system efficiency, compromised worker welfare, and weak governance outcomes. The study examines socio-economic conditions, occupational health risks, institutional support, and policy awareness of waste pickers Himachal Pradesh, India, while examining the interplay among these elements to elucidate the pathways toward formal integration.

METHODS: The study adopts an integrated mixed-methods approach. Primary data were collected through structured questionnaires administered to 200 waste pickers. Field observations took place at various waste collection and segregation points, and semi-structured interviews were conducted with municipal officials and representatives from non-governmental organizations. Quantitative data were examined through descriptive statistics in conjunction with chi-square tests to evaluate associations, while qualitative insights were employed to provide context for institutional and policy-related gaps.

FINDINGS: The results reveal that only 45 percent of waste pickers were aware of the Solid Waste Management Rules, 2016, and just 35 percent were registered under municipal or cooperative programs, indicating low formal system penetration. Inadequate occupational safety conditions were observed, with only 20 percent of the workforce consistently using personal protective equipment. Additionally, 70 percent involved in manual lifting 6–8 hours daily, managing approximately 60–90 kilograms waste per day. Institutional support was limited effectiveness, reflected through a budget allocation United States Dollars 30,000, 12 training sessions, and a 40 percent cooperative membership rate, which did not translate higher coverage or safety adoption. Access to healthcare and social protection continued to be limited, with merely 30 percent coverage. Waste management performance indicators showed 40 percent segregation efficiency and 25 percent processing through composting or biogas systems, suggesting suboptimal resource recovery. Qualitative findings underscore notable shortcomings in policy awareness, administrative protocols, and monitoring frameworks that impede formal inclusion.

CONCLUSION: The study highlights structural and administrative constraints limiting effective integration of informal waste pickers within formal waste management systems. Enhanced institutional collaboration, better policy communication, and tailored occupational safety measures continue to be crucial. Broadening access to social protection and optimizing administrative processes can positively impact inclusion outcomes. The integrated mixed-method framework offers a systematic approach to identify and address multi-dimensional inclusion gaps within waste governance systems.

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INTRODUCTION

Informal waste pickers play a vital role in municipal solid waste management (MSWM), enabling recycling, resource recovery, and cost-effective waste handling, yet they remain largely unrecognized within formal policy frameworks (Balasubramanian, 2018; Buch *et al.,* 2021). These employees make substantial contributions to the circular economy by reclaiming recyclable materials, minimizing reliance on landfills, and promoting sustainable waste management systems (Alqaralleh *et al.,* 2026). Despite this role, they operate under precarious conditions with limited social protection, irregular incomes, and inadequate occupational safety (Chokhandre *et al.,* 2017). In Himachal Pradesh, characterized through mixed urban–rural settlements and dispersed municipal systems, integration of informal waste pickers into formal programs is hindered by geographic challenges, administrative heterogeneity, and uneven municipal infrastructure (Sharma and Acharya, 2019). This situation serves as a pertinent framework to investigate the impact of geographic dispersion, institutional variation, and infrastructure shortcomings on policy implementation, worker inclusion, and waste management effectiveness (Shaherani *et al.,* 2026)**.** Although India has established national frameworks such as the Solid Waste Management Rules (SWMR), 2016, issued by the Ministry of Environment, Forest and Climate Change (MoEFCC, 2016), their uptake and implementation at the grassroots level remain limited. Low awareness of legal provisions and registration under municipal or cooperative programs restrict access to welfare schemes, health coverage, and institutional support. Occupational health risks remain critical. Waste pickers handle heavy loads of 60–90 kilograms (kg) daily over 6–8 hours (h) while limited personal protective equipment (PPE) use exposes them to musculoskeletal strain, cuts, respiratory hazards, and skin infections (Thakur *et al.,* 2018). Subsequent studies have primarily focused on socio-economic vulnerabilities or occupational health independently, showing a lack of attention to the relationship between policy awareness, governance structures, and waste management effectiveness (Singh *et al.,* 2023). Institutional interventions, including municipal budget allocations, training programs, and cooperative facilitation, aim improved inclusion and welfare, yet remain inconsistent across districts and insufficiently address gender-specific challenges (Li and Chen, 2025). Female waste pickers encounter further obstacles stemming from gender-specific labor roles, limited access to social protection, and reduced involvement in cooperatives (Misra and Tewari, 2022). Consequently, a knowledge gap persists regarding how policy awareness, occupational safety practices, and institutional mechanisms collectively influence inclusion, operational efficiency, and welfare outcomes (Pedroso *et al.,* 2024). Existing studies concerning informal waste pickers predominantly concentrate on singular facets such as health hazards associated with their occupation (Chokhandre *et al.,* 2017; Thakur *et al.,* 2021), socio-economic vulnerabilities (Singh *et al.,* 2023), and gender-based precarity (Misra and Tewari, 2022), with limited integration of governance and policy dimensions. Broader reviews emphasize fragmented evidence and the absence of holistic frameworks (Pedroso *et al.,* 2024). These overlapping discussions suggest a redundancy concerning roles and gaps, necessitating consolidation for enhanced clarity. Despite this body of work, a clearly defined linkage between policy awareness, institutional mechanisms, and measurable waste management outcomes remains insufficiently articulated, limiting analytical precision in existing studies. Empirical studies seldom link policy awareness, institutional frameworks, and the results of operational waste management within a cohesive structure. To address this gap, the current study formulates a comprehensive assessment framework that connects policy awareness under the SWMR, 2016, occupational safety practices, and institutional support with quantifiable waste

management performance indicators. This framework is conceptually based on an interactional systems perspective linking governance inputs, worker-level practices, and system-level outcomes. In this context, governance variables act as independent drivers, worker-level practices operate as mediating mechanisms, and waste management performance indicators denote outcome dimensions. The comprehensive analysis offers a clear insight into the ways in which how institutional, social, and occupational elements collectively impact inclusion, efficiency, and sustainability in MSWM systems (Kala and Bolia, 2024). This integrated assessment highlights gaps within policy implementation and occupational safety infrastructure while identifying opportunities for strengthening institutional support. The results are designed to inform strategies that elevate policy outreach, increase cooperative participation, and advance municipal training programs, consequently bolstering occupational safety and the effectiveness of waste management. The study also addresses gender disparities, healthcare access, and welfare inclusion barriers often overlooked in informal waste work research. Overall, it provides actionable insights for policymakers, urban planners, and social welfare agencies seeking to strengthen sustainable and inclusive MSWM systems in the Indian Himalayan context. The study is structured around the following aims: i) to assess the degree of policy awareness among waste pickers and their registration status under MSWM programs; ii) to assess occupational safety conditions and ergonomic risks associated with waste collection and handling practices; iii) to analyze the function of governance mechanisms, training programs, and institutional assistance on improving waste management efficiency; and iv) to analyze access to healthcare and social protection programs in order to pinpoint obstacles that hinder welfare inclusion for informal waste workers. These objectives are directly operationalized through corresponding hypotheses (H1–H4), ensuring explicit alignment between research aims and testable relationships. Collectively, these goals establish a systematic approach to address current research deficiencies, evaluate the operational and social aspects of integrating waste pickers, and support evidence-driven policy and program initiatives designed to enhance both worker welfare and municipal waste management outcomes. The study was conducted at the Department of Government and Public Administration, Lovely Professional University, Punjab, India, in 2025.

MATERIALS AND METHODS

This study presents the methodological framework of the study, including research design, data collection procedures, use of quantitative and qualitative methods, and analytical techniques ensuring reliability, validity, and systematic interpretation. This study specifically employs a convergent mixed-methods design, wherein quantitative and qualitative data are gathered simultaneously, analyzed independently, and subsequently integrated during the interpretation phase. The integration of multiple methods provides a comprehensive basis for examining the research problem.

Research design

A mixed-methods design was adopted to analyze governance structures, policy awareness, occupational safety, and institutional integration of waste pickers in MSWM systems in Himachal Pradesh, India (Rani *et al.,* 2025). Waste pickers are essential to the activities of waste segregation, recycling, and organic waste management, yet they are predominantly excluded from formal governance and social protection systems. The study integrates structured surveys, stakeholder interviews, and field observations to examine relationships among governance mechanisms, policy implementation, occupational conditions, and waste management efficiency, addressing both technical and institutional dimensions.

Study area description

The study was conducted in Shimla, Mandi, Solan, Kangra, and Dharamshala, representing diverse urban local bodies in Himachal Pradesh, India with 30°–33° north (N), 75°–79° east (E); 350–6,900 meters (m) altitude, (MoEFCC, 2017). The state has varied climatic zones from subtropical to alpine, which affects the processes of waste generation and management processes. Himachal Pradesh comprises 61 urban local bodies generating about 346 tonnes (T) of municipal solid waste daily, of which 332 tonnes are collected, 221 tonnes processed, and 111 tonnes disposed (Central Pollution Control Board (CPCB), 2021; CPCB, 2020). Selected municipalities represent variations in population density, infrastructure, and informal recycling activity.

Sampling strategy and sample size determination

Selection of municipalities

Five urban local bodies, Shimla, Mandi, Solan, Kangra, and Dharamshala, were purposively selected to capture heterogeneity in population density, MSWM infrastructure, and informal recycling activities, consistent with established approaches in informal sector studies (Etikan *et al.,* 2016). The selection was influenced by specific inclusion criteria that included differences in population size and density, levels of MSWM infrastructure, presence of informal recycling activities, and geographic representation. Municipalities that did not meet these criteria were excluded. The inclusion of five municipalities was deemed sufficient to capture variability and enable meaningful comparative analysis across diverse urban contexts within the study scope. The selection process was conducted using stratified purposive sampling to ensure representation of diverse urban contexts, thereby enabling a comparative evaluation of MSWM systems (Gupta *et al.,* 2017).

Selection of stakeholder groups

Three stakeholder groups were identified to provide comprehensive perspectives on MSWM. Waste pickers represented operational practices, municipal officers provided insights into governance and policy implementation, and NGO/cooperative representatives contributed information on institutional support mechanisms, reflecting the multi-actor structure of informal waste systems. Inclusion of these groups allowed triangulation of data and enhanced reliability and validity of findings (Singh *et al.,* 2023). However, the reliance on purposive and accessibility-based sampling could lead to selection bias, which means that the results are viewed as generally indicative rather than completely representative of the entire waste picker population.

Sample size

The sample size was calculated by the Slovin formula, using Eq. 1 (Etikan *et al.,* 2016):

$$n = N / (1 + N \times e^2) \quad (1)$$

where, n denotes the required sample size, N represents the population, and e indicates the margin of error.

The margin of error was set at 5 percent (%) to maintain statistical rigour. Based on an estimated waste picker population of 550, the calculated sample size was approximately 231 respondents. The Slovin formula was embraced as a practical method for determining sample size when detailed population variance data is lacking, a situation often encountered in informal sector research contexts. Considering field feasibility and operational constraints, the final sample included 225 respondents, comprising 200 waste pickers, 15 municipal officers, and 10 NGO/cooperative representatives (Etikan *et al.,* 2016). The reduced count of NGO and cooperative representatives signifies their constrained presence and specialized function within the study area, where merely a few organizations are actively engaged in MSWM-related activities; hence, their inclusion was guided on relevance and expertise rather than statistical representation (Table 1). The marginal

Table 1: Study population characteristics and data collection methods

Category	Subcategory	Waste Pickers	Municipal Officers	NGO/Cooperative Representatives	Total
Sample size	–	200	15	10	225
Data collection method	–	Structured questionnaire	Semi-structured interviews	Key informant interviews	–
Age (years)	18–25	30	2	1	33
	26–40	105	8	5	118
	41–60	65	5	4	74
Gender	Male	80	10	6	96
	Female	120	5	4	129
Experience (years)	<5	50	–	–	50
	5–10	90	–	–	90
	>10	60	–	–	60
Education	No formal schooling	40	–	–	40
	Primary	90	–	–	90
	Secondary	50	–	–	50
	Higher	20	15	10	45
Primary work activity	Collection	120	–	–	120
	Segregation	50	–	–	50
	Recycling / resale	30	–	–	30
Registration status	Registered with municipal/cooperative	80	–	10	90
	Not registered	120	15	–	135

reduction from the calculated sample size (231) to the achieved sample (225) was due to non-response and field constraints and is not expected to significantly affect statistical reliability or the overall interpretation of results. Furthermore, while the sample size is based on statistical methods, factors such as field accessibility and participant willingness can impact its representativeness, which are frequent constraints in studies concerning the informal sector.

Pre-testing of questionnaire

The structured questionnaire was pre-tested with ten waste pickers to evaluate clarity, relevance, and reliability, consistent with occupational survey practices in informal settings (Chokhandre *et al.,* 2017). Feedback from the pre-test guided the enhancement of the instrument, ensuring it aligns with research goals and reduces measurement error. Content validity was ensured through expert review and alignment of questionnaire items with study objectives, while construct validity was addressed by designing items based on established concepts in MSWM and informal sector research. Additionally, internal consistency reliability was assessed using Cronbach's alpha, yielding a value of 0.82**.** This indicates a good level of reliability as values above 0.7 are considered acceptable and those above 0.8 reflect good internal consistency**.** This confirms that the items in the questionnaire effectively measure the intended constructs (Chokhandre *et al.,* 2017).

Data sources and study design

A mixed-methods research approach was adopted, incorporating quantitative surveys, qualitative interviews, field observations, and secondary data analysis to explore MSWM and the integration of waste picker inclusion, as recommended in occupational health studies of informal workers (Rani *et al.,* 2025).

Primary data collection

Structured questionnaires were administered to 200 waste pickers to obtain quantitative information on demographic characteristics, occupational profiles, education, registration status, awareness of SWMR, 2016, occupational

safety practices, PPE usage, healthcare access, and income levels, reflecting common vulnerability dimensions in waste picker populations (Misra and Tewari, 2022). Semi-structured interviews were conducted with 15 municipal officers to examine governance structures, program implementation, monitoring systems, budget allocation, regulatory enforcement, and informal worker integration. Participants for qualitative interviews were selected purposively based on their direct involvement and expertise in MSWM and informal sector activities, and interviews followed a semi-structured protocol with predefined thematic guides to ensure consistency and reproducibility. Interviews conducted with 10 representatives from NGOs and cooperatives gathered information regarding training initiatives, advocacy programs, cooperative membership, and institutional support frameworks, consistent with inclusive waste management approaches (Buch *et al.,* 2021). Field observations were conducted at waste collection points and informal sorting sites to document segregation practices, PPE usage, and ergonomic conditions associated with occupational health risks (Singh and Chokhandre, 2015).

Secondary data sources

Secondary data were obtained from the CPCB annual report (2021), Swachh Bharat Mission–Urban (SBM-U) datasets (Ministry of Housing and Urban Affairs (MoHUA), 2025), and the annual report 2024–2025 published by the MoEFCC, (2025). Regulatory frameworks, including the SWMR, 2016 and Street Vendors Act, 2014, were reviewed to assess institutional mandates and informal worker inclusion policies (MoEFCC, 2016; Government of India, 2014). Secondary data were incorporated via comparative analysis alongside primary data to provide context for the findings and confirm the identified patterns. Data collection process was executed in a sequential multi-stage process, with fieldwork carried out during a specified study period, utilizing local language administration and trained enumerators to ensure respondent comprehension, consistency, and data quality. Survey instruments captured demographic and occupational characteristics of waste pickers, who are known to experience high levels of occupational vulnerability (Chokhandre *et al.,* 2017). Interviews with municipal officials explored governance constraints and implementation gaps.

Data analysis

Quantitative analysis: Quantitative data from 200 respondents were analyzed using descriptive statistics, including frequencies, percentages, and cross-tabulations. The factors taken into account were PPE usage, healthcare accessibility, and income, all of which are essential factors influencing occupational health outcomes within informal waste sectors (Uhunamure *et al.,* 2021). Results indicated low awareness of SWM Rules, limited registration coverage, and low PPE usage.

Qualitative analysis

Qualitative data were analyzed using thematic analysis. A systematic coding procedure was followed, involving initial open coding, categorization of codes into themes, and iterative refinement; coding was conducted manually using a predefined thematic guide, and consistency was ensured through repeated review and cross-verification of coded data. Key themes comprised governance capacity, deficiencies in policy implementation, constraints in training, and the state of occupational safety, consistent with the findings on the precarious situation of informal waste workers (Shankar and Sahni, 2018). An analytical framework was applied to examine relationships between key variables, such as policy awareness and PPE usage, using cross-tabulation to identify patterns and associations relevant to occupational safety outcomes. Ergonomic hazards and musculoskeletal tension were commonly documented, consistent with findings derived from health studies on waste pickers (Singh and Chokhandre, 2015).

Data triangulation

Triangulation integrated surveys, interviews, field observations, and secondary datasets to enhance validity. Triangulation was conducted by cross-validating findings across data sources to ensure consistency and strengthen interpretation. Convergence of evidence indicated structural governance restrictions and occupational health hazards exist among waste pickers (Rani *et al.,* 2025).

Statistical analysis

Statistical analysis was conducted using the statistical package for the social sciences (SPSS) (Version 29). Advanced techniques, including correlation analysis, multiple regression, and analysis of variance (ANOVA), were employed to examine relationships among socio-economic, occupational, and institutional variables affecting waste picker welfare. Before model estimation, assumptions for statistical tests, including normality, linearity, independence, and homoscedasticity, were assessed using appropriate diagnostic tests such as normality plots, residual analysis, and Durbin–Watson statistics. Additionally, multicollinearity among independent variables was assessed using variance inflation factors (VIF) to ensure the robustness of the regression models. Categorical variables were dummy-coded, and missing values were handled through listwise deletion.

Ethical considerations and informed consent

Ethical approval was obtained from the Institutional Ethics Committee prior to data collection. Participation was voluntary, and informed consent was obtained from all respondents. Confidentiality and anonymity were preserved during the entire study, and the data were utilized exclusively for academic purposes.

Hypotheses development

In accordance with the aims of the study and the existing literature, four hypotheses (H1 to H4) were formulated. Each hypothesis was aligned with specific analytical techniques, including cross-tabulation, correlation analysis, and regression models, to empirically examine relationships between variables.

i. H1: Waste pickers with higher awareness of SWMR, 2016 are more likely to be registered under municipal or cooperative programs, consistent with governance–compliance relationships (Kala and Bolia, 2024).
ii. H2: Female waste pickers have lower access to healthcare services and social protection compared to male waste pickers, which illustrates the gender inequalities that exist within informal work (Misra and Tewari, 2022).
iii. H3: Waste segregation efficiency and organic waste processing are positively associated with training participation and governance support, consistent with cooperative-driven waste management outcomes (Buch *et al.,* 2021).
iv. H4: Poor ergonomic practices and lack of PPE significantly increase occupational health risks among waste pickers, as widely documented in occupational health studies (Thakur *et al.,* 2021).

RESULTS AND DISCUSSION

Quantitative analysis

This section presents quantitative analysis of survey data pertaining to waste pickers, examining socio-demographic characteristics, occupational safety, governance support, and access to healthcare and social protection. Descriptive statistics, percentage distributions, and institutional indicators derived from field surveys, municipal records, and program data are used to assess key patterns. Table 2 and Figs. 1 to 4, including the structured questionnaire, illustrate variations in policy awareness, registration status, work practices, governance support, and welfare access.

Table 2: Structured questionnaire for waste pickers (N = 200)

Construct	Sample items / questions	Response type / Likert scale	Purpose
Policy awareness	Awareness of Solid Waste Management (SWM) Rules, 2016	1 = Not aware 5 = Fully aware	Measures knowledge and understanding of municipal waste policies
Registration status	Registered with municipal/cooperative program	0 = No 1 = Yes	Assesses formal inclusion in governance and municipal programs
Occupational safety	Use of PPE, frequency of manual lifting	1 = Never 5 = Always	Evaluates adherence to occupational safety practices and risk exposure
Workload	Hours worked per day; average quantity of waste handled	Continuous / numeric	Quantifies operational intensity and physical workload
Healthcare access	Access to insurance, healthcare services	1 = No access 5 = Full access	Measures coverage under social protection schemes and occupational health support
Governance participation	Cooperative membership, participation in training programs	1 = Never 5 = Frequently	Captures engagement with institutional mechanisms and skill-building initiatives
Income	Average daily income from recycling activities	Continuous / numeric	Assesses socio-economic outcomes and financial dependency on waste work

Interview insights from municipal officers, NGOs, and waste picker representatives provide contextual interpretation. The integrated analysis highlights the level of formal inclusion in MSW systems and identifies gaps in occupational safety, institutional support, and social protection coverage (Government of Himachal Pradesh, 2025). The structured questionnaire administered to 200 waste pickers integrated both closed-ended and Likert-scale items, capturing multiple dimensions of informal waste work, including policy awareness, occupational safety, governance participation, social protection, workload, and income. Likert-scale items enabled quantitative measurement of behaviors, perceptions, and engagement levels, forming the basis for descriptive statistics, cross-tabulations, and correlation analyses in subsections 3.1.1 – 3.1.4. This instrument, designed with scientific principles, guarantees reliability, validity, and comparability across the study population, in accordance with established practices in occupational risk and informal worker assessment frameworks (Rani *et al.,* 2025; Yamane *et al.,* 2023).

Waste picker awareness, registration, and socio-demographics

Fig. 1 illustrates the patterns of waste picker awareness and registration with respect to age groups, showing variations in policy awareness and participation in municipal or cooperative registration programs. It may be noted from Fig. 1 that waste picker awareness of the SWMR, 2016 was relatively limited. Survey results indicated that 45% of respondents were aware of the rules and 35% were registered with municipal or cooperative programs. The number of registrations was notably higher for women in the 26 to 40 age bracket, reflecting increased participation in recycling efforts and local waste management systems. About 70% of respondents with secondary or higher education were aware of the SWM Rules, compared to 25% among those with no schooling. Qualitative interviews confirmed that limited outreach and complex procedures restrict inclusion (Singh *et al.,* 2023; Misra and Tewari, 2022). These results emphasize the necessity for focused policy communication and streamlined registration procedures to enhance involvement in official municipal waste management initiatives.

Occupational safety, health, and work practices

Fig. 2 illustrates occupational safety conditions and work practices among waste pickers, including PPE usage, manual lifting activities, work duration, and the average quantity of waste handled per day, daily exposure frequency and intensity, consistent with documented occupational exposure patterns in informal waste systems (Yamane *et al.,* 2023).

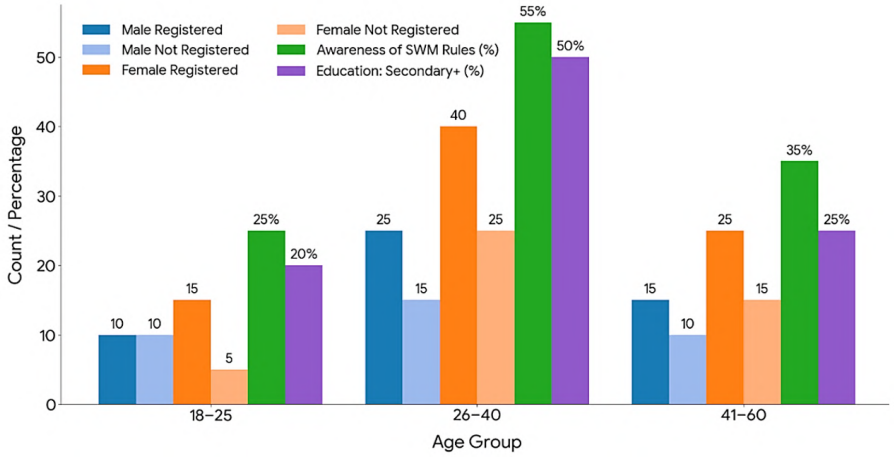

Fig. 1: Waste picker awareness and registration patterns

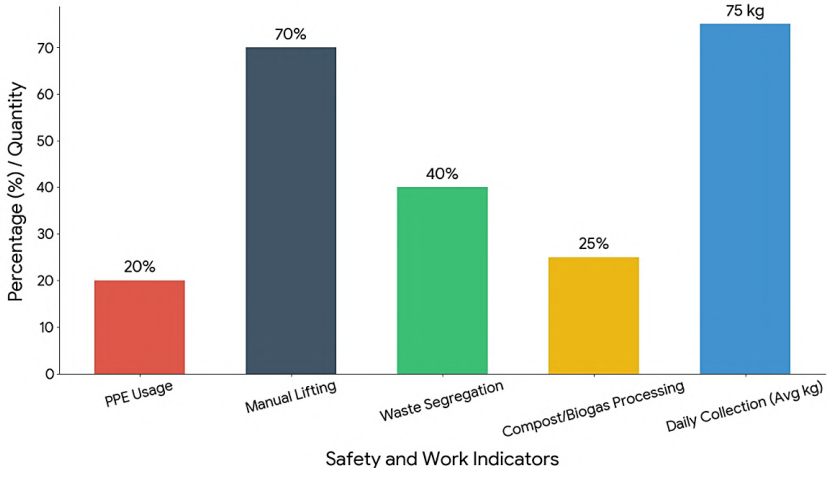

Fig. 2: Occupational safety and work practices

It is evident from Fig. 2 that waste pickers demonstrate low compliance with occupational safety practices. Only 20% consistently used PPE, while 70% engaged in manual lifting, increasing exposure to musculoskeletal strain and injury. Daily work duration ranged from 6 to 8 hours, with 60–90 kg of waste handled per worker. Interviews conducted with municipal representatives and NGOs highlighted the prevalence of sprains, cuts, and fatigue, especially among older workers, which is consistent with the occupational health hazards associated with informal urban livelihoods (Singh *et al.,* 2023). These conditions indicate that low PPE use and intensive manual work substantially increase occupational health risks among workers. These findings highlight significant occupational health risks and emphasize the need for ergonomic training, improved PPE provision, and regular health monitoring programs to enhance worker safety and working conditions in MSWM systems for informal waste workers.

Governance, institutional support, and policy implementation

Fig. 3 presents the governance and institutional metrics related to MSWM, including budget allocation, training programs conducted,

cooperative membership among waste pickers, and levels of policy enforcement. Municipal governance and institutional support for SWM showed moderate but uneven implementation. Municipal records indicated that approximately 30,000 United States dollars (USD) was allocated for SWM welfare programs, with 12 training sessions conducted across six districts during the study period. The survey results indicated that 40% of waste pickers were affiliated with cooperatives, reflecting a degree of institutional integration. Policy enforcement varied, with 20% reporting strong enforcement, 50% moderate, and 30% weak, reflecting fragmented institutional capacity (Kala and Bolia, 2024). Interviews revealed a moderate level of collaboration among multiple stakeholders in three out of five municipalities; however, there remain ongoing deficiencies in monitoring, training, and awareness (Sharma *et al.,* 2018). These findings reflect fragmented institutional capacity, limiting effective translation of cooperation and enforcement into implementation outcomes. Institutional support remains uneven, constraining MSWM implementation and formal inclusion of waste pickers. Strengthening budget allocation, training programs, and cooperative facilitation mechanisms could improve policy outcomes and enhance institutional effectiveness.

Access to healthcare and social protection

Fig. 4 illustrates the level of access to healthcare and social protection among waste pickers, highlighting differences in coverage based on age group, gender, and registration status. Access to healthcare and social protection among waste pickers in Himachal Pradesh was limited. Survey findings revealed that 30% of participants possessed healthcare or insurance coverage, whereas the majority did not have formal protection. Coverage was higher among registered workers (45%) than unregistered ones (20%), showing the role of formal inclusion (Misra and Tewari, 2022). Women reported slightly higher coverage (32%) than men (28%), linked to cooperative and NGO participation (Dutta *et al.,* 2021; Wittmer, 2021). Workers aged 26–40 years and those with 5–10 years' experience had greater access to schemes. Interviews revealed obstacles including limited awareness, complicated processes, and insufficient outreach. These results indicate that healthcare access is largely determined by institutional registration and support mechanisms rather than demographic factors alone. Integration between quantitative results and qualitative insights is strengthened through clearer transitions across subsections, explicitly linking statistical patterns with interview-based evidence to enhance interpretative continuity. Quantitative findings on awareness, safety, governance, and healthcare access are directly contextualized using stakeholder perspectives, improving coherence between datasets. This alignment guarantees a more uniform narrative progression and promotes a deeper comprehension of the institutional and operational dynamics that affect the inclusion and welfare of waste pickers.

Qualitative analysis

This section presents the qualitative analysis of semi-structured interviews conducted with municipal officers (n = 15) and NGO/cooperative representatives (n = 10) to examine governance mechanisms, policy implementation, training initiatives, occupational safety practices, and institutional integration challenges affecting waste pickers in MSWM systems. Thematic analysis was employed to examine interview transcripts, systematically coding and categorizing responses into key themes, in alignment with recognized methodologies in informal waste governance research (Singh *et al.,* 2023). Table 3 summarizes the identified themes, associated indicators, the number and proportion of respondents addressing each theme, and key insights derived from the analysis. Combining these qualitative insights with quantitative survey data offers a thorough comprehension of institutional limitations, operational difficulties,

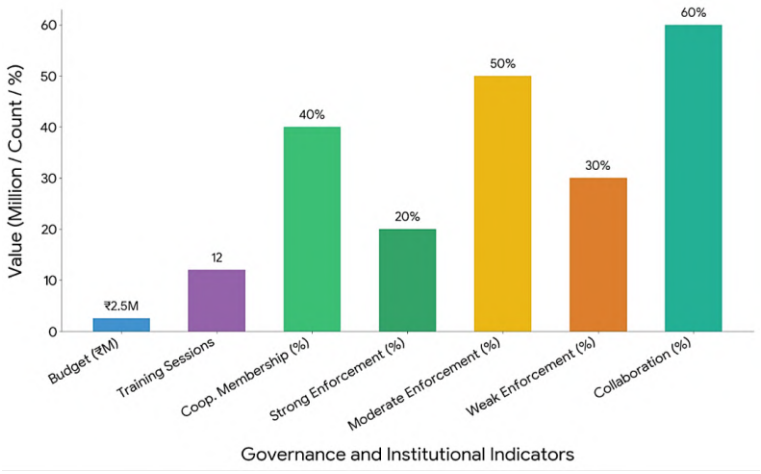

Fig. 3: Governance and institutional metrics

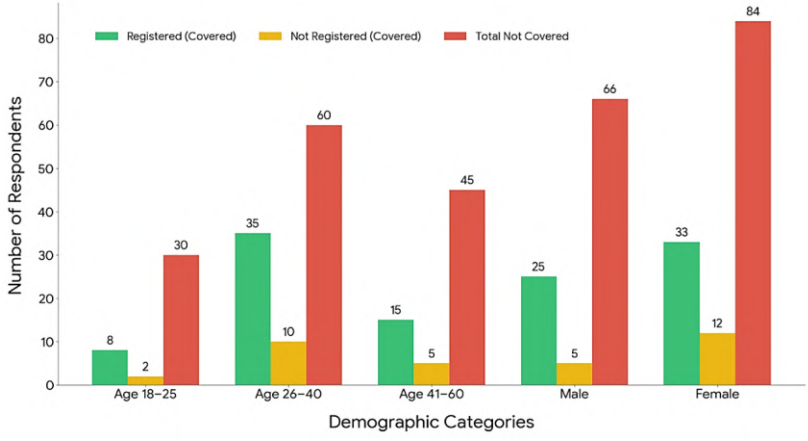

Fig. 4: Access to healthcare and social protection among waste pickers

and the efficacy of current support systems. The thematic analysis, as summarized in Table 3, highlights critical institutional, operational, and policy-level factors influencing waste picker inclusion in formal MSWM. Governance limitations, weak policy enforcement, inconsistent training, and occupational safety gaps were recurrently reported, aligning with evidence on structural vulnerabilities in informal waste systems (Rani *et al.,* 2025). These findings reveal that institutional shortcomings are interrelated and mutually exacerbate exclusion, operational inefficiencies, and occupational dangers, which hinders the formal incorporation of waste pickers. Integrating these qualitative insights with the quantitative survey findings, the study provides a robust evidence base for evaluating institutional support mechanisms, identifying operational constraints, and formulating targeted interventions to enhance formal inclusion, occupational safety, and welfare of informal waste workers.

Mixed-method interpretation

This mixed method of interpretation integrates quantitative survey data with qualitative insights from municipal officers and NGO representatives to examine policy awareness, governance mechanisms, institutional support, and occupational safety conditions of waste pickers.

Table 3: Key themes and insights from qualitative interviews

Theme	Indicators	Number of respondents (X)	Percentage of responses (Y%)	Key insight
Governance and institutional mechanisms	Budget allocation, monitoring systems	8	32%	Limited staff capacity and uneven monitoring coverage across municipalities
Policy implementation	Awareness of SWM Rules and registration procedures	7	28%	Waste pickers had limited awareness; NGOs facilitated outreach
Training and Skill development	Workshops, cooperative membership	4	16%	Skill-building programs exist but reach and coverage are limited
Occupational safety	PPE use, ergonomic practices	3	12%	PPE usage inconsistent; musculoskeletal strain and safety risks observed
Integration challenges	Inclusion in municipal programs	3	12%	Administrative barriers and lack of registration impede formal inclusion
Total	—	25	100%	—

Quantitative indicators are supported by interview-based observations to identify institutional gaps, barriers to social protection, and areas for system improvement. The collective analysis delivers an extensive comprehension of how the implementation of policies, allocation of resources, and operational strategies impact theinclusion and welfare of informal waste workers. The integration of quantitative and qualitative evidence is streamlined to improve analytical clarity and coherence. Integrated assessment of policy, institutional, and occupational indicators derived from mixed-method analysis is presented in Table 4.

Policy awareness, integration, and social protection

It may be noted from Table 4 that awareness of the SWMR, 2016 remains limited, with only 45% of waste pickers reporting knowledge of these policies. Despite 40% of respondents being enrolled in cooperatives, active participation in municipal programs is low (20%), highlighting gaps in formal integration. Healthcare access is confined to 30% those surveyed, with women being underrepresented, which underscores the importance of implementing targeted social protection measures. Qualitative insights confirm that NGOs provide partial registration support, but administrative complexities and limited outreach constrain policy implementation, consistent with evidence on gendered vulnerability and exclusion in informal waste work (Misra and Tewari, 2022). Collectively, these insights highlight the importance of raising awareness, streamlining registration processes, and reinforcing cooperative engagement as vital components for enhancing the inclusion and welfare of waste pickers, ensuring that the terminology and descriptions of indicators are aligned for consistency across different dimensions.

Governance, budget allocation, and institutional resilience

It may be noted from Table 4 that municipal budget allocation for waste management welfare programs is moderate (USD 30,000), yet only 35% of waste pickers benefit, indicating implementation gaps due to limited monitoring and enforcement. NGO training programs reach just 20% of the target population, suggesting that training coverage is inadequate to build widespread capacity. The implementation of the municipal program reveals a low inclusion rate of 15%, which reflects challenges in coordination and operational effectiveness. Collectively, these observations underscore the need to strengthen institutional coordination, expand training, and ensure effective budget utilization to enhance program reach and resilience, as also reflected in cooperative-based waste governance models (Buch *et al.,* 2021). Logical sequencing of findings is refined to improve interpretative clarity and coherence.

Table 4: Integrated assessment of policy, institutional, and occupational indicators from mixed-method analysis

Indicator	Quantitative observation	Qualitative insight	Interpretation
Policy awareness, integration, and social protection			
Awareness of SWM Rules, 2016	45% aware	Limited understanding of registration procedures among workers	Low policy awareness constrains formal participation
Participation in Municipal Programs	20% actively participate	NGOs facilitate partial registration support	Simplified and digital registration systems can improve inclusion
Access to Healthcare	30% covered	Lower representation of women in formal schemes	Gender-sensitive interventions required to improve equity
Cooperative Membership	40% enrolled	Limited reach of skill development programs	Cooperatives strengthen inclusion and access to training
Governance, budget allocation, and institutional resilience			
Municipal budget for swm welfare (USD)	30,000	Partial coverage of intended beneficiaries (35%)	Monitoring and implementation gaps limit effectiveness
NGO training programs (USD)	18,000	Limited training reach (20% of target group)	Expansion of training coverage required for capacity building
Municipal program execution USD)	12,000	Low inclusion levels (15%) reported	Coordination and institutional efficiency require strengthening
Engineering interventions, waste processing, and occupational safety			
Source segregation efficiency	40% compliance	Inconsistent segregation practices observed	Improved enforcement needed to enhance recovery efficiency
Waste processing (Compost/biogas)	25% processed	Limited adoption of decentralized technologies	Scope for scaling resource recovery interventions
PPE usage	20% usage	Low compliance observed during field assessment	PPE provision and ergonomic training required
Manual handling of waste	70% engaged in manual lifting	Reports of musculoskeletal strain and fatigue	Mechanical aids and ergonomic interventions needed to reduce risk

Engineering interventions, waste processing, and occupational safety

It may be noted from Table 4 that compliance with waste segregation at source is low (40%), and only 25% of waste is processed for compost or biogas, reflecting limited adoption of resource recovery practices. PPE usage is minimal (20%), and the majority of workers (70%) engage in manual lifting, leading to musculoskeletal strain and occupational health risks. Qualitative observations validate the inconsistent compliance with safety protocols and the limited implementation of engineering solutions, aligning with occupational hazard assessments in municipal waste workers (Thakur *et al.,* 2018). These findings highlight the need for ergonomic training, mechanical aids, and enhanced adoption of small-scale waste processing technologies to improve both efficiency and worker safety in MSWM (Prayogo *et al.,* 2022). Integration of quantitative and qualitative findings reveals systemic gaps in policy awareness, institutional support, occupational safety, and social protection for waste pickers in Himachal Pradesh. A lack of awareness regarding policies, minimal involvement in municipal initiatives, inconsistent budget allocation, and insufficient training suggest shortcomings in governance. In parallel, poor safety compliance, heavy manual handling, and limited ergonomic interventions highlight occupational and health risks, as supported by comparative studies on informal waste worker vulnerability and urban inequality (Beall, 1997). The collective findings establish a foundation for targeted interventions, which encompass simplified registration processes, the enhancement of cooperative efforts, gender-sensitive social protection measures, and ergonomic and engineering solutions designed to foster inclusion and welfare. Additionally, this framework consolidates mixed-method evidence to bolster coherence and retain analytical depth.

Comparative analysis of existing waste picker studies and novel contributions of the present study

A comparative assessment of existing waste picker studies across selected Indian cities, summarizing thematic focus, key findings, research gaps, and distinctive contributions of the present study conducted in Himachal Pradesh, is presented in Table 5. This analysis facilitates a structured recognition of the shortcomings in previous studies and delineates the role of the current research within the wider academic framework. The comparative analysis (Table 5) demonstrated that existing studies in Indian contexts predominantly examine fragmented dimensions of informal waste work. Research carried out in Mumbai and Ghaziabad highlights the health risks associated with various occupations, providing substantial evidence of morbidity and outcomes linked to exposure (Chokhandre *et al.,* 2017; Singh and Chokhandre, 2015). Studies in Chandigarh and Assam focus on socio-economic vulnerability and gender-based precarity, highlighting structural inequalities but lacking integration with municipal systems (Singh *et al.,* 2023; Misra and Tewari, 2022). Investigations in Delhi and Ahmedabad contribute insights into awareness and lived experiences; however, these remain either population-level or qualitative in orientation without linkage to operational waste management indicators (Wittmer, 2021; Bhawal Mukherji *et al.,* 2016). Studies conducted in Himachal Pradesh and Shimla yield crucial observations about the effectiveness of waste management practices and the risks associated with occupational exposure (Sharma *et al.,* 2020). Across the reviewed literature, limited empirical evidence exists connecting policy awareness, formal registration, occupational safety practices, and governance support with measurable waste management performance indicators, as also reflected in occupational risk assessments of waste workers (Kumar and Panigrahi, 2021). These external studies are largely incorporated to substantiate observed patterns rather than being critically interrogated across contextual, methodological, and evidentiary dimensions, thereby restricting deeper analytical comparison of heterogeneity in institutional settings, measurement approaches, and outcome linkages. The current study confronts these limitations by utilizing a comprehensive analytical framework that combines quantitative and qualitative evidence. Statistical results demonstrate strong associations between policy awareness and registration, and between registration and healthcare access, indicating that formal inclusion functions as a critical pathway linking policy provisions with welfare outcomes. Moderate connections with cooperative membership emphasize the importance of institutional mechanisms in bolstering inclusion and training access. Lower association of PPE usage suggests dependence on institutional provision rather than individual behavior, reinforcing the importance of governance interventions, consistent with findings on institutional determinants of waste worker safety. Furthermore, the incorporation of system-level indicators, including source segregation efficiency and waste processing rates, alongside worker-level variables, offers a comprehensive view of MSWM performance. This approach enables simultaneous evaluation of social inclusion, occupational safety, and operational efficiency, which remains absent in prior studies on informal waste governance systems (Thakur *et al.,* 2021). Overall, the analysis establishes that the novelty of the present study lies in bridging policy, occupational, institutional, and operational dimensions within a single empirical framework, thereby contributing context-specific and evidence-based insights relevant to sustainable and inclusive MSWM systems in geographically complex regions, while also supporting informed policy interventions and adaptive governance strategies for strengthening long-term waste management sustainability outcomes across diverse socio-environmental and administrative contexts.

Table 5: Comparative assessment of existing waste picker studies and novel contributions of the present study

Study location	Primary focus and key findings	Research gap	Contribution of present study	References
Mumbai	Occupational health and morbidity; high prevalence of health risks and musculoskeletal disorders	Absence of policy and governance linkage	Integrates health risks with policy awareness, registration, and institutional support	Chokhandre *et al.,* (2017) Singh and Chokhandre, (2015)
Chandigarh	Socio-economic vulnerability; income instability and social exclusion	Limited governance and system-level analysis	Links vulnerability with institutional participation and waste management outcomes	Singh *et al.,* (2023)
Assam	Gender and migration; gender-based precarity and exclusion	Lack of policy and operational integration	Combines gender analysis with policy awareness and healthcare access	Misra and Tewari, (2022)
Ghaziabad	Occupational and environmental health; high exposure to respiratory and physical risks	Limited institutional and policy perspective	Connects occupational risks with PPE usage and governance mechanisms	Rani *et al.,* (2025)
Delhi	Public participation in waste management; variation in awareness and participation	Excludes informal waste picker role	Integrates worker-level awareness with policy and system performance	Bhawal Mukherji *et al.,* (2016)
Ahmedabad	Well-being and lived experience; gendered work conditions influence well-being	Predominantly qualitative; lacks quantitative linkage	Combines qualitative insights with measurable indicators such as PPE use and registration	Wittmer, (2021)
Shimla	Waste management and worker health; health risks and municipal challenges	Limited institutional integration analysis	Expands to governance, policy awareness, and cooperative systems	Sharma and Acharya, (2019)
Himachal Pradesh	Waste systems and occupational exposure; moderate processing efficiency and exposure risks	Lack of micro-level worker and policy interaction data	Integrates system-level and worker-level indicators within a unified framework	CPCB, (2021) Thakur *et al.,* (2018)
Bhubaneswar	Occupational health among general workers; risks linked to health outcomes	Not specific to waste pickers or MSWM systems	Applies occupational analysis within informal waste picker and MSWM context	Kumar and Panigrahi, (2021)

Statistical analysis

Statistical analysis, including correlation, multiple regression, and ANOVA, provides insights into relationships among factors influencing waste picker welfare, such as policy awareness, registration status, cooperative participation, PPE usage, and healthcare access. These findings enhance previous descriptive and mixed-method results by providing a precise understanding of interactions between socio-economic, occupational, and institutional variables shaping welfare outcomes.

Correlation analysis - key institutional and occupational variables

Table 6 shows strongest correlations between policy awareness and registration (r = 0.62), and between registration and healthcare access (r = 0.58), indicating closer alignment of institutional variables than behavioural factors. Cooperative membership demonstrates a moderate correlation with registration (r = 0.54) and healthcare access (r = 0.46). In contrast, PPE usage is weakly associated, suggesting limited impact without institutional support. External evidence similarly reports significant associations between informal work exposure and health outcomes (odds ratio (OR) > 2; level of significance (p) < 0.05), including respiratory and musculoskeletal morbidity. (Chokhandre *et al.,* 2017; Rani *et al.,* 2025), with landfill exposure further confirming elevated risk (adjusted odds ratio (AOR) = 1.733; p = 0.041) (Uhunamure *et al.,* 2021). Furthermore, the observed correlations imply a structured hierarchy where institutional factors play a more crucial role in explaining healthcare access than individual factors such as PPE usage. This suggests that institutional embedding is the dominant underlying determinant of welfare outcomes.

Table 6: Correlation matrix of policy awareness, registration, cooperative membership, PPE usage, and healthcare access among waste pickers (N = 225)

Variables	Policy awareness	Registration status	Cooperative membership	PPE usage	Healthcare access
Policy awareness	1.00	0.62	0.48	0.35	0.41
Registration status	0.62	1.00	0.54	0.32	0.58
Cooperative membership	0.48	0.54	1.00	0.29	0.46
PPE usage	0.35	0.32	0.29	1.00	0.38
Healthcare access	0.41	0.58	0.46	0.38	1.00

Regression analysis - predictors of healthcare access

From Table 7, it could be noted that registration status is the strongest predictor (standardized regression coefficient (β) = 0.41, $p < 0.001$), followed by policy awareness (β = 0.28) and cooperative membership (β = 0.25). PPE usage contributes positively but less strongly (β = 0.14). This is consistent with elevated risks of morbidity and musculoskeletal disorders in waste pickers, identified through logistic regression and propensity score matching (PSM) (Chokhandre *et al.,* 2017; Singh and Chokhandre, 2015). Formal inclusion and occupational factors significantly predict health outcomes (Rani *et al.,* 2025; Uhunamure *et al.,* 2021). The model explains 46% of variance ($R^2 = 0.46$), with diagnostics indicating no serious multicollinearity (VIF range = 1.32–2.18; tolerance = 0.46–0.76) and acceptable residual distribution (Durbin–Watson = 1.89; Kolmogorov–Smirnov p = 0.112), supporting model stability and specification validity. The results demonstrate notable correlations among institutional, occupational, and welfare variables; however, due to the cross-sectional nature of the study, these associations ought to be understood as correlational instead of causal, representing structural connections without any temporal implications.

ANOVA - Differences in healthcare access by registration status

It could be noted from Table 8 that healthcare access differs significantly across registration categories, with registered pickers reporting approximately 45% access versus 20% for unregistered workers. Rani *et al.* (2025) similarly discovered that formalized groups exhibit improved health outcomes ($p < 0.05$), thereby reinforcing the notion that registration serves as a crucial structural determinant of welfare.

ANOVA - differences in PPE usage by work experience

It could be observed from Table 9 that PPE usage varies significantly by experience, with workers having 5–10 years of experience showing slightly higher adoption. Singh and Chokhandre (2015) reported a higher prevalence of musculoskeletal disorders (MSDs) among less experienced pickers, while Rani *et al.* (2025) noted variations in occupational risk based on worker characteristics, supporting the present study's observation. From Tables 6 to 9, it may be inferred that the survey of 225 waste pickers, complemented by qualitative interviews, highlights the determinants of formal inclusion, occupational safety, and welfare access. 45% of pickers were aware of the SWMR, 2016, and 35% were registered, with women and educated workers participating slightly more. Only 20% used PPE consistently, while 70% handled 60–90 kg of waste daily. Occupational exposures show significant associations with health morbidities and formal inclusion (Chokhandre *et al.,* 2017). Higher prevalence of musculoskeletal disorders among waste pickers has also been reported in prior studies (Singh and Chokhandre, 2015). Formal inclusion and occupational conditions have a substantial impact on health outcomes (Rani *et al.,* 2025). Strong relationships between exposure levels and health risks have also been observed in related research (Uhunamure *et al.,* 2021).

Table 7: Multiple regression analysis of institutional and occupational determinants of healthcare access (N = 225)

Independent variable	β	Standard error (SE)	T-static	p-value	VIF
Policy Awareness	0.28	0.07	4.02	0.001	1.74
Registration Status	0.41	0.08	5.12	0.000	2.18
Cooperative Membership	0.25	0.06	3.64	0.002	1.62
PPE Usage	0.14	0.05	2.31	0.021	1.32
Constant	0.12	0.04	2.05	0.043	—

Model Summary: multiple correlation coefficient (R) = 0.68; coefficient of determination (R^2) = 0.46; Adjusted R^2 = 0.44

Table 8: One-way ANOVA of healthcare access across registration categories (registered, cooperative, unregistered; N = 225)

Source of variation	Sum of squares	df	Mean square	F-static	p-value
Between Groups	18.42	2	9.21	7.84	0.001
Within Groups	261.35	222	1.18	—	—
Total	279.77	224	—	—	—

Table 9: One-way ANOVA of PPE usage across experience groups (0–5, 5–10, 10–15, >15 years; N = 225)

Source of variation	Sum of squares	df	Mean square	F-static	p-value
Between groups	12.75	3	4.25	4.62	0.004
Within groups	203.64	221	0.92	—	—
Total	216.39	224	—	—	—

In-depth statistical analyses reveal robust correlations between policy awareness and registration (r = 0.62), as well as between registration and access to healthcare (r = 0.58). Regression identifies registration, awareness, and cooperative membership as predictors of healthcare access (R^2 = 0.46), while ANOVA shows significant differences in healthcare access and PPE use by registration and experience. These results indicate that formal inclusion and institutional support are crucial factors influencing welfare, health protection, and integration of waste pickers into MSWM systems. Essentially, these results indicate that enhancements in welfare are contingent upon the fortification of institutional registration systems, which serve as the main gateway for accessing services. This should be complemented by organized cooperative frameworks and focused administrative support that translate policy awareness into quantifiable service utilization, rather than relying solely on the assumption of behavioral change**.** These statistical relationships show that policy awareness alone is insufficient without formal registration and institutional linkage under SWMR, 2016. Strong correlations between awareness, registration, and healthcare access indicate that formal inclusion is the key pathway translating policy into benefits. Cooperative membership moderately improves access to welfare and training, while PPE usage reflects dependence on institutional support rather than individual behavior (Bhawal Mukherji *et al.,* 2016). ANOVA confirms that registered workers have better healthcare access and safety outcomes (Sharma and Acharya, 2019). Overall, inadequacies in registration, enforcement, and institutional capacity restrict the successful execution of policies and the provision of welfare within MSWM systems.

Policy gap analysis under SWMR, 2016

Findings indicate divergence between provisions of the SWMR, 2016 and ground-level implementation in municipal systems of Himachal Pradesh. The Rules emphasize inclusion of informal waste workers, source segregation, occupational safety, and institutional responsibility; however, empirical evidence reveals partial compliance across these dimensions. Table 10 illustrates a systematic comparison of policy deficiencies, the evidence that supports them, and contributions of the study.

Table 10: Policy gaps, empirical evidence, and study contributions

Policy gap	Evidence from study	Study contribution	References
Limited policy awareness and outreach	45% awareness; qualitative evidence shows weak outreach and complex procedures	Identifies awareness gaps and need for targeted communication and simplified registration	Singh and Chokhandre, (2015)
Low registration in formal systems	35% registered under municipal / cooperative programs	Examines barriers limiting formal inclusion and highlights administrative constraints	Kala and Bolia, (2024)
Weak occupational safety implementation	20% PPE usage; 70% manual handling with 60–90 kg loads	Links occupational risks with policy gaps; supports ergonomic training and PPE provision	Thakur *et al.,* (2018)
Uneven institutional support	USD 30,000 budget; 40% cooperative membership; 20% training coverage	Evaluates governance support and identifies limited reach of training and cooperative mechanisms	Buch *et al.,* (2021)
Variability in policy enforcement and monitoring	20% strong, 50% moderate, 30% weak enforcement; monitoring gaps reported	Highlights institutional capacity and coordination limitations	Sharma and Acharya, (2019)
Low segregation and processing efficiency	40% source segregation; 25% composting/biogas processing	Connects engineering performance with policy implementation gaps	CPCB (2021)
Limited healthcare and social protection	30% coverage; higher among registered workers	Demonstrates link between formal inclusion and welfare access	Misra and Tewari, (2022)
Gender and inclusion disparities	Variation in participation and access; qualitative barriers identified	Highlights need for inclusive and gender-sensitive policy design	Rani *et al.,* (2025)

The analysis in Table 10 indicated that policy intent under the SWMR, 2016 does not fully translate into practice due to limitations in awareness, institutional capacity, and enforcement mechanisms, consistent with weak outreach and procedural complexity in informal waste systems (Singh and Chokhandre, 2015). Low awareness (45%) and limited registration (35%) reduce participation in municipal and cooperative systems, restricting access to welfare schemes and formal inclusion, as reflected in administrative barriers to integration (Kala and Bolia, 2024). The complexity of administrative processes further hinders inclusion, especially for workers who have less education. Occupational safety provisions remain weakly implemented, with low PPE usage (20%) and high dependence on manual handling (70%), leading to significant health risks, consistent with documented occupational exposure patterns (Thakur *et al.,* 2018). Institutional support exists through budget allocation and training programs; however, coverage remains limited and uneven across districts, with only 20% training reach, reflecting constrained cooperative and governance mechanisms (Buch *et al.,* 2021). Variability in enforcement and monitoring capacity further reduces effectiveness of policy implementation (Sharma and Acharya, 2019). Waste management performance remains partial, with low source segregation (40%) and limited processing (25%), indicating weak operational efficiency (CPCB, 2021). The level of healthcare and social protection coverage is notably low at 30%, but it is higher for registered workers, underscoring the significance of formal inclusion. The findings show that awareness, registration, institutional support, and occupational safety are strongly interconnected. Limited awareness reduces registration, weak coordination affects training and monitoring, and poor safety practices increase occupational risks. Gender disparities additionally affect access and participation, thereby reinforcing gaps in inclusion within informal waste systems (Rani *et al.,* 2025). The study integrates these dimensions to highlight the need for improved communication, simplified registration, stronger governance, and enhanced occupational safety mechanisms for sustainable informal waste sector integration.

Policy implications

Statistical evidence derived from correlation, regression, and ANOVA analyses indicates that policy awareness, registration status, cooperative participation, and occupational safety practices significantly influence welfare access and integration outcomes. These results establish a foundation for focused, evidence-based policy measures aimed at enhancing the effectiveness of implementation.

Policy awareness and registration

Strong correlation exists between policy awareness and registration ($r = 0.62$) and between registration and healthcare access ($r = 0.58$), indicating a structured association between informational exposure and institutional uptake. Strengthening decentralized awareness mechanisms and simplifying registration procedures is essential. Coordination between municipal bodies and NGOs can improve outreach (Singh and Chokhandre, 2015; Kala and Bolia, 2024). These patterns indicate that enhanced awareness could promote entry into formal systems via administrative pathways.

Institutional strengthening

Regression results identify registration ($\beta = 0.41$, $p < 0.001$) and cooperative membership ($\beta = 0.25$, $p = 0.002$) as significant predictors, with moderate model explanatory power ($R^2 = 0.46$). Correlations further indicate associations between cooperative membership and registration ($r = 0.54$) and healthcare access ($r = 0.46$). Enhancing the integration of registration systems with welfare eligibility mechanisms, in conjunction with collaborative expansion, could lead to increased institutional efficiency (Buch *et al.,* 2021; Sharma and Acharya, 2019). These results indicate the centrality of institutional embeddedness in shaping access pathways.

Occupational safety

PPE usage shows weaker association with healthcare access ($r = 0.38$) and lower predictive strength ($\beta = 0.14$, $p = 0.021$). ANOVA indicates significant variation across experience groups ($F = 4.62$, $p = 0.004$), suggesting heterogeneity in safety practices. Institutional provision of PPE and mechanized handling systems is consequently more pertinent than individual compliance mechanisms (Thakur *et al.,* 2018). This reflects structurally conditioned occupational safety outcomes.

Healthcare and social protection

Registration is significantly associated with healthcare access ($\beta = 0.41$; $F = 7.84$, $p = 0.001$), supported by correlations with cooperatives ($r = 0.46$) and awareness ($r = 0.41$). Regression and ANOVA results indicate that formal inclusion is linked with improved healthcare access. Broadening social protection to include unregistered workers and tackling gender inequalities through focused and inclusive enrollment strategies are essential policy objectives aimed at minimizing exclusion and improving equitable welfare access (Wittmer, 2021). These findings indicate that formal system integration is closely associated with improved welfare access.

Waste management performance

Moderate levels of segregation and processing indicate partial achievement of resource recovery objectives. Reinforcing the enforcement of source segregation, alongside the encouragement of decentralized composting and biogas systems, has the potential to enhance the efficiency of waste processing. Associating worker inclusion with performance-driven waste recovery metrics could improve both operational efficiency and social integration in MSWM systems (CPCB, 2021; Pedroso *et al.,* 2024). These associations suggest

that inclusion-oriented governance may support operational efficiency gains.

Hypotheses analysis

Hypotheses integrated results for the four hypotheses using quantitative survey data, qualitative interviews, and mixed-method interpretation. The combined analysis links measurable indicators, stakeholder perspectives, and institutional context to evaluate socio-economic conditions, governance mechanisms, occupational safety, and social protection among waste pickers.

H1: *Policy awareness and registration*

Quantitative data showed that 45% of waste pickers were aware of the SWM Rules, 2016, while 35% were registered under municipal or cooperative programs, with awareness rising to 70% among respondents with secondary or higher education. Through qualitative interviews, it was found that a significant number of waste pickers did not possess knowledge regarding registration procedures. NGOs were instrumental in aiding enrolment, which emphasizes the barriers created by administrative complexity and the lack of local advocacy. Mixed-method interpretation indicates that policy awareness is a key determinant of formal participation, as workers with higher understanding of municipal rules were more likely to be registered, thereby supporting H1, suggesting that targeted communication and simplified registration processes could enhance inclusion (Singh and Chokhandre, 2015).

H2: *Gender differences in access to healthcare and social protection*

Survey results indicated that only 30% of waste pickers had access to healthcare or insurance schemes, with women slightly higher at 32% and men at 28%. PPE usage was low overall, at 20%, and female workers reported marginally lower access to protective equipment in some locations. Qualitative interviews suggested that women were often inadequately represented in municipal welfare schemes because of informal employment, challenges with documentation, and the restricted outreach of social protection services. Mixed-method analysis shows that institutional constraints and informal employment structures restrict equitable access, partially supporting H2, emphasizing the need for gender-sensitive policy interventions and improved enrolment procedures (Misra and Tewari, 2022).

H3: *Governance support and waste processing efficiency*

Quantitative observations indicated that 40% of municipal waste was segregated at source and 25% processed for compost or biogas, while 40% of waste pickers were members of cooperatives and 12 training sessions were conducted across six districts. Qualitative findings highlighted that training programs were inconsistently implemented, and monitoring capacity was constrained by limited staff and resources. The interpretation of mixed methods indicates that training programs, collaborative involvement, and governance assistance improve the efficiency of waste segregation and processing. However, the limited scope and inconsistent application only partially validate H3, highlighting the necessity for broader training, enhanced monitoring, and reinforced institutional support (Buch *et al.,* 2021).

H4: *Occupational health risks and ergonomic practices*

Quantitative survey results showed that 70% of waste pickers engaged in manual lifting, handling 60–90 kg of waste per day for 6–8 h, with only 20% consistently using PPE. Qualitative interviews and field observations reported frequent musculoskeletal strain, sprains, cuts, and fatigue due to repetitive manual handling and inadequate protective equipment. Mixed-method interpretation confirms that poor ergonomic

practices and low PPE usage substantially increase occupational health risks, thereby supporting H4, highlighting the necessity of ergonomic training, improved PPE provision, and regular health monitoring programs to enhance worker safety. The integrated examination of all four hypotheses underscores that policy awareness, governance backing, and institutional frameworks play a crucial role in determining the formal inclusion, occupational safety, and social protection of waste pickers. H1 demonstrated that higher awareness of the SWM Rules, 2016 promotes registration, indicating that targeted outreach and simplified registration processes are essential (Kala and Bolia, 2024). H2 uncovered gender-based inequalities in access to healthcare and social protection, indicating the necessity for gender-sensitive program development and fair welfare enrolment (Misra and Tewari, 2022). H3 showed that governance support and training programs partially improve waste segregation and organic waste processing, emphasizing the importance of scaling cooperative engagement and enhancing monitoring systems. Finally, H4 confirmed that poor ergonomic practices and low PPE usage exacerbate occupational health risks, underscoring the necessity of ergonomic interventions, PPE provision, and regular health monitoring (Thakur *et al.,* 2018). Collectively, these findings present a robust evidence foundation for municipal authorities, NGOs, and cooperatives to execute integrated strategies aimed at enhancing formal inclusion, operational efficiency, occupational safety, and socio-economic welfare of informal waste workers, while also tackling both institutional and gender-specific constraints. Additionally, the findings support the development of inclusive policy frameworks that strengthen long-term sustainability and resilience within urban MSWM systems through participatory stakeholder engagement approaches.

Novelty of the study

This study advances research on informal waste pickers through an integrated framework examining policy awareness under SWMR, 2016, occupational safety, institutional support, and waste processing efficiency. Prior studies in India conducted in India focuses on specific factors including occupational health, socio-economic vulnerability, and gender disparities, but they show a limited connection to governance and operational outcomes. The study integrates quantitative indicators including source segregation efficiency, PPE usage, training coverage, registration status, and municipal budget distribution alongside qualitative perspectives from municipal officials and NGOs. The mixed-method approach evaluates interactions between worker-level conditions and institutional mechanisms. Integration of engineering, social, policy, and governance aspects offers a comprehensive understanding of inclusion and system performance. Evidence from a geographically complex Himalayan region highlights relationships among policy implementation, institutional capacity, and occupational practices influencing formal integration and welfare outcomes in MSWM systems.

Limitations of the study

The study is limited by its sample size of 200 waste pickers, which may not fully represent the diversity of informal waste workers across Himachal Pradesh. Data collection was partially dependent on self-reported survey responses, which introduced the potential for reporting bias. Furthermore, the restricted access to longitudinal municipal data on waste processing performance and worker health outcomes limited the capacity to perform more in-depth statistical analyses and assess long-term effects of institutional interventions.

Recommendations

To improve formal inclusion and occupational welfare of waste pickers, the study recommends expanding policy awareness campaigns and registration programs. Municipal authorities should increase funding for PPE distribution and targeted occupational safety training. Enhancing cooperative frameworks can bolster institutional backing and worker representation, whereas better monitoring and evaluation systems can guarantee accountability in waste management initiatives. Community-level initiatives such as decentralized composting and localized waste segregation can further enhance efficiency and sustainability.

Future scope of the study

Future research should focus on longitudinal assessment of occupational health outcomes among waste pickers to understand long-term risks. Advanced statistical modelling and geospatial analysis can be applied to optimize waste management efficiency. The influence of digital registration systems and improved cooperative frameworks on worker inclusion must be analyzed. Additionally, engineering interventions including mechanized waste handling and decentralized waste-to-energy systems could be explored to reduce occupational hazards and promote sustainable municipal waste management practices.

CONCLUSON

The study highlights the vital contribution of informal waste pickers to MSWM in Himachal Pradesh, India, while identifying persistent gaps in policy implementation, institutional support, occupational safety, and social protection, consistent with the stated background and objectives. Informal waste pickers are crucial to recycling, resource recovery, and economical waste management; nevertheless, their exclusion from formal systems hampers both operational efficiency and welfare results. In line with the study objectives, the analysis examines socio-economic conditions, occupational health risks, institutional support mechanisms, and policy awareness, and evaluates how these factors interact to influence formal integration. Employing a mixed-methods strategy, primary data collected from 200 waste pickers, along with field observations and interviews with municipal officials and NGOs, establishes a thorough evidence base. Survey results indicate that 45% of respondents were aware of the Solid Waste Management Rules, 2016, while only 35% were formally registered under municipal or cooperative programs. This gap reflects limited translation of policy awareness into institutional participation, primarily due to administrative complexity, inadequate outreach, and procedural barriers identified through qualitative insights. The state of occupational safety remains unsatisfactory. Merely 20% of the workforce regularly utilized personal protective gear, while 70% were involved in manual lifting, highlighting persistent physical strain and considerable risk of occupational hazards. Institutional support was moderate but uneven. Governance indicators show a municipal allocation of USD 30,000, and 40% cooperative membership, yet limited coverage, weak monitoring systems, and inconsistent implementation reduce overall effectiveness. Healthcare and social protection access continues to be constrained, with only 30% of waste pickers participating in any program, which signifies a lack of proper integration into welfare systems. Waste management performance reflects partial achievement of policy objectives, with 40% source segregation efficiency and 25% processing, suggesting underutilization of resource recovery potential. Statistical analysis reinforces these findings by demonstrating that registration status significantly influences healthcare access, while policy awareness and cooperative participation contribute to formal

inclusion. These relationships imply that simply being aware of policies is inadequate without institutional ties, and that registration plays a vital role in bridging policy provisions with welfare outcomes. Rather than reiterating empirical results, the study synthesizes these findings to demonstrate that effective integration of informal waste pickers depends on the convergence of policy awareness, simplified institutional access, and occupational safeguards, highlighting registration as the central mechanism linking governance structures with welfare and environmental outcomes. The study provides a theoretical advancement by broadening the scope of MSWM governance literature. It integrates informal labor, institutional inclusion, and vulnerability as interconnected factors that influence formalization. This study further enriches existing literature by empirically demonstrating a multi-level interaction between policy awareness, institutional registration, and cooperative participation, which act as joint determinants of formal inclusion in informal waste management systems**.** Methodologically, it strengthens evidence generation by applying a mixed methods design that triangulates survey, field observation, and stakeholder interviews, thereby enhancing the robustness and depth of informal sector analysis. However, the claim of a "comprehensive evidence base" should be interpreted with caution, as reliance on a single-state sample, limited sample size, and potential reporting and selection biases constrain generalizability; the mixed-methods design improves depth, but the evidence remains context-specific rather than fully comprehensive. The study offers a theoretical contribution by establishing a relationship between informal labor, institutional inclusion, and vulnerability within MSWM governance. It also adopts a mixed-methods approach that that integrates surveys, observations, and interviews, thus enhancing the analysis by incorporating policy institutional, and welfare aspects into a cohesive framework. The study underscores the need for strengthened institutional frameworks, enhanced policy communication, and improved occupational safety measures to support informal waste pickers. Furthermore, these guidelines continue to be somewhat vague and would benefit from an emphasis on prioritization and feasibility considerations, particularly in making a clear distinction between immediate low-cost actions (including the supply of PPE and simplified registration processes) and medium- to long-term structural reforms (such as the integration of institutions and the broadening of social protection coverage), enhance practical implementation. Expanding training programs, simplifying registration procedures, strengthening monitoring systems, and increasing access to social protection are essential for effective integration into formal MSWM systems. The findings provide evidence-based policy insights for improving both environmental performance and worker well-being, while future research may examine long-term impacts of formal inclusion and technological interventions to reduce manual handling.

AUTHOR CONTRIBUTIONS

K. Nithiananthan conceptualized the study, designed the methodology, conducted data collection and analysis, and prepared the original manuscript draft. Manvendra Singh contributed to data interpretation, statistical analysis, and critical revision of the manuscript. J. Nouri provided expert guidance on environmental and public health aspects, contributed to the study design, and reviewed and edited the manuscript. All authors read and approved the final version of the 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, were observed by the authors.

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ABBREVIATIONS

%	Percent
°E	Degree east (Longitude)
°N	Degree north (Latitude)
Adjusted R^2	Adjusted coefficient of determination
ANOVA	Analysis of Variance
AOR	Adjusted odds ratio
CI	Confidence interval
CPCB	Central Pollution Control Board
df	Degrees of freedom
e	Margin of error
F	F-statistic (ANOVA test value)
h	Hour
H1–H4	Hypotheses 1 to 4
kg	Kilogram
m	Meter
MoEFCC	Ministry of Environment, Forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MSDs	Musculoskeletal disorders
MSWM	Municipal solid waste management
N	Total sample size
n	Sub-sample size
NGO	Non-governmental organization
OR	Odds ratio
p	Probability value (level of significance)
PPE	Personal protective equipment
PSM	Propensity score matching
r	Correlation coefficient

R	Multiple correlation coefficient
R²	Coefficient of determination
SBM-U	Swachh Bharat Mission–Urban
SE	Standard error
SSPS	Statistical package for the social sciences
SWM	Solid waste management
SWMR	Solid waste management rules
T	T-statistic (regression test value)
T	Tonnes
USD	United States dollars
VIF	Variance inflation factors
β	Standardized regression coefficient

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ORIGINAL RESEARCH PAPER

Government power to promote substantive biodiversity disclosure and compliance with environmental requirements

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ABSTRACT

BACKGROUND AND OBJECTIVES: Biodiversity disclosure is an important component of sustainability reporting, especially in environmentally sensitive industries where corporate activities affect ecosystems, species, and natural habitats. The prevalence of fragmented and symbolic disclosure practices in developing countries may be attributed to the uneven application of institutional pressures and regulatory oversight. The present research examines the influence of government power on biodiversity disclosure, specifically assessing whether regulatory frameworks can drive corporate shifts from symbolic gestures to substantive, compliance-based transparency.

METHODS: By leveraging panel data from 1,225 firm-year observations within Indonesia's environmentally sensitive sectors, this study applies instrumental variable two-stage least squares estimation to account for endogeneity risks associated with omitted variables and reverse causation. Government power is proxied by the Program for Pollution Control, Evaluation, and Rating, a public environmental compliance rating program that combines monitoring, public evaluation, enforcement signals, and reputational incentives. Biodiversity disclosure is measured using a weighted index covering 20 ecological disclosure items, while an unweighted binary score ranging from 0 to 20 is used as an alternative dependent variable for robustness testing.

FINDINGS: The results show that government power has a positive and statistically significant relationship with biodiversity disclosure. The main instrumental variable model produces a coefficient of 0.141, whereas the ordinary least squares cluster models produce smaller coefficients ranging from 0.074 to 0.086. Results remain consistent when utilizing an alternative dependent variable specification, which generates a positive coefficient of 0.139, significant at the conventional levels. These findings indicate that the relationship remains consistent after addressing endogeneity, including year and industry fixed effects, adding firm-level controls, and applying an alternative disclosure measurement.

CONCLUSION: The findings highlight the role of regulatory monitoring, public evaluation, and reputational mechanisms in promoting biodiversity disclosure. It is imperative to note, however, that increased disclosure should not be misconstrued as a definitive indicator of improved ecological outcomes. Disclosure mechanisms need to be integrated with science-based environmental metrics, independent verification, and site-level monitoring to strengthen the link between corporate transparency and biodiversity accountability.

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INTRODUCTION

Despite growing attention to biodiversity loss, corporate biodiversity reporting remains fragmented, inconsistent, and often disconnected from measurable ecological outcomes, creating a need for stronger transparency and accountability mechanisms (Trapero *et al*., 2023). Biodiversity disclosure has therefore become an important dimension of sustainability reporting, particularly in environmentally sensitive industries where corporate activities affect ecosystems, species, and natural habitats (Adler *et al*., 2017; Atkins and Maroun, 2020; Maroun *et al*., 2018; Samkin *et al*., 2014). A key challenge is distinguishing symbolic disclosure, which consists of general, rhetorical, and non-verifiable environmental statements, from substantive disclosure, which provides site-specific, measurable, and outcome-oriented information on biodiversity impacts, mitigation, restoration, monitoring, and management actions (Boiral, 2014; Maroun *et al*., 2018; Atkins and Maroun, 2020). This distinction is critical, as expanded disclosure may enhance corporate transparency without fundamentally demonstrating compliance with environmental mandates or facilitating improved biodiversity outcomes (Mair *et al*., 2024). Biodiversity reporting frameworks also remain difficult to standardize, measure, and connect to organizational accountability (Jones and Solomon, 2013; Gaia and Jones, 2019). Environmentally sensitive industries provide an appropriate setting for examining biodiversity disclosure because sectors such as mining, forestry, and agribusiness affect ecosystems through land-use change, habitat conversion, resource extraction, pollution, waste, and climate-related risks (Gardner *et al*., 2013; Orazalin *et al*., 2024). Reporting standards for these industries mandate the provision of site-specific and impact-driven information, moving beyond the use of broad, generalized narratives (Roberts *et al*., 2021; Sun and Lange, 2022). The significance of this matter is amplified in megabiodiversity countries like Indonesia, where the coexistence of ecological abundance and intense industrial activity creates complex environmental challenges. Corporate-induced ecological damage in such contexts may have irreversible consequences for species, habitats, and ecosystem services (Bebbington *et al*., 2024; Bland *et al*., 2019; Mair *et al*., 2024). However, evidence from Indonesia and comparable developing contexts shows that biodiversity-related disclosures often remain limited in quality, standardization, and measurability, weakening their role in ecological accountability (Khan, 2014; Pujiningsih and Utami, 2024; Syarifuddin and Damayanti, 2019; Zhao and Li, 2022). In developing institutional contexts, uneven enforcement capacity, regulatory consistency, and public monitoring may allow firms to rely on symbolic rather than verifiable biodiversity information. Government involvement is thus essential, functioning as both a formal regulatory instrument and a form of coercive pressure that significantly influences corporate biodiversity disclosure and adherence to environmental standards (Mair *et al*., 2024; Zhao and Li, 2022; Nouri, 2005). The limitations of conventional environmental, social, and governance (ESG) metrics further reinforce the need for more reliable biodiversity reporting. ESG metrics often suffer from inconsistency, data opacity, and greenwashing risks, weakening the connection between reported information and actual environmental outcomes (Mamytova *et al*., 2026). Scholars have therefore called for biodiversity disclosure approaches that incorporate science-based standards, site-level traceability, and ecological accounting systems, such as the red list of ecosystems (RLE) and the system of environmental-economic accounting (SEEA) (Armsworth *et al*., 2006; Bland *et al*., 2019; Blanco-Zaitegi *et al*., 2022). Within environmentally sensitive sectors, these strategies are especially pertinent, as the breadth of direct and indirect ecological footprints necessitate the provision of verifiable biodiversity information

(Bebbington *et al*., 2024; Gardner *et al*., 2013). Prior research has identified several determinants of biodiversity and environmental disclosure, including corporate governance structures, sustainability committees, board independence, gender diversity, non-governmental organization (NGO)-affiliated directors, ownership structure, firm characteristics, and broader stakeholder and institutional pressures (Acar *et al*., 2021; Carvajal *et al*., 2021; Hambali and Adhariani, 2024; Toukabri and Alwadai, 2024; Velte, 2022; Solimene *et al*., 2024; Maroun and Ecim, 2024; Velte, 2023). However, while these studies highlight internal governance and stakeholder influences, the role of external institutional factors, particularly government intervention through program-based monitoring and public evaluation, remains relatively underexplored in developing-country biodiversity disclosure settings. This study is anchored in stakeholder salience and institutional theories. Stakeholder salience theory maintains that corporate prioritization is determined by stakeholder power, legitimacy, and urgency, whereas institutional theory highlights the role of coercive state pressure in shaping organizational behavior (DiMaggio and Powell, 1983). In biodiversity disclosure, government actors are powerful stakeholders because they can monitor firms, impose sanctions, and create disclosure incentives through public evaluation, reputational exposure, and risk-related pressures (Treepongkaruna, 2024). Accordingly, government power is conceptualized as the coercive, evaluative, and reputational capacity of the state to influence corporate environmental behavior beyond the existence of formal regulation. This perspective explains why government power may encourage firms to move from symbolic reporting toward more substantive and compliance-oriented biodiversity disclosure. While government intervention is acknowledged as a primary catalyst for corporate environmental accountability, its efficacy is fundamentally contingent upon enforcement quality, monitoring capacity, institutional credibility, and the transparency of regulatory consequences (Mann *et al*., 2023; Saeed *et al*., 2025; Hambali and Adhariani, 2024). Several gaps remain in biodiversity disclosure research. First, limited causal evidence explains how specific government instruments influence biodiversity disclosure, particularly in developing countries where institutional conditions differ from developed-market settings (Mair *et al*., 2024; Virah-Sawmy *et al*., 2014). Second, prior studies often rely on broad or aggregate disclosure measures, with limited attention to site-level, ecosystem-specific, and outcome-oriented biodiversity information (Khan, 2014; Pujiningsih and Utami, 2024). Third, biodiversity measurement remains inconsistent because different indices, tools, and ESG reporting frameworks reduce comparability across firms and studies (Sutikno *et al*., 2023; Roeder and Utz, 2025; Sobkowiak, 2023). Despite comprehensive research into governance structures and environmental regulation, government power—conceptualized as a distinct program-based institutional force—has received limited academic attention in the context of environmentally sensitive sectors (Ali *et al*., 2023; Velte, 2023). Based on these gaps, this study hypothesizes that government power has a positive effect on biodiversity disclosure. This hypothesis is based on the expectation that stronger regulatory monitoring, public evaluation, enforcement signals, and reputational exposure increase firms' incentives to provide more substantive and compliance-oriented biodiversity disclosure. Aiming to fill these identified gaps, the present study analyzes how government power influences biodiversity disclosure practices among environmentally sensitive Indonesian firms. Government power is proxied by the Indonesian Program for Pollution Control, Evaluation, and Rating (PROPER), which captures regulatory monitoring, public evaluation, enforcement signals, and reputational exposure more directly

than broad governance indicators or static proxies such as state ownership. This study utilizes a 20-item weighted index, customized for the Indonesian institutional setting, to measure biodiversity disclosure by assessing both the volume and the quality of the information provided. Methodologically, this study uses panel data to capture temporal variation in environmental disclosure and regulatory conditions (Sánchez *et al*., 2023). It also applies instrumental variable two-stage least squares estimation to address potential endogeneity, while year fixed effects, industry fixed effects, firm-level controls, and an alternative unweighted disclosure measure are used to assess the robustness of the findings (Eugster, 2020; Zahid *et al*., 2020). This study extends stakeholder salience theory by providing empirical evidence of how government power functions as a coercive institutional force, specifically influencing biodiversity disclosure within a developing nation context. Based on the theoretical and empirical arguments above, Fig. 1 presents the conceptual framework of the study. The framework integrates stakeholder salience theory and institutional theory to explain how government power, proxied by PROPER, may influence biodiversity disclosure through regulatory monitoring, public evaluation, enforcement signals, and reputational exposure. Consistent with established literature, the empirical model accounts for firm-level characteristics—including age, size, leverage, and profitability—alongside industry and year fixed effects to ensure the robustness of the findings. The objective of this study is to evaluate the influence of government power on biodiversity disclosure within Indonesia's environmentally sensitive sectors, verifying the consistency of the findings through endogeneity checks and alternative measurement specifications. The empirical analysis uses panel data from firms operating in environmentally sensitive industries over the period 2018 to 2023.

MATERIALS AND METHODS

Research design

A quantitative causal research design using panel data is adopted to examine the effect of government power on biodiversity disclosure in environmentally sensitive companies. Utilizing a panel data approach is particularly advantageous in this context, given that biodiversity disclosure is not a static occurrence; rather, it fluctuates over time under the influence of both firm-specific and institutional dynamics. Compared to cross-sectional analysis, panel data allow the study to control for unobserved heterogeneity across firms, such as differences in environmental exposure, organizational culture, and geographical characteristics, which may bias the estimation results if omitted (Kumari *et al.,* 2022; Velte, 2023). Furthermore, biodiversity disclosure is characterized by path dependency; consequently, current reporting levels are inherently influenced by a firm's prior disclosure trajectory. Panel data models enable the incorporation of dynamic structures and lagged relationships that cannot be captured in cross-sectional designs (Eugster, 2020). Moreover, panel data allow the study to exploit temporal variation in government intervention, particularly through PROPER ratings, which change over time and create variation that can be used to identify causal effects (Hambali and Adhariani, 2024). Government power is operationalized through the Indonesian Program for Pollution Control, Evaluation, and Rating (PROPER). PROPER is suitable for this study because it captures more than the existence of formal regulation. It reflects regulatory monitoring, public evaluation, reputational exposure, and enforcement signals. By publicly categorizing the environmental performance of firms, this rating system establishes a framework of reputational accountability for those failing to meet regulatory standards. Therefore, PROPER provides a more direct proxy for coercive and evaluative government power than static measures such as

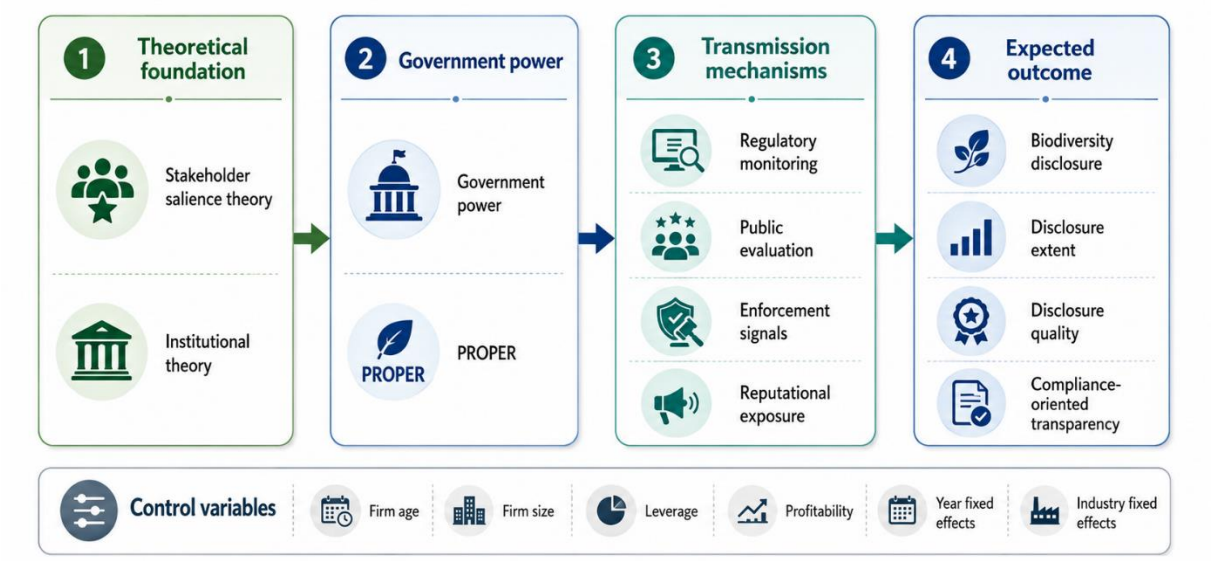

Fig. 1: Conceptual framework of the study

state ownership or broad country-level governance indices. Given the potential endogeneity between government power and biodiversity disclosure, an instrumental variable approach using two-stage least squares (IV/2SLS) are employed. The potential for endogeneity is significant, as it can be attributed to factors such as reverse causality, omitted variables, measurement error, and the inherent dynamic nature of the variables involved (Zahid *et al.,* 2020; Radhouane *et al.,* 2018). To address this issue, the first lag of PROPER (L1_PROPER) is used as an instrumental variable. The use of L1_PROPER is justified by temporal precedence. Current biodiversity disclosure cannot influence past regulatory ratings. The instrument is also theoretically relevant because previous regulatory evaluations are expected to influence current regulatory exposure and corporate responses. Furthermore, the validity of the exclusion restriction hinges on the assumption that lagged PROPER scores impact current biodiversity disclosure primarily via current regulatory mechanisms, rather than through an autonomous direct channel. Although this assumption cannot be tested directly, the model reduces this concern by controlling for firm age, firm size, leverage, profitability, year fixed effects, industry fixed effects, and additional robustness specifications. This limitation is also acknowledged when interpreting the causal results.

Instrument validity

The validity of the instrumental variable is assessed through relevance, strength, and theoretical exogeneity. Instrument relevance is supported by the strong relationship between lagged PROPER and current PROPER ratings. This outcome is anticipated, as environmental performance ratings typically exhibit temporal persistence driven by consistent regulatory monitoring and established corporate environmental management systems. The robustness of the instrument is subsequently verified using the first-stage F-statistic. A value above the conventional threshold of 10 indicates that the instrument is not weak. The exogeneity of L1_PROPER is justified conceptually through its temporal ordering. Since L1_PROPER represents a past regulatory rating, current biodiversity disclosure cannot influence it. This helps reduce simultaneity bias. However, past regulatory ratings may be associated with prior environmental disclosure behavior or persistent

firm characteristics. To mitigate this concern, panel estimation and fixed-effects robustness checks are used to account for time-related variation and sectoral heterogeneity. Consequently, the instrumental variable findings are presented as providing stronger causal insights, although it is recognized that the underlying exclusion restriction assumptions require rigorous and careful interpretation.

Population, sample, and data sources

The population of this study consists of 568 environmentally sensitive companies listed on the Indonesia Stock Exchange during the period 2018–2023. This study focuses on environmentally sensitive industries, as their core operations exert significant pressure on biodiversity via habitat transformation, resource depletion, and the degradation of local ecosystems. Using purposive sampling criteria, the final sample comprises 472 companies with a total of 1,225 firm-year observations. The sampling criteria include: 1) the company operates in environmentally sensitive sectors; 2) the company publishes annual or sustainability reports; 3) biodiversity-related information is available; and (4) data for PROPER, firm age, firm size, leverage, and profitability are accessible. In the IV/2SLS estimation, the effective sample size is reduced to 703 firm-year observations across 340 firm clusters due to the use of lagged instruments and the unbalanced panel structure. Secondary data are collected from corporate annual reports, sustainability reports, financial statements, and official government publications related to PROPER. The panel dataset is structured at the firm-year level, with each observation corresponding to a specific firm within a single reporting year. Data availability differs across firms and years because not all firms publish complete biodiversity-related information or receive publicly available PROPER ratings in each year. Therefore, the panel is unbalanced. Observations with missing data for the dependent variable, PROPER rating, firm age, or firm size are excluded from the relevant estimation. This study employs a cross-checking procedure to mitigate measurement errors; specifically, financial information is verified against formal statements, while biodiversity items are identified through a systematic review of annual and sustainability reports. For the categorical PROPER distribution in the descriptive statistics, only observations with available PROPER ratings are reported. This explains the difference between the total firm-year observations used for continuous variables and the frequency distribution of PROPER categories. Although the use of lagged instruments reduces the effective sample size, this trade-off is necessary to ensure identification and mitigate simultaneity bias. However, this approach prioritizes internal validity over sample size, which is critical for causal inference.

Construction of the biodiversity disclosure index

Biodiversity disclosure is measured using a weighted Biodiversity Disclosure Index developed specifically for this study. Relative to binary or unweighted measures, a weighted index provides a more nuanced assessment of disclosure quality by prioritizing substantive ecological data, including site-specific impacts, restoration efforts, and quantifiable outcomes (Hassan *et al*., 2020; Adler *et al*., 2018). The initial items were derived from biodiversity accounting literature, sustainability reporting practices, and environmental disclosure requirements, and were validated through focus group discussions, interviews, and expert questionnaires. The expert panel consisted of 35 respondents: 16 academics from biology, environmental science, forestry, mining, and accounting; 9 practitioners from energy, mining, and forest business sectors; and 10 regulators from relevant ministries and conservation agencies. Conducted through both offline and online channels in September 2023, the focus group discussions required respondents to evaluate item importance via a seven-point Likert scale. These assessments subsequently informed the calculation of item ratings and their

respective relative weights. The average item rating was 4.755, and the final weighted index was normalized around a mean value of 1.000. Items with weights greater than 1 indicate above-average importance, while weights below 1 indicate below-average importance based on expert assessment. All 20 items were valid because their item-total correlations exceeded the r-table value of 0.3338, and the reliability coefficient was 0.8749. The construction of the index follows a six-stage process, as presented in Table 1. The index captures biodiversity disclosure quality and compliance-relevant information related to impacts, mitigation, restoration, monitoring, expenditure, partnerships, management plans, and stakeholder engagement initiatives across different operational contexts. While the index does not directly quantify ecological performance, it evaluates the scope of corporate disclosures concerning biodiversity management, monitoring, and compliance-oriented transparency. The weighted index enhances measurement validity and sensitivity to disclosure quality (Sobkowiak, 2023; Mair *et al*., 2024). To ensure the robustness of the primary findings, an unweighted binary measure is also employed; this metric assigns a value of 1 for each disclosed item and 0 otherwise, resulting in a composite score between 0 to 20. The final index consists of 20 items covering biodiversity impacts, management actions, monitoring, restoration, and governance aspects, as shown in Table 2.

Variable measurement

The variables used in this study are presented in Table 3. Biodiversity disclosure is measured using a weighted index constructed from multiple disclosure items capturing biodiversity impacts, management practices, and outcomes. Government power is proxied by the PROPER rating, an environmental performance evaluation program issued by the Indonesian Ministry of Environment. PROPER is coded from 0 to 5 for descriptive and empirical purposes, where 0 indicates firm-year observations without an available PROPER category and values 1 to 5 represent the official PROPER performance ratings: 1 = Black (worst), 2 = Red, 3 = Blue, 4 = Green, and 5 = Gold (best). Environmental and regulatory metrics are captured via a 1–5 rating system, where higher scores signify stronger outcomes. To ensure statistical robustness, firm size is operationalized as the natural log of total assets—minimizing distributional skew—while firm age is determined by the number of years since the entity's inception. To address potential endogeneity, a lagged value of PROPER is used as an instrumental variable. Although PROPER is presented descriptively as a categorical variable, the empirical analysis treats the ordered PROPER ratings as a continuous measure to capture the ordinal nature of environmental performance evaluation and facilitate more robust statistical interpretation across sampled firms. For descriptive statistics, total assets are converted into billion United States Dollar (USD) to improve international comparability.

Data analysis techniques

The analysis proceeds in several stages. First, descriptive statistics are used to summarize the data. Second, correlation analysis is conducted to examine relationships between variables. Third, the baseline model is estimated using ordinary least squares (OLS) with clustered standard errors (SE). Fourth, endogeneity is tested using the Durbin–Wu–Hausman test. Given the presence of endogeneity, the main estimation uses IV/2SLS. The choice of L1_PROPER as an instrument is justified by its temporal precedence and strong correlation with current PROPER, while mitigating reverse causality (Kumari *et al.,* 2022; Mair *et al.,* 2024). To address potential endogeneity, specifically simultaneity bias, this study utilizes lagged PROPER; this ensures that contemporary disclosures do not impact past regulatory evaluations. Consistent with prior panel studies in this domain, the baseline empirical model is formalized in Eq. 1 (Kumari et al., 2022; Velte, 2023):

Table 1: Stages in constructing the biodiversity disclosure index

Stage	Process	Objective
Stage 1	Defining biodiversity disclosure	To determine the scope of biodiversity-related information
Stage 2	Identifying items from literature, standards, and regulations	To develop the initial disclosure items
Stage 3	Validating items through focus group discussions, interviews, and expert questionnaires	To ensure content validity and practical relevance
Stage 4	Assessing item importance using a seven-point Likert scale	To determine item ratings and relative weights
Stage 5	Testing validity and reliability	To ensure valid and reliable disclosure items
Stage 6	Constructing the weighted index	To produce final biodiversity disclosure score

Table 2: Biodiversity disclosure index items

No	Weight	Disclosure Item
1	0.96	Animal species richness
2	0.92	Plant species richness
3	0.98	Types of ecosystems
4	0.98	Area of ecosystem types
5	0.96	Direct impacts on species
6	1.06	Indirect impacts on species
7	1.04	Direct impacts on ecosystems
8	1.03	Indirect impacts on ecosystems
9	0.96	Sources of biodiversity impacts
10	0.98	Impact anticipation
11	1.01	Impact minimization
12	1.00	Restoration actions
13	1.03	Biodiversity monitoring
14	1.03	Species restored
15	1.05	Area restored
16	1.02	Biodiversity-related expenditure
17	1.06	Biodiversity partnerships
18	0.90	Biodiversity inventory division
19	1.01	Public awareness of biodiversity importance
20	1.02	Biodiversity management plan

Note: Weights greater than 1 indicate above-average importance based on expert assessment, while weights below 1 indicate below-average relative importance.

Table 3: Variable measurement

Type	Variable	Symbol	Measurement
Dependent	Biodiversity disclosure	Biod	Weighted biodiversity disclosure index based on multiple disclosure items reflecting biodiversity impacts, management, and outcomes
Independent	Government power	PROPER	PROPER rating coded from 0 to 5: 0 = No Category, 1 = Black (worst), 2 = Red, 3 = Blue, 4 = Green, and 5 = Gold (best). Higher values from 1 to 5 indicate stronger environmental performance and regulatory evaluation (Ministry of Environment Regulation, 2013)
Control	Firm age	Age	Number of years since firm establishment
Control	Firm size	Size	Natural logarithm of total assets
Control	Leverage	Lev	Total debt divided by total assets
Control	Profitability	Prof	Net income divided by total assets
Instrument	Lagged PROPER	L1_PROPER	One-period lag of PROPER rating

$$Biod_it = \beta0 + \beta1PROPER_it + \beta2Age_it + \beta3Size_it + \beta4Lev_it + \beta5Prof_it + \varepsilon_it \quad (1)$$

Following prior studies that address endogeneity in sustainability disclosure research, the instrumental variable model is specified using Eq. 2 (Eugster, 2020; Zahid et al., 2020):

$$Biod_it = \beta0 + \beta1PROPER_hat_it + \beta2Age_it + \beta3Size_it + \beta4Lev_it + \beta5Prof_it + \varepsilon_it \quad (2)$$

Robustness checks include models with and without firm-level control variables, year fixed effects, industry fixed effects, and an alternative dependent variable specification. The alternative dependent variable is constructed using an unweighted binary scoring approach. This specification examines the stability of the primary relationship by substituting the expert-weighted index with a binary measure of biodiversity disclosure presence.

Validity and ethical considerations

Internal validity is strengthened by using panel data and an instrumental variable approach to address unobserved heterogeneity and endogeneity. Measurement validity is supported by the weighted biodiversity disclosure index, expert-based weighting, validity testing, and reliability testing. External validity is enhanced by the inclusion of a large cohort of environmentally sensitive firms; however, caution is warranted when extrapolating these results beyond comparable organizational environments. Ethical considerations are addressed by using publicly available secondary data, applying a structured disclosure checklist, and avoiding manipulation or misrepresentation of information. The exclusion restriction is also interpreted carefully because it cannot be directly tested.

RESULTS AND DISCUSSION

Descriptive statistics

The following analysis presents the empirical findings, followed by a discussion that reconciles these results with theoretical expectations, prior research, and relevant policy considerations. The analysis is structured sequentially, beginning with descriptive statistics, correlation analysis, endogeneity tests, and regression results, followed by theoretical interpretation, robustness discussion, mechanisms of government power, policy implications, limitations, and future research directions. Table 4 reports the descriptive statistics for continuous variables and the distribution of PROPER. Biodiversity disclosure has a mean value of 5.876 and a standard deviation of 3.797, indicating substantial variation in disclosure practices among environmentally sensitive firms. Biodiversity disclosure varies substantially across firms, indicating that some firms provide limited biodiversity-related information while others disclose more extensively. Firm age averages approximately 33.6 years, showing that the sample includes both young and well-established firms. Firm size also varies widely, with a mean of 0.759 billion USD and a maximum of 28.928 billion USD. Leverage has a mean of 0.267, indicating that debt accounts for about 26.7 percent of firms' financing structure, while profitability ranges from -61.558 to 61.634, with a mean of 3.845, reflecting substantial differences in financial performance. Data for PROPER is unavailable for 77.14% of the sample (945 firm-year observations); this discrepancy arises because a subset of environmentally sensitive firms does not receive public ratings in every reporting cycle. Among rated firms, blue is the largest category with 159 observations, followed by green with 65, gold with 47, and red with 9, while no firm-year observation is classified as black. This distribution indicates that rated firms are concentrated in moderate to strong environmental performance categories.

Correlation analysis

Table 5 shows that biodiversity disclosure is positively and significantly correlated with government power, measured by PROPER, with a coefficient of 0.3715. While biodiversity disclosure

Table 4: Descriptive statistics

1- Continuous variables:					
Variable	Obs	Mean	Standard deviation (SD)	Min.	Max.
Biodiversity disclosure	1,225	5.876	3.797	0.899	16.106
Firm age (years)	1,225	33.638	19.305	2.000	117.000
Firm size (billion USD)	1,225	0.759	2.284	0.001	28.928
Leverage	1,225	0.267	0.193	0.0001	1.008
Profitability	1,225	3.845	9.332	-61.558	61.634
2- Categorical variable:					
Variable	Category	Frequency	Percentage (%)		
PROPER	0 (No Category)	945	77.14		
	1 (Black)	0	0.00		
	2 (Red)	9	0.73		
	3 (Blue)	159	12.98		
	4 (Green)	65	5.31		
	5 (Gold)	47	3.84		
	Total	1,225	100.00		

Table 5: Pearson correlation matrix

Variable	Biod	PROPER	Age	Size	Lev	Prof
Biod	1.0000					
PROPER	0.3715***	1.0000				
Age	0.1497***	0.2523***	1.0000			
Size	0.0982***	0.0037	0.1194***	1.0000		
Lev	0.0696**	0.0172	-0.0273	0.0076	1.0000	
Prof	0.0696***	0.1100***	0.0510*	0.0237	-0.2907***	1.0000

Note: ***p < 0.01, **p < 0.05, *p < 0.10

is positively and significantly correlated with firm age, size, leverage, and profitability, the coefficients suggest these relationships are comparatively modest. The correlations among independent and control variables are generally low, with the largest absolute value observed between leverage and profitability (-0.2907), suggesting that severe multicollinearity is unlikely. PROPER is also positively and significantly correlated with firm age, suggesting that older firms may obtain higher environmental performance ratings. Correlations among the independent and control variables remain relatively low, suggesting that multicollinearity is unlikely to bias the empirical results. Overall, the correlation matrix provides preliminary evidence of a positive relationship between government power and biodiversity disclosure and supports the inclusion of firm-level controls in the regression analysis.

Regression analysis results

Endogeneity test and instrument strength

Before estimating the main model, the endogeneity of the variable PROPER is tested. This step is necessary because endogeneity can bias the estimation results if not properly addressed (Table 6). Table 6 reports the instrument relevance and endogeneity tests. The instrument demonstrates significant explanatory power, as evidenced by a first-stage partial R-squared of 0.1913, which confirms its relevance in predicting current PROPER classifications. The first-stage F-statistic is 97.0246 and statistically significant at the 1 percent level. This value is substantially higher than the conventional threshold of 10, suggesting that L1_PROPER is not a weak instrument and has sufficient relevance for explaining current government power. The Durbin–Wu–Hausman test produces an F-statistic of 12.7522 with a p-value of 0.0004. This result

Table 6: Instrument relevance and endogeneity tests

Test	Statistic	p-value	Conclusion
First-stage partial R-squared	0.1913	-	Instrument relevance supported
First-stage F-statistic	F(1,339) = 97.0246	0.0000	Strong instrument
Durbin-Wu-Hausman	F(1,339) = 12.7522	0.0004	Endogenous

rejects the null hypothesis of exogeneity and confirms that PROPER is endogenous. Consequently, relying solely on Ordinary Least Squares may yield biased estimates, as it fails to account for endogeneity stemming from reverse causality, omitted variable bias, and measurement errors. These results support the use of the instrumental variable two-stage least squares approach as the main estimation strategy.

Main results and robustness checks

Table 7 presents the main estimation results and robustness checks. Results from the main instrumental variable specification indicate that PROPER has a positive impact on biodiversity disclosure, with a coefficient of 0.141 significant at the 1 percent level. This implies that stronger government oversight fosters greater corporate transparency regarding biodiversity. The IV model without firm-level controls produces a similar coefficient of 0.148, suggesting that the relationship is not driven solely by firm age, firm size, leverage, or profitability. The IV model without firm-level controls also shows a positive and significant coefficient of 0.148, which is close to the main IV estimate. The consistency of these results indicates that the association between government regulatory power and biodiversity disclosure remains robust and is not merely a byproduct of firm-level characteristics such as age, firm size, leverage, or profitability. The OLS-cluster models also produce positive and significant coefficients, both with controls at 0.074 and without controls at 0.086. However, these coefficients are smaller than the IV estimates, suggesting that conventional OLS estimation may underestimate the relationship. This pattern is consistent with the endogeneity test results and supports the use of IV/2SLS as the main estimation approach. Utilizing an unweighted binary score for biodiversity disclosure produces a significant positive coefficient of 0.139, suggesting that the core findings are robust to alternative measurement approaches and independent of the specific expert-based weighting procedure. The inclusion of year fixed effects and industry fixed effects in all specifications further strengthens the results by controlling for time-specific reporting trends and sectoral differences in ecological exposure, regulatory intensity, and disclosure norms. Therefore, the positive coefficient of PROPER remains robust after accounting for alternative model specifications, disclosure measurement, and temporal and sectoral heterogeneity. As shown in Table 8, the industry specific IV/2SLS model further clarifies the relationship between PROPER and biodiversity disclosure across different sectors. The coefficient of PROPER is positive in all estimable industry-specific models, although the level of statistical significance differs across industries. The effect of PROPER is positive and statistically significant for Basic materials, Energy, Infrastructure, and Properties and real estate, while the coefficients for Consumer non-cyclicals and Industrials remain positive but are not statistically significant. The IV/2SLS model for Transportation and logistics could not be estimated because L1_PROPER has no variation in this subsample and was omitted due to collinearity. The sectoral results are intended as descriptive insights; therefore, they should not be interpreted as a rigorous evaluation of industry moderation or comparative cross-industry effects. Overall, they indicate that the positive association between PROPER and biodiversity disclosure appears in most estimable sectors and is not confined to a single industry group.

Table 7: Main results and robustness checks

Variable	Main Result	IV without controls	Ordinary least squares (OLS)-cluster	Ordinary least squares (OLS)-cluster without controls	Alternative DV IV
PROPER	0.141**	0.148**	0.074**	0.086**	0.139**
	(0.025)	(0.022)	(0.011)	(0.010)	(0.024)
Age	0.001		0.003**		0.001
	(0.001)		(0.001)		(0.001)
Size	0.008		0.011		0.008
	(0.011)		(0.010)		(0.011)
Lev	0.141		0.310**		0.138
	(0.117)		(0.093)		(0.116)
Prof	0.004*		0.005**		0.004*
	(0.002)		(0.002)		(0.002)
_Cons	1.760	2.076	1.125	1.661	1.774
	(0.326)	(0.067)	(0.280)	(0.085)	(0.323)
Observations	703	703	1,225	1,225	703
Clusters	340	340	471	471	340
R-squared	0.3382	0.3208	0.3865	0.3601	0.3412
Year FE	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes
Instrument	L1_PROPER	L1_PROPER	-	-	L1_PROPER

Note: SE in parentheses. *p < 0.05, *p < 0.10, **p < 0.01

Table 8: Industry-specific IV/2SLS estimates of the relationship between PROPER and biodiversity disclosure

Variable	Basic materials	Consumer non-cyclicals	Energy	Industrials	Infrastructure	Properties and real estate	Transportation and logistics
PROPER	0.149***	0.069	0.206***	0.078	0.080***	0.408**	Not estimated
	(0.039)	(0.073)	(0.047)	(0.058)	(0.014)	(0.183)	-
Age	-0.005	0.003	-0.003	0.014***	0.007***	0.005	-
	(0.004)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	-
Size	0.001	-0.019	0.024	-0.014	0.012	0.011	-
	(0.023)	(0.024)	(0.024)	(0.033)	(0.021)	(0.029)	-
Lev	-0.047	0.583**	-0.081	-0.259	0.071	-0.033	-
	(0.234)	(0.261)	(0.313)	(0.445)	(0.178)	(0.306)	-
Prof	0.002	0.013***	0.001	-0.012	-0.002	-0.000	-
	(0.005)	(0.005)	(0.004)	(0.011)	(0.006)	(0.009)	-
_Cons	2.259	2.157	1.559	1.468	1.222	1.327	-
	(0.632)	(0.695)	(0.734)	(0.918)	(0.583)	(0.800)	-
Observations	155	177	110	57	88	83	-
Clusters	65	86	47	33	41	47	-
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Instrument	L1_PROPER	L1_PROPER	L1_PROPER	L1_PROPER	L1_PROPER	L1_PROPER	Not identified

Note: Standard errors are in parentheses. Standard errors are clustered at the firm level. PROPER is instrumented by L1_PROPER. All estimable models include year fixed effects and firm-level controls: age, size, leverage, and profitability. ***p < 0.01, **p < 0.05, *p < 0.10. The IV/2SLS model for Transportation and logistics could not be estimated because L1_PROPER has no variation in this subsample and was omitted due to collinearity. R-squared is not reported because it is not always meaningful or available in IV/2SLS estimations.

Regarding the control variables, firm age and leverage achieve statistical significance only within the OLS-cluster model. In contrast, firm size remains insignificant across all reported specifications. Profitability maintains a positive and significant association with disclosure in the primary IV model, the OLS-cluster model, and the alternative dependent variable specification, despite a relatively small coefficient magnitude. These results suggest that firm-level characteristics may explain some variation in biodiversity disclosure, but their effects are less consistent than government power. Taken together, the findings show that PROPER is

positively and consistently associated with biodiversity disclosure across IV, OLS, control, no-control, and alternative dependent variable specifications. However, the results should not be interpreted as implying that biodiversity disclosure is driven exclusively by government power; rather, government power is an important institutional factor that strengthens biodiversity disclosure in environmentally sensitive firms.

Reassessing stakeholder salience: power versus symbolism

By establishing government power as a primary driver of biodiversity reporting, this study lends empirical weight to stakeholder salience theory in the context of environmentally sensitive firms. Rather than redefining stakeholder salience theory, the results offer a contextual extension by demonstrating how the power attribute becomes particularly salient in a regulatory environment where biodiversity impacts are difficult to measure and verify. According to the stakeholder salience framework, the degree to which managers grant priority to specific stakeholders depends on the perceived presence of power, legitimacy, and urgency (Mitchell *et al*., 1997). In the context of biodiversity disclosure, the findings suggest that coercive pressure from government may strengthen firms' incentives to move beyond general symbolic statements toward more substantive biodiversity-related information. This interpretation is consistent with prior biodiversity and sustainability disclosure literature. Prior research indicates that in the absence of verifiable ecological outcomes, corporate biodiversity disclosures may serve symbolic purposes—such as organized hypocrisy or impression management—rather than reflecting substantive environmental performance (Boiral, 2014; Maroun *et al*., 2018). Social expectations, non-governmental organization (NGO) advocacy, and legitimacy pressures may encourage disclosure, but they do not always guarantee that the reported information is substantive, measurable, or compliance oriented. Therefore, the present findings do not imply that legitimacy and urgency are irrelevant. Instead, they suggest that government power can complement and reinforce these pressures by introducing monitoring, evaluation, enforcement signals, and reputational consequences. PROPER provides an example of how government power operates through visible and evaluative mechanisms. The public rating system, environmental assessment protocols, and associated reputational exposure collectively translate regulatory pressure into tangible organizational incentives. This mechanism elucidates why firms attaining superior PROPER ratings exhibit a greater propensity for comprehensive biodiversity disclosure. The finding is also consistent with recent studies showing that regulatory pressure, institutional factors, and environmental performance systems can influence corporate biodiversity and environmental disclosure practices in emerging and international contexts (Saeed *et al*., 2025; Hambali and Adhariani, 2024; Velte, 2023). Accordingly, the findings should be interpreted modestly. These results do not imply that biodiversity disclosure is governed exclusively by state authority, nor do they suggest that power consistently supersedes other stakeholder attributes across all institutional contexts. Rather, the results indicate that government power is a robust institutional factor that becomes especially relevant in environmentally sensitive industries, where biodiversity impacts are complex, stakeholder verification is difficult, and symbolic disclosure remains a persistent concern. Compared with prior studies, the present findings are consistent with evidence that institutional and regulatory pressures can influence environmental and biodiversity disclosure practices (Saeed *et al*., 2025; Hambali and Adhariani, 2024; Velte, 2023). This study extends the existing discourse by demonstrating that the observed relationship remains positive and significant after rigorously addressing endogeneity and accounting for year and industry fixed effects. The magnitude of the IV coefficients, ranging from 0.139 to 0.148 across

the main and alternative specifications, indicates that government power has a consistent positive association with biodiversity disclosure. Simultaneously, these findings must be interpreted in light of potential alternative explanations, such as firm visibility, reporting capacity, and varying degrees of stakeholder scrutiny. These factors may interact with government power in shaping disclosure behavior and should be examined further in future research.

Endogeneity as a substantive, not merely technical, problem

Endogeneity in this study is both econometric and substantive. Econometrically, PROPER may be correlated with the error term due to reverse causality, omitted variables, measurement error, or persistence in firm behavior. This issue is significant because much of the existing environmental disclosure literature relies on OLS or cross-sectional frameworks. Such models often overlook the potential for endogeneity, implicitly treating regulatory pressure as exogenous despite the likelihood of reverse causality and omitted variable bias (Eugster, 2020; Zahid *et al*., 2020). The Durbin–Wu–Hausman test confirms endogeneity, supporting the use of L1_PROPER as an instrumental variable because current biodiversity disclosure cannot influence past PROPER ratings. Substantively, endogeneity suggests that biodiversity disclosure and regulatory evaluation may evolve together. Firms with higher environmental exposure may attract stronger regulatory attention, while firms subject to stronger evaluation may increase disclosure. Consistent with extant sustainability disclosure literature, this finding underscores the dual influence of firm-specific attributes and exogenous institutional forces in shaping corporate transparency (Eugster, 2020; Zahid *et al*., 2020). Empirically, the PROPER coefficient increases from the OLS-cluster estimates of 0.074–0.086 to the IV estimates of 0.141–0.148, suggesting that conventional OLS models may underestimate the relationship when endogeneity is ignored. However, this should not be interpreted as an unrestricted causal effect. Although L1_PROPER demonstrates strong relevance and temporal precedence, the exclusion restriction is subject to the typical limitation that lagged variables may still capture persistent firm-specific factors or past disclosure behavior. Therefore, firm-level controls, year fixed effects, industry fixed effects, and alternative specifications are used to strengthen credibility while supporting a cautious interpretation of causality.

Robustness of the relationship between government power and biodiversity disclosure

The robustness checks provide additional support for the positive relationship between government power and biodiversity disclosure. As shown in Table 7, PROPER remains positive and statistically significant across all specifications. The stability of the coefficient between the main IV model (0.141) and the baseline model without controls (0.148) confirms that the results are not driven solely by firm age, firm size, leverage, or profitability. The OLS-cluster models also show positive and significant coefficients, although smaller, at 0.074 with controls and 0.086 without controls, suggesting that conventional OLS estimation may underestimate the relationship. The alternative dependent variable specification further confirms the robustness of the findings, with a positive and significant coefficient of 0.139. The inclusion of year fixed effects and industry fixed effects indicates that the relationship is not explained solely by temporal trends or sector-level differences. Nonetheless, these findings warrant a cautious interpretation, as exogenous factors—including corporate governance frameworks, ownership structures, and profitability—alongside external pressures from investors and NGOs, may also exert significant influence on biodiversity disclosure.

Government power: From monitoring to disclosure incentives

The results suggest that government power may operate through monitoring, public evaluation, and reputational exposure. As a monitoring mechanism, PROPER can reduce information asymmetry by making firms' environmental performance more visible to regulators and stakeholders. Consistent with information-governance frameworks, this study suggests that transparency serves as a regulatory tool to reduce information asymmetry, thereby shaping corporate behavior through increased institutional visibility and comparative benchmarking (Martínez-Ferrero *et al*., 2016; Bebbington *et al*., 2024; Mair *et al*., 2024). It is also consistent with the empirical results in Table 7, where the coefficient of PROPER remains positive and statistically significant across the main IV model, IV without controls, OLS-cluster models, and the alternative dependent variable specification. This interpretation is consistent with the conceptual framework presented in Fig. 1, which positions PROPER as a program-based government mechanism that links regulatory evaluation with firms' biodiversity disclosure incentives. It is important to note that these results do not imply that government power acts as the exclusive driver of corporate biodiversity reporting. Rather, PROPER appears to strengthen disclosure incentives by combining regulatory monitoring, public assessment, and reputational visibility. In this sense, government power may complement other disclosure drivers, such as legitimacy concerns, stakeholder expectations, corporate governance mechanisms, investor pressure, and NGO scrutiny. Adopting a cautious interpretation is essential, as biodiversity disclosure is influenced by a complex interplay of organizational and institutional factors that the current empirical model may not exhaustively capture. This interpretation is consistent with prior studies showing that corporate biodiversity and environmental disclosure may be influenced by institutional and regulatory pressures (Hambali and Adhariani, 2024; Velte, 2023). The evidence further indicates that government authority facilitates a transition in disclosure practices toward compliance-oriented transparency, reinforcing the role of the state in standardizing corporate reporting. In weak regulatory environments, firms may rely on symbolic disclosure or broad environmental narratives that are difficult to verify. Prior studies in the field of biodiversity accounting suggest that firms often utilize environmental reporting for symbolic legitimacy, leveraging organized hypocrisy when disclosures lack a foundation in measurable ecological outcomes (Boiral, 2014; Maroun *et al*., 2018). PROPER's evaluation and public rating mechanisms may reduce this tendency by increasing the visibility of firms' environmental performance. Nevertheless, increased disclosure should not be equated automatically with improved biodiversity outcomes. Transparency through disclosure is a necessary but insufficient condition for accountability; ensuring measurable ecological outcomes requires rigorous site-specific oversight, external auditing, and standardized scientific metrics (Bebbington *et al*., 2024; Mair *et al*., 2024).

Implications for theory, measurement, and policy

This study offers a contextual empirical extension of stakeholder salience theory by demonstrating that government power serves as a pivotal institutional determinant of corporate biodiversity disclosure. The findings do not suggest that power dominates all other stakeholder attributes in every setting. Rather, they indicate that the power attribute becomes especially salient in environmentally sensitive industries, where biodiversity impacts are difficult to measure, verify, and translate into standardized reporting. Government power serves as a critical institutional catalyst, reinforcing disclosure incentives by integrating enhanced monitoring capacity, clear enforcement signals, and heightened reputational consequences into the firm's strategic environment. The study addresses

endogeneity in the relationship between government power and biodiversity disclosure. The Durbin–Wu–Hausman test supports the use of an instrumental variable approach, and the larger IV estimates compared with OLS-cluster estimates suggest that conventional models may underestimate the relationship when endogeneity is not addressed. The transition from association to causation is made with caution, acknowledging that the validity of the exclusion restriction relies on theoretical justification rather than direct statistical verification. The inclusion of firm-level controls, year fixed effects, industry fixed effects, and an alternative dependent variable specification strengthens the credibility of the findings without overstating the causal claim. Measurement contribution. The study operationalizes government power through PROPER, a program-based measure of regulatory monitoring, public evaluation, and reputational exposure. Additionally, this study constructs a weighted biodiversity disclosure index designed to evaluate reporting quality; specifically, it assigns higher weights to disclosures concerning biodiversity impacts, monitoring, restoration, and management interventions. The robustness check using an unweighted binary scoring approach confirms that the main finding is not driven solely by the expert-based weighting procedure. Policy contribution. The findings suggest that regulatory design matters for improving biodiversity disclosure. Programs that combine monitoring, public evaluation, public rating, and reputational incentives may encourage firms to disclose more biodiversity-related information. It is imperative that future disclosure policies do not merely incentivize data proliferation but rather foster a robust nexus between transparency mechanisms and measurable biodiversity conservation. Science-based indicators, site-level ecological metrics, independent assurance, and continuous monitoring systems are therefore needed to ensure that transparency contributes to environmental accountability.

Limitations and future research directions

Despite its contributions, this study has several limitations that open avenues for future research. The reliance on a single-country setting may constrain the degree of institutional variation; consequently, future studies should employ cross-country comparative designs to enhance the generalizability of these findings. First, the focus on Indonesian environmentally sensitive firms limits external generalizability, particularly to developed markets with different regulatory regimes. Second, the use of L1_PROPER as an instrument, while methodologically justified, reduces the effective sample size and may not capture all dimensions of regulatory dynamics. Third, while PROPER serves as a robust proxy for formal regulatory pressure, it may not encapsulate informal institutional mechanisms, such as sub-national enforcement variations, political idiosyncrasies, or the intensity of media scrutiny. Fourth, this study does not directly examine governance and ownership characteristics, such as board structure, board independence, ownership concentration, institutional ownership, or NGO-affiliated directors. These variables may also influence biodiversity disclosure; however, complete governance data across all firm-year observations were beyond the scope of this study due to data availability constraints. Subsequent studies ought to incorporate these factors to elucidate how internal corporate governance and external state authority jointly shape the landscape of biodiversity transparency. Finally, an important unresolved question remains: does increased biodiversity disclosure lead to improved biodiversity outcomes, or does it primarily enhance transparency without substantive ecological impact? Addressing this question requires integrating disclosure data with ecological indicators and longitudinal environmental outcomes. Collectively, these constraints underscore the necessity of adopting more integrative and interdisciplinary frameworks to advance the study of corporate biodiversity disclosure.

CONCLUSION

This study examines the effect of government power on biodiversity disclosure in environmentally sensitive companies. Utilizing PROPER as a program-based proxy for government power within an instrumental variable framework, this study demonstrates that regulatory monitoring, public evaluation, and reputational exposure exert a positive and statistically significant influence on biodiversity disclosure. The main IV estimate shows a coefficient of 0.141, while the OLS-cluster estimates range from 0.074 to 0.086. The alternative dependent variable specification, based on an unweighted binary scoring approach ranging from 0 to 20, also produces a positive and significant coefficient of 0.139. These findings demonstrate that the positive relationship remains robust to the treatment of endogeneity, the inclusion of year and industry fixed effects, and the application of alternative proxy measures for biodiversity disclosure. The study contributes to biodiversity disclosure literature in three main ways. First, it provides a contextual empirical extension of stakeholder salience theory by showing that government power is an important institutional factor in shaping disclosure incentives in environmentally sensitive industries. Second, it addresses potential endogeneity by employing lagged PROPER scores as an instrumental variable, while maintaining a cautious stance regarding the resulting causal inferences. Third, it develops a weighted biodiversity disclosure index and confirms the robustness of the finding using an unweighted presence-based score. Collectively, these contributions demonstrate that biodiversity disclosure is shaped by a dual set of determinants: internal corporate characteristics and program-based regulatory mechanisms. The findings also have policy implications. Regulatory programs such as PROPER can encourage firms to provide more biodiversity-related information when they combine monitoring, public rating, enforcement signals, and reputational consequences. However, increased disclosure must not be conflated with substantive improvements in biodiversity outcomes. Disclosure requirements should therefore be integrated with science-based ecological indicators, independent verification, site-level monitoring, and compliance mechanisms to ensure that corporate transparency contributes to measurable environmental accountability. This study is subject to several limitations, most notably its focus on environmentally sensitive firms within the Indonesian context, which may constrain the generalizability of the findings to jurisdictions with divergent institutional and regulatory frameworks. PROPER captures formal regulatory pressure but may not fully reflect informal enforcement, political influence, media scrutiny, or local institutional variation. To advance this field, subsequent studies ought to adopt comparative cross-national designs and account for the influence of corporate governance and ownership structures. Crucially, research must bridge the gap between reporting and reality by linking disclosure data to verifiable ecological outcomes. Such research would help clarify whether increased disclosure leads to actual biodiversity conservation improvements or mainly strengthens transparency.

AUTHOR CONTRIBUTIONS

M. Almunawwaroh conceived the research idea, collected the data, constructed the biodiversity disclosure index, conducted the statistical analysis, interpreted the results, and prepared the initial manuscript draft. D. Suhardjanto, the corresponding author, supervised the research, contributed to the conceptual framework and methodology, interpreted the findings, and critically revised the manuscript. S. Honggowati supervised the research process, contributed to the development of the measurement framework, and reviewed the manuscript draft. W. Widarjo contributed to the methodological design, data analysis, interpretation of the results, and revision of the 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, were observed by the authors.

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ABBREVIATIONS

%	Percent
2SLS	Two-stage least squares
DV	Dependent variable
ESG	Environmental, social, and governance
Eq.	Equation
FE	Fixed effects
Fig.	Figure
IV	Instrumental variable
L1_PROPER	One-period lag of program for pollution control, evaluation, and rating
Lev	Leverage
NGO	Non-governmental organization
OLS	Ordinary least squares
Prof	Profitability
PROPER	Program for pollution control, evaluation, and rating
RLE	Red list of ecosystems
SD	Standard deviation
SE	Standard error
SEEA	System of environmental-economic accounting
USD	United States dollar

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ORIGINAL RESEARCH ARTICLE

Ecological risk assessment for phytomelioration planning of a dried sea-bed

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ABSTRACT

BACKGROUND AND OBJECTIVES: The Aral Sea disaster is widely recognized as one of the worst human-caused environmental catastrophes of the twentieth century. The study objectives were to provide a comprehensive ecological assessment of the dried Aral Sea-bed in Kazakhstan to support phytomelioration planning.

METHODS: Field work was carried out from 24 April to 20 May 2023, covering an area of 1,071,967 hectares. The study combined climate analysis (1991-2024 data), groundwater surveys (27 observation wells), soil studies (68 soil pits, 348 samples), and vegetation mapping (93 plots) using geographic information system and remote sensing tools. By December 2023, laboratory analyses had been finalized. The mapping of ecological risk zones was conducted through the application of weighted overlay analysis with six parameters.

FINDINGS: The study documented extreme desert conditions with only 120 millimeters of annual rainfall and a humidification coefficient K = 0.20. By the year 2050, it is anticipated that the average annual air temperature will rise by 2.0-2.8 degrees Celsius in comparison to the current climate. The groundwater exhibited a high salinity level, varying from 37.6 to 104.6 grams per liter, depths of 1.2 to 5.2 meters. Soils were mostly solonchaks with surface salt content reaching 35.9 percent. A total of 368 plant species were recorded, and black saxaul (*Haloxylon aphyllum*) plantations exhibiting survival rates ranging from 22 percent and 100 percent. Four distinct classes of forest site conditions were established: favorable (7 percent), marginally favorable (34 percent), unfavorable (27 percent), and unsuitable (32 percent).

CONCLUSION: Using six weighted parameters, four ecological risk zones were mapped: low (7 percent), moderate (37 percent), elevated (25 percent), and high (31 percent). The high-risk regions align with bare solonchaks and migrating dunes, identified as the principal contributors to salt-dust storms. The four-tier forest site classification system developed in this study, specifically calibrated for groundwater salinity levels up to 104.6 grams per liter, provides a preliminary scientific foundation for phytomelioration planning under Kazakhstan's National Afforestation Program.

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46	7	6

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INTRODUCTION

The desiccation of the Aral Sea is one of the most striking examples of large-scale anthropogenic environmental change in the twentieth century. Historically recognized as the fourth-largest inland lake globally, the Aral Sea has experienced a significant reduction in both its volume and surface area since the 1960s due to prolonged river diversion for irrigation purposes. This transformation has produced a vast new desert, commonly referred to as the Aralkum, across the exposed sea-bed (Micklin, 2007; Gaybullaev *et al.*, 2012). Covering over 5.5 million hectares (Mha), the Aralkum has become one of the largest human-made deserts in the world, comparable in scale to desertification processes in the Sahel, Australian rangelands, and the margins of the Gobi. Insights gained from restoration initiatives in this area are pertinent to the approximately 1.5 billion hectares (Gha) of degraded drylands worldwide. Before the 1960s, the Aral Sea was the world's fourth-largest lake, covering about 68,000 square kilometers (km^2) and containing more than 1,000 cubic kilometers (km^3) of water (Zavialov, 2005). Nevertheless, the substantial redirection of the Amu Darya and Syr Darya rivers for irrigation, especially for cotton farming, drastically decreased the inflow to the sea (Micklin, 2016). As a result, the Aral Sea has now lost over 90 percent (%) of its water volume and 74% of its surface area, while the exposed seabed has been transformed into the Aralkum desert (Opp *et al*., 2017; Issanova and Abuduwaili, 2017). The decline of the Aral Sea has resulted in extensive environmental damage. This encompasses alterations in local weather patterns, frequent salt-dust storms, loss of plant and animal species, and a deterioration in public health (Crighton *et al.*, 2011; Anchita *et al.*, 2021). Recent studies indicate that the sea's drying has increased atmospheric dust loading over Central Asia by 7% over the past thirty years, with yearly dust emissions from the Aralkum rising from 14 to 27 million tonnes (Mt) (Banks *et al.*, 2022; Chen *et al*., 2022). Dust storms composed of salt particles that arise from the dried Aral Sea-bed (DASB) have the potential to traverse hundreds of kilometers, thereby exacerbating soil salinization and diminishing crop yields in agricultural areas (Nishonov *et al.*, 2023; Wang *et al.*, 2022). Extreme climatic events, including heatwaves, strong windstorms, and salt-dust storms, play a critical role in shaping the dried sea-bed landscape (Nishonov *et al*., 2023; Banks *et al*., 2022) and were explicitly incorporated into the ecological risk assessment as the highest-weighted parameters. The influence on the glaciers of the Pamir and Tien Shan is especially concerning. Dark dust particles deposited on glacier surfaces reduce albedo and accelerate melting, threatening water resources for more than one billion people who depend on runoff from Central Asian mountain systems (Xi and Sokolik, 2015). Simultaneously, recent findings indicate that close to two-thirds of dust emissions take place when the sky is overcast, which poses challenges for tracking them with standard satellite techniques (Banks *et al*., 2022). Climatic changes induced by the Aral Sea's desiccation include an increase in mean annual air temperature by 2-6 degrees Celsius (°C) during summer months, amplification of diurnal temperature ranges, a 23% reduction in relative humidity in the coastal zone, and intensification of aridity (Small *et al.*, 1999; Lioubimtseva, 2014). Based on climate forecasts, it is anticipated that the air temperature in the area will rise by 2.5-3.3°C by the year 2050, which will exacerbate evaporation and heighten regional aridity (Wang *et al.*, 2023; Chen *et al.*, 2016). Modeling studies indicate that the sea's desiccation itself accounts for 50-66% of the observed warming in the region (Khan *et al*., 2004). One key way to mitigate the adverse effects of the Aral Sea's decline is phytomelioration – planting protective vegetation on the DASB (Wucherer *et al*, 2012a). The main species employed for this objective is black saxaul (*Haloxylon aphyllum*), a shrub that exhibits tolerance to drought and salt, making it adapted to extreme desert environments (Dimeyeva *et al*.,

2012). A mature saxaul plant can hold up to 4 tonnes (t) of blowing sand, and in 7-year-old plantations, wind speed drops to near zero, stopping salt-dust storms (UNDP, 2024a). In Uzbekistan, saxaul has been planted on 1.8 Mha of the 2.9 Mha of the DASB (UNDP, 2024b). In Kazakhstan, planting began in 1988, with plans to cover 1.1 Mha by 2025 (Ministry of Ecology and Natural Resources of Kazakhstan, 2024). However, planting success varies greatly depending on local soil and groundwater conditions. Previous studies indicates that the survival rates of saxaul vary between 0.12% and 78%, influenced by factors such as soil texture, salinity, and groundwater depth (Salmukhanbetova *et al*., 2021; Dimeyeva and Permitina, 2006). Interannual climate variability, including drought years and occasional wetter periods, further influences these outcomes. In years of drought, diminished rainfall coupled with heightened evaporation speeds up the upward movement of salt via capillary action, which raises salinity levels in the root zone and decreases the survival rates of saxaul rates. Research in the Aral Sea region confirms that when groundwater depth is less than 7–8 m, groundwater salinity exerts a stronger negative effect on vegetation development than precipitation provides a positive effect (An *et al*., 2022). These dynamics underscore the necessity for long-term climate-conscious strategies in phytomelioration planning. In wetter periods, increased precipitation enhances groundwater recharge, temporarily lowering salinity concentrations and improving conditions for saxaul establishment. A crucial element for the effective growth of saxaul is the presence of a sandy layer exceeding 100 centimeters (cm) in thickness, characterized by low salt content in the root zone (Matsui *et al*., 2019). In areas with heavy soils, high clay content, and high salinity, seedling death rates reach 75-100%. On crusty and puffy solonchaks, saxaul survival stays below 10%, meaning the soil must be treated first or more salt-tolerant species like Halocnemum strobilaceum should be used (Wucherer *et al.*, 2012b). A comparable method for landscape evaluation was applied in the zoning the Syr Darya River delta (Zinabdin *et al*., 2022). That work combined natural, social, economic, and environmental factors to create land use guidelines for the ecological disaster zone. Recent study on the ecological zoning of the Aral Sea underscores the importance of a thorough investigation into the ecological conditions of the Aral Sea (Bao *et al*., 2024). The authors note that the absence of regional planning and zoning leads to unsatisfactory outcomes of environmental measures. Integration of data on soil types, salinity, groundwater levels, normalized difference vegetation index (NDVI), and aerosol optical depth enables the creation of a scientifically grounded basis for phytomelioration planning. The Kazakhstan part of the DASB covers about 3 Mha and is officially an ecological disaster zone (Law of the Republic of Kazakhstan, 1992). Despite extensive research, comprehensive studies on groundwater and soil in the eastern DASB, including laboratory analysis, had not been performed prior to this. This lack of data hinders optimal site selection for the best sites for planting and to plan long-term forest growth. Unlike the Uzbekistan part of the DASB, where planting efforts have been well studied (UNDP, 2024b; Novitskiy, 2012), the Kazakhstan sector lacks baseline data that combines groundwater, soil, and plant information in one spatial framework. Also, no previous study has established quantitative standards for rating forest site conditions at the extreme salt levels with over 60 grams per liter (g/L) found in the eastern DASB. Phytomelioration of dried lake beds has been studied in several regions worldwide. In Lake Urmia, located in Iran, vegetation-oriented restoration techniques encounter comparable difficulties related to severe soil salinity and dust generation, although groundwater salinities rarely go beyond 50 g/L (Parsinejad *et al*., 2022). The present study addresses conditions of significantly higher groundwater salinity (up to 104.6 g/L), representing an extreme case not previously

covered by existing classification frameworks. The deficiency in knowledge restricts the planning associated with Kazakhstan's National Afforestation Program for the period of 2021-2025. This study differs from previous work in the Aral Sea region in four fundamental ways. First, it provides the first field-based ecological assessment of the eastern Kazakhstan DASB sector (1,071,967 ha) with integrated hydrogeological, pedological, and geobotanical data — previous studies (Bao *et al*., 2024; Novitskiy, 2012) focused predominantly on the Uzbekistan sector. Second, the forest site classification system established in this context is meticulously adjusted for extreme groundwater salinity levels reaching up to 104.6 g/L, which is considerably greater than the 25–60 g/L range considered in frameworks based in Uzbekistan (Novitskiy, 2012). Third, this study introduces quantitative scoring criteria for site selection that integrate groundwater salinity, soil texture, and vegetation indicators into a single decision-support tool applicable under Kazakhstan's National Afforestation Program. Fourth, the identification of Atriplex pratovii communities as reliable bioindicators of favorable planting conditions (85–100% saxaul survival) represents a novel practical contribution not previously documented for the Kazakhstan DASB. The purpose of this study was to carry out a detailed ecological evaluation of the eastern Kazakhstan DASB to enhance phytomelioration planning. The objectives of the study were: 1) describe climate conditions and predict future changes; 2) map groundwater depth and salt content; 3) classify soil types and assess their suitability for tree planting; 4) study plant communities and existing saxaul plantations; and 5) create ecological risk zones to inform management decisions. As a consequence of this study, four unique forest site condition categories were identified within the DASB, and species specific planting suggestions were created for every classification. Using six environmental parameters with weighted overlay analysis, an ecological risk zoning map was produced that identifies priority areas for intervention. The findings show that only 7% of the territory has favorable conditions for afforestation, while 31% falls within high-risk zones that serve as the main sources of salt-dust storms. The four-tier classification framework created in this study, specifically adjusted for groundwater salinity levels of up to 104.6 g/L, marks a significant enhancement over prior strategies aimed at the less saline region of Uzbekistan. These results contribute to the scientific basis for phytomelioration planning, recognizing that the limitations of sampling and the reliance on expert weighting necessitate additional validation under Kazakhstan's National Afforestation Program and can be applied to other degraded drylands encountering comparable issues. The study was conducted in the eastern part of the DASB within the Aral District of Kyzylorda Region, Kazakhstan, and field investigations were carried in 2023.

MATERIALS AND METHODS

Study area

The study area covers the eastern part of the DASB in Kazakhstan, lying between 44°30’-46°05’N and 59°45’- 61°07’E in the Aral District of Kyzylorda Region (Fig. 1). The area totals 1,071,967 hectares (ha), stretching from the old shoreline at 53 m elevation (1960 water level) to the current edge of the eastern Large Aral Sea. Ground elevations vary from 53 meters (m) in the eastern region to between 25 and 30 m in the western area.

Data

Data were collected through fieldwork conducted on the DASB, in addition to archival resources: 1:500,000 scale maps, the soil map from the Atlas of functional zoning of Aral district (2016), and climate data sourced from Kazhydromet for 1991-2024. Climate data came from two weather stations (Kulandy and Kaukei) run by the Republican state enterprise (RSE) "Kazhydromet" under Kazakhstan's Ministry of ecology and natural resources.

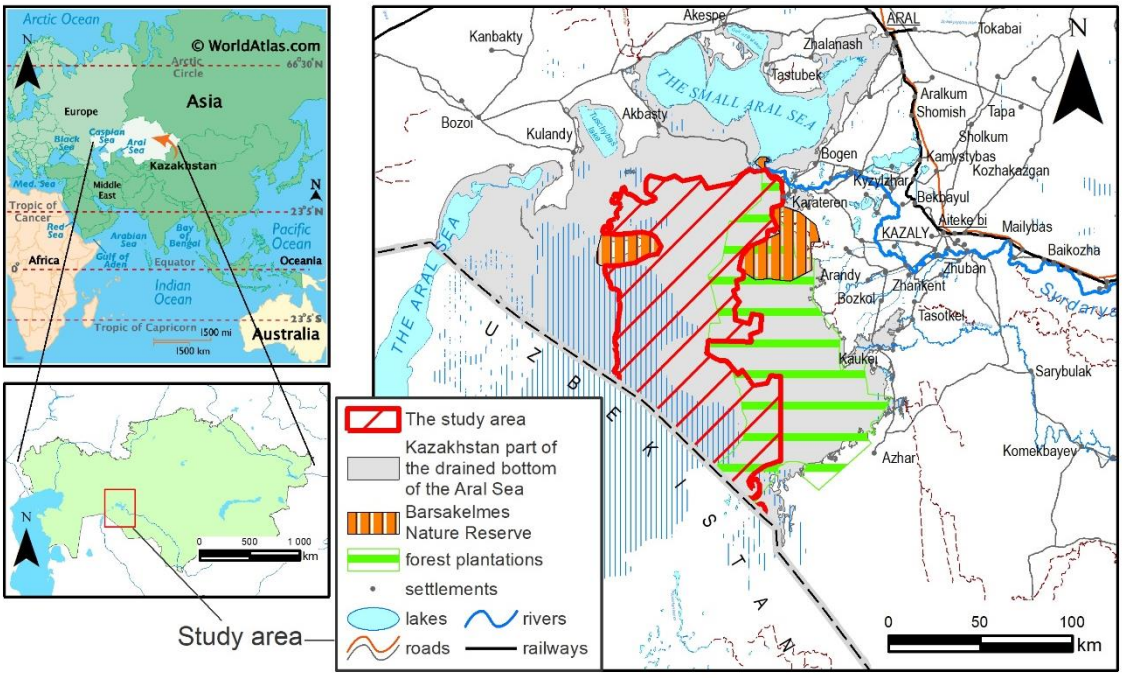

Fig. 1: Geographical location of the study area in the eastern part of the DASB within the Aral District of Kyzylorda Region, Kazakhstan

Field investigations

Field work took place from 24 April to 20 May 2023, during the spring pre-growing season. The research team included specialists in climate, groundwater, soil science, botany, geographic information system (GIS), and remote sensing. Sampling locations were predetermined using satellite imagery to encompass all types of landscapes within the study area. The sampling strategy was designed to achieve spatial representativeness across the eight identified landscape units of the study area. Sampling points were allocated in proportion to all significant soil types and vegetation communities identified through preliminary remote sensing analysis that utilized Sentinel-2 and Landsat imagery. The sampling density of 27 groundwater wells (1 well per 39,700 ha), 68 soil pits (1 pit per 15,800 ha), and 93 vegetation plots (1 plot per 11,500 ha) reflects the logistical constraints of operating in a remote, roadless hyperarid environment, and is consistent with sampling densities reported in comparable large-scale dryland surveys (Bao *et al*., 2024; Salmukhanbetova *et al*., 2021). Spatial interpolation employing application of kriging techniques in ArcGIS 10.8 was conducted to produce continuous maps from point data, thereby minimizing the influence of restricted sampling density on the overall accuracy of the final map. Laboratory analyses were finished by December 2023, followed by full data processing, GIS mapping, spatial analysis, and manuscript writing during 2024-2025. For climate study, long-term averages (1991-2023), mean maximum and minimum values, and extreme values of weather parameters were calculated. To measure moisture during the growing season, the humidification coefficient during the growing season (K) was used, which combines cold-season rainfall (November-April), rainfall from the warm season, and the cumulative daily temperatures recorded during the growing season (May-August) (Baisholanov *et al*., 2025; Baisholanov *et al*., 2017). To measure growing season drought, the Selyaninov hydrothermal coefficient (HTC) was used, which combines rainfall and the sum of daily

temperatures for May-August (Baisholanov *et al*., 2025; WMO and GWP, 2016). A day characterized by a hot and arid wind was identified by a deficiency in humidity during the midday hours. A day counted as a hot dry wind day if the humidity deficit at noon was above 20 hectopascal (hPa) (weak), 30 hPa (moderate), or 40 hPa (intense) with wind speed below 8 meters per second (m/s) (Baisholanov *et al.,* 2017). For groundwater study, observation wells were manually drilled, and water samples were gathered. Samples were sourced from drilled wells, existing wells, and surface water. Full chemical analysis was done at the certified laboratory of the U.M. Akhmedsafin Institute of Hydrogeology and Geoecology (Almaty, Kazakhstan, certificate KZ.T.02.0782). For the purpose of soil analysis, soil pits were dug to a depth of 1.5 m, and samples were collected. Analysis was done at the U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry (Almaty, Kazakhstan). Particle size was determined using the Kachinsky method according to GOST (Gosudarstvennyy Standart) 12536-79, while water-soluble salts, including electrical conductivity, pH, calcium, and magnesium in water extracts, were analyzed following GOST 26423-85 and GOST 26428-85. Carbonate content, potential of hydrogen (pH), organic matter (Tyurin method), total nitrogen and phosphorus, and exchangeable bases were also determined. For the purpose of studying plants, the species, plant cover, and community structure were observed and recorded in plots of 100 square meters (m^2) plots. All field points were mapped using global navigation satellite system (GNSS) equipment (Spectra SP60). Drone surveys (DJI Phantom 4 Multispectral, 15 flights, 2,906 RGB images and 12,130 multispectral images) were conducted to obtain high-resolution data. To map ecological risk zones, weighted overlay analysis was conducted utilizing six factors: 1) K (weight 0.4); 2) number of dust storm days per year (weight 0.4); 3) surface soil salt content (weight 0.3); 4) soil particle size (weight 0.3); 5) NDVI vegetation index (weight 0.2); and 6) groundwater salinity (weight 0.1). Prior to integration into the weighted overlay analysis, all input variables were standardized and categorized into four equal-interval score classes (1–4). Climate parameters (K and dust storm days) were derived from long-term station data (1991–2024) and spatially interpolated using inverse distance weighting. Soil salinity and texture data from 68 pits were processed using kriging in ArcGIS 10.8. NDVI was calculated from Sentinel-2 multispectral imagery (May 2022) in ENVI 5.4 and resampled to match the 1:500,000 map scale. The allocation of weight was determined according to a hierarchy of ecological significance for the establishment of saxaul in hyperarid saline environments, as supported by literature. Moisture availability (K and dust storm frequency) received the highest weights (0.4 each) because water deficit is the primary limiting factor for initial seedling survival in arid ecosystems (Matsui *et al*., 2019; Baisholanov *et al*., 2025). Soil properties (salinity and texture) received intermediate weights (0.3 each) as they determine root-zone conditions after establishment (Salmukhanbetova *et al*., 2021). The groundwater salinity was given the least weight, at 0.1, because it primarily influences the survival of mature plants instead of the initial establishment phase (Wucherer *et al.,* 2012b). The weights were assigned using an expert-based prioritization approach analogous to the Analytic Hierarchy Process (AHP) principle, where pairwise comparisons of parameter importance were made based on published phytomelioration literature. A preliminary sensitivity evaluation was undertaken by modifying individual weights by ±0.1 while keeping the other weights constant; the resulting risk zone boundaries shifted by less than 5% of total area, thus affirming the robustness of the weighting scheme. Prior to analysis, the six raw weights (sum = 1.7) were normalized by dividing each by the total sum, yielding normalized weights of: K = 0.235, dust storm frequency = 0.235, soil salinity = 0.176, particle size = 0.176, NDVI = 0.118, and groundwater salinity = 0.059 (sum = 1.000), as required for weighted overlay analysis in ArcGIS

10.8. The six parameters were identified due to their recognized function as major factors influencing the establishment and survival of saxaul in hyperarid saline environments. The selection criteria prioritized: (1) direct influence on plant water availability (K, dust storm frequency); (2) root-zone soil conditions (salinity, texture); (3) vegetation status (NDVI); and (4) groundwater quality. Wind erosion intensity is indirectly measured by the frequency of dust storms, which serves as an indicator of aeolian activity across the study area. Soil moisture variability is represented by the humidification coefficient K, which integrates precipitation and temperature data. Salt crust dynamics are reflected in the surface soil salinity parameter. While other elements could improve the analysis, the six identified parameters are the most consistently measurable and spatially interpolatable variables available for this remote and data-sparse context. Forest site conditions were rated using a scoring method with four parameters and weights (Table 1). Based on total scores, four forest site condition classes were defined: favorable (3.1-4.0), marginally favorable (2.1-3.0), unfavorable (1.1-2.0), and unsuitable (≤1.0). Map work and spatial analysis were done in ArcGIS 10.8 at 1:500,000 scale. While field investigations were conducted within the eastern Kazakhstan DASB (1,071,967 ha), the weighted overlay analysis and ecological risk zoning were applied to the full Kazakhstan DASB extent (~3,086,004 ha) using spatially interpolated layers derived from field data. Consequently, the areas classified as risk zones, as indicated in Table 6, pertain to the entire Kazakhstan DASB. The ecological risk zones were validated by overlaying the delineated risk map with a Sentinel-2-derived NDVI map of the study area (imagery acquired 16–23 May 2022, cloud cover <5%), processed in ENVI 5.4. Low-risk zones (7% of the area) spatially corresponded to NDVI values above 0.075, indicating established vegetation cover, while high-risk zones coincided with NDVI values below 0.025, confirming bare salt-affected surfaces. This strategy is in accordance with NDVI-based validation approaches utilized in analogous dryland studies (Duan et al., 2024), and confirms the reliability of the delineated risk zones.

RESULTS AND DISCUSSION

Current climate

To define the present climate conditions of the DASB region, long-term data spanning from 1991 to 2024 were examined from the Kulandy and Kaukey meteorological stations (Table 2). The DASB region is defined by a dry desert climate that exhibits significant continental characteristics. Average annual air temperature approximates 10.0°C, with average January temperature around -9.0°C (absolute minimum -33.5°C) and average July temperature around 27.5°C (absolute maximum 45.7°C). Spring frosts typically conclude by 11 April, with a frost-free duration extending for 185 days until 12 October. Spring starts on 10 March, summer on 22 April, autumn on 25 September, and winter on 15 November. Summer lasts 156 days; winter lasts 115 days. The heat resources for growing heat-loving crops are 3600°C (above 15°C). The annual precipitation is notably low, estimated at around 120 millimeters (mm), with about 60 mm occurring during the warmer season. Average annual relative humidity is approximately 55%, characterized as reduced humidity. In the warm season, dry air with humidity levels below 30% dominates the daytime for a duration of 160 days. Throughout the year, weak winds predominate with speeds of 3-4 m/s. The growing season K averages 0.20, indicating severe moisture deficit. The drought index HTC indicates severe aridity at 0.10-0.12. Beginning in early May, hot dry wind conditions last for 150 days, concluding on September 20. Intensive hot dry winds causing intensive evaporation and plant tissue dehydration persist for 40-50 days. The occurrence of dust storm days escalates from 20 days in the east to 50 days in the west throughout the DASB.

Table 1: Criteria for scoring assessment of forest site conditions

Parameter	Score 4	Score 3	Score 2	Score 1	Weighting Coefficient
Soil salinity	0-2%	2-4%	4-10%	>10%	0.4
Particle size distribution	Sandy/loamy sand	Light loam	Medium loam	Heavy loam	0.3
Groundwater mineralization	up to 45 g/L	45-50 g/L	50-60 g/L	>60 g/L	0.2
Groundwater depth	1-2 m	2-3 m	3-5 m	0-1 m and >5 m	0.1

Table 2: Main indicators of the current climate in the DASB territory

Indicator	Value
Average annual air temperature	9.7-10.3°C
Average January air temperature (absolute minimum)	-8.2 to -9.2°C (-33.5°C)
Average July air temperature (absolute maximum)	27.5-27.7°C (+45.7°C)
Frost-free period (duration)	11.04-12.10 (185 days)
Onset dates of spring, summer, autumn, winter (duration of spring, summer, autumn, winter)	10.03; 22.04; 25.09; 15.11 (43 days; 156 days; 51 days; 115 days)
The sum of the average daily air temperatures above 15°C	3600-3680°C
Annual precipitation (warm period)	110-124 mm (56-62 mm)
Average annual relative humidity (July)	54-57% (33-37%)
Number of days with minimum relative humidity ≤30%	160 days
Average annual wind speed (March)	3.2-3.5 m/s (3.6-4.0 m/s)
K	0.18-0.20 (severe moisture deficit)
Drought index - Selyaninov HTC	0.10-0.12 (severely arid)
Number of days with hot dry winds (intensive hot dry winds)	144-150 days/year (40-50 days/year)
Number of days with dust storms	20-50 days/year

Expected climate change

The RSE Kazhydromet makes a forecast of air temperature and precipitation. For this purpose, Models of the General circulation of the atmosphere and ocean (MGCAO) recommended by the Intergovernmental Panel on Climate Change (IPCC) are used within the framework of the coupled model intercomparison project (CMIP) global climate Models. The predictions are derived from information obtained from updated iterations of climate models that were involved in the sixth phase of the global initiative aimed at comparing coupled general circulation models and Earth system models (CMIP6). CMIP6 models include new and better representations of physical, chemical, and biological processes, as well as higher resolution (Eighth National Communication, 2022; CMIP Phase (2023)). The 6th phase of the project (CMIP-6) uses SSP-RCP scenarios. Shared socio-economic pathway (SSP) signifies collective approaches to socio-economic development. Representative concentration pathway (RCP) is characterized as a representative trajectory depicting the concentration of atmospheric contaminants, which encompasses greenhouse gases and aerosols. SSP is the number of the socio-economic development path (1, 2, 3, 4, 5), and RCP is the amount of radiation balance (1.9; 2.6; 3.4; 4.5; 6.0; 7.0; 8.5 watts per square meter (W/m^2)). For example, the SSP5-8.5 scenario considers path number 5, and the radiation balance value is 8.5 W/m^2 (O'Neill *et al*., 2016). The rates of model predictions regarding scenarios of human influence on the climate system are described as follows: weak climate change scenario - SSP1-2.6; moderate climate change scenario - SSP2-4.5; severe climate change scenario - SSP5-8.5. As part of the preparation of the Eighth National Communication of the Republic of Kazakhstan on Climate Change, the climatologists of Kazhydromet RSE have made forecasts of the future climate of Kazakhstan. The SSP2-4.5 and SSP5-8.5 scenarios were used here (Eighth National Communication, 2022). According to scenarios SSP2-4.5 and SSP5-8.5 (CMIP-6), the following climate change is predicted on average in Kazakhstan (Eighth National Communication, 2022): 1) the average

annual air temperature will increase by 2.5-3.3°C by 2050, and by 3.6-6.8°C by 2090; 2) Annual precipitation will change by 7-8% by 2050 and by 11-14% by 2090. According to this data, the anticipated climatic conditions for the DASB region have been projected for the year 2050. According to scenarios SSP2-4.5 and SSP5-8.5, the climatologists of Kazhydromet calculated the expected changes in monthly air temperatures by 2050 (average for 2041-2060) relative to the average air temperature values for the period 1986-2005 at the nodes of the coordinate grid of latitude 1° by longitude 1°. The computations encompassed the region extending from 34.5° to 59.5° latitude and from 41.5° to 92.5° longitude. Values representing the anticipated fluctuations in monthly air temperatures across the DASB area were assembled. Based on long-term data at the Kulandy and Kaukey weather stations, the average monthly air temperature values for the period 1986-2005 were determined. Subsequently, the associated values of anticipated variations in monthly air temperatures were incorporated into these long-term averages. Thus, the average monthly air temperature values expected by 2050 were determined in accordance with the climate change scenarios SSP2-4.5 and SSP5-8.5. According to the scenarios SSP2-4.5 and SSP5-8.5, the climatologists of Kazhydromet have computed the anticipated alterations in monthly precipitation levels as a percentage by the year 2050 (averaged over 2041-2060), in relation to the average figures for the period 1986-2005, at the nodes of the coordinate grid of latitude 1° by longitude 1° (Table 3). Samples of the expected changes in monthly precipitation amounts across the DASB territory were made. Based on long-term data, monthly precipitation amounts for the period 1986-2005 were determined at 2 weather stations. Subsequently, the anticipated monthly precipitation totals for the period of 2050 (2041-2060) were established. The K and the HTC were calculated based on the expected air temperature and precipitation by 2050. By 2050, compared with the current climate (average for 1991-2024), according to the SSP2-4.5 scenario, the air temperature will increase by an average of 2.0°C per year, by 2.8°C in January, and by 2.0°C in July. According to the SSP5-8.5 scenario, the air temperature will increase by an average of 2.8°C per year, by 3.7°C in January, and by 2.9°C in July. Consequently, by the year 2050, the overall air temperature exceeding 15°C is projected to rise by 200-330°C. By 2050, a slight change in precipitation is expected, by minus 1% - plus 2%. Simultaneously, an increase in precipitation is anticipated during the winter months, while a decrease is expected in the spring and summer months. The annual precipitation is expected to increase by 5-8 mm according to the SSP2-4.5 scenario, by 6-9 mm according to the SSP5-8.5 scenario. In the warm season, precipitation is expected to increase by 3-4 mm according to the SSP2-4.5 scenario, and by 4-5 mm according to the SSP5-8.5 scenario. Consequently, by the year 2050, a minor decline in the values of K and HTC is anticipated, suggesting a slight rise in the aridity of the growing season.

Groundwater

A total of 27 observation wells were manually drilled to depths ranging from 1.3 to 5.2 m. Groundwater samples were obtained from these 27 drilled wells, in addition to 2 pre-existing wells, and 3 surface water bodies. Complete chemical analysis of water samples was performed. The top aquifer lies in recent marine deposits 1-8 m thick (Table 4, Figs. 2 and 3). Groundwater depth ranges from 1.2 to 5.2 m (average 2.7 m). The salinity levels are significantly high, ranging from 37.6 to 104.6 g/L, with an average of 65.4 g/L. The water exhibits chloride-sulfate sodium chemistry and a pH value between 7.63 and 7.95. The extremely high groundwater salinity is the main barrier to planting. Even highly salt-tolerant species grow worse when salinity tops 60 g/L (Dimeyeva and Permitina, 2006). The present study revealed that 78% of wells recorded salinity levels exceeding this threshold, elucidating the reason for the minimal land available for agricultural purposes.

Table 3: Main climatic indicators in the DASB territory by 2050

Indicator	Scenario	Value
Average annual air temperature	SSP2-4.5	11.7-12.2°C
	SSP5-8.5	12.5-13.0°C
Average January air temperature	SSP2-4.5	-5.4 to -6.4°C
	SSP5-8.5	-4.5 to -5.5°C
Average July air temperature	SSP2-4.5	29.5-29.7°C
	SSP5-8.5	30.4-30.6°C
The sum of the average daily air temperatures above 15°C	SSP2-4.5	3800-3860°C
	SSP5-8.5	3930-4000°C
Annual precipitation (warm period)	SSP2-4.5	115-132 mm (59-66 mm)
	SSP5-8.5	116-133 mm (58-64 mm)
K	SSP2-4.5	0.17-0.20 (severe moisture deficit)
	SSP5-8.5	0.17-0.19 (severe moisture deficit)
Drought index - Selyaninov HTC	SSP2-4.5	0.10-0.11 (severely arid)
	SSP5-8.5	0.10-0.11 (severely arid)

Table 4: Characteristics of groundwater in the modern marine aquifer

Parameter	Range	Average
Depth to water table, m	1.2-5.2	2.7
Mineralization, g/L	37.6-104.6	65.4
pH	7.63-7.95	-
Hardness, milligram equivalents per liter (mg-eq/L)	115-345	-
Chemical composition	chloride-sulfate sodium	-

Soil tests show that salt buildup in the surface layer (up to 35.9%) from water rising through capillary action creates toxic conditions in root zones on heavy soils. The results align with the conclusions drawn by Matsui *et al*. (2019) regarding the critical role that sandy layer thickness (greater than 100 cm) plays in the successful establishment of saxaul. In areas with heavy soil texture and shallow groundwater (under 2 m), survival in the present study was below 35%. Seasonal fluctuations in groundwater depth further amplify this process. During the warm season, which spans from May to August, significant evaporation induces an upward capillary movement of saline groundwater, resulting in root-zone salinity levels that can increase by as much as 2 to 3 times in comparison to those observed in spring (An *et al*., 2022). In the study area, groundwater depths of 1.2–5.2 m create varying capillary rise intensities across the landscape, directly determining the spatial distribution of surface salt accumulation patterns observed in soil surveys (0.157–35.867%). Shallow groundwater zones (below 2 m) with significant salinity (greater than 60 g/L) are thus the least appropriate for phytomelioration regardless of soil texture. Under field conditions in the study area, *Haloxylon aphyllum* demonstrated measurable growth at groundwater salinities up to 60 g/L when combined with sandy soil texture and adequate depth (1–2 m). Above this threshold, survival rates dropped below 25%, consistent with the findings of Dimeyeva and Permitina (2006) and Matsui *et al*. (2019). The texture of the soil affects the salinity threshold: saxaul is able to endure greater groundwater salinity in sandy soils due to a lower intensity of capillary rise. Conversely, in heavy loam soils, the effective tolerance threshold is diminished, as salt accumulation in the root zone occurs more swiftly under the same groundwater conditions. Fig. 2 demonstrates the spatial gradient of groundwater depth, ranging from 1.2 m in the western hydromorphic zone to 5.2 m in the eastern elevated areas, with the shallowest depths concentrated near the current shoreline. As depicted in Fig. 3, groundwater with extreme salinity levels greater than 60 g/L occupies 78% of the study area, while the highest salinity values, exceeding 90 g/L, are primarily located in the central solonchak zone.

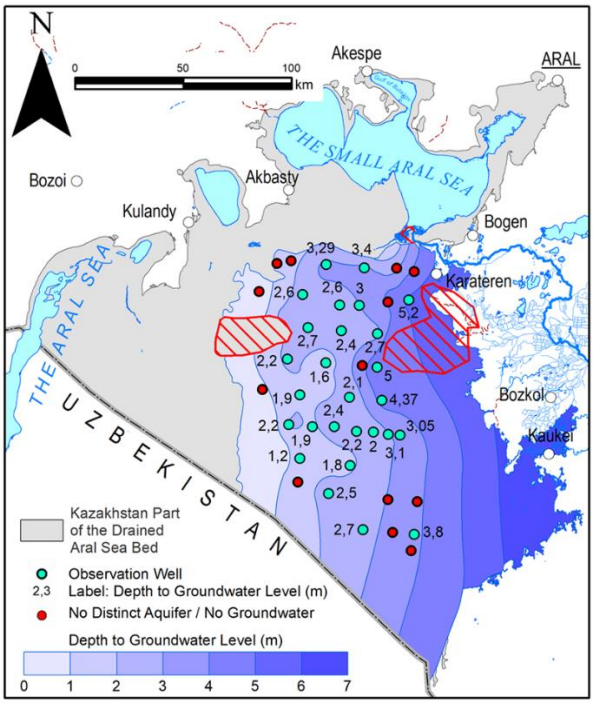

Fig. 2: Groundwater depth contour map

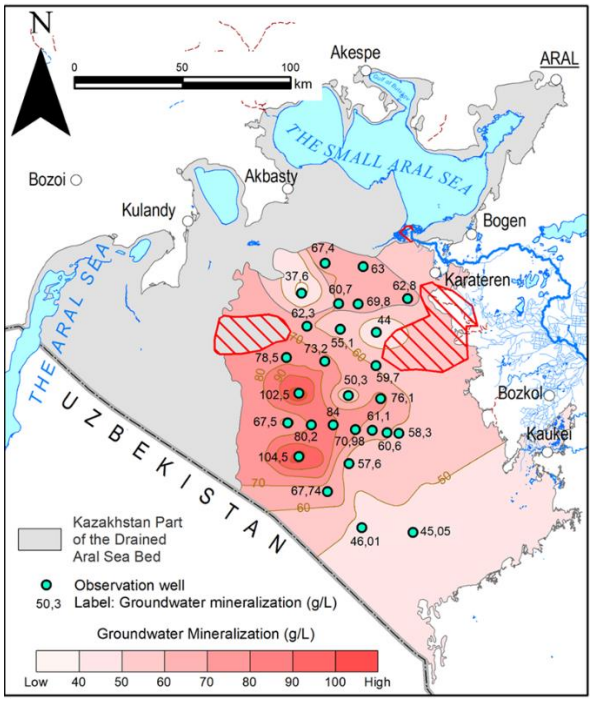

Fig. 3: Groundwater mineralization map

Soils

A total of 68 soil pits were analyzed to 1.5 m depth and 348 soil samples were collected. Particle size, salt content, carbonate, pH, organic matter, nitrogen, phosphorus, and exchangeable bases were tested. Eight soil types were identified, grouped into five main categories (Fig. 4): wind-blown sands (stabilized sandy soils), crusty salt soils (coastal and typical solonchaks), brown desert soils (desert solonetzic saline soils, brown desert solonetz), waterlogged solonchaks (takyr-like solonchaks, coastal soils with sand cover), and dry-land solonchaks (primitive saline coastal soils). The content of surface salt varies between 0.157% and 35.867%, while the organic matter is between 0.03% and 1.7% (predominantly below 0.5%). The pH levels are observed to range from 8.06 to 9.87. As shown in Fig. 4, crusty solonchaks and waterlogged solonchaks comprise over 70% of the study area, thereby affirming the prevalence of salt-affected soils as the main limitation for afforestation. Four classes of forest site conditions were delineated in (Fig. 5 and Table 1). Favorable, slightly salty soils (0-2%), sandy texture, groundwater at 1-2 m depth with salinity up to 45 g/L; Marginally favorable - salty soils (2-4%), light loam texture, groundwater at 2-3 m depth, salinity 45-50 g/L; Unfavorable - salty soils (4-10%), medium loam texture, groundwater at 3-5 m depth, salinity 50-60 g/L; Unsuitable - very salty soils (over 10%), heavy clay, groundwater within 1 m depth with salinity over 60 g/L. The species recommended for planting are contingent upon the classification of the forest site conditions. In favorable areas, black saxaul (*Haloxylon aphyllum*), Salsola arbusculiformis, Suaeda acuminata, and Atriplex pratovii are recommended. In marginally favorable territories, planting of Tamarix and black saxaul is advisable. In unfavorable areas, planting of the most salt-tolerant species is possible: Halocnemum strobilaceum, Tamarix, black saxaul, Salsola arbusculiformis, and Suaeda. These multi-species recommendations embody a comprehensive strategy that strengthens ecological resilience in contrast to monoculture planting, as the diversity

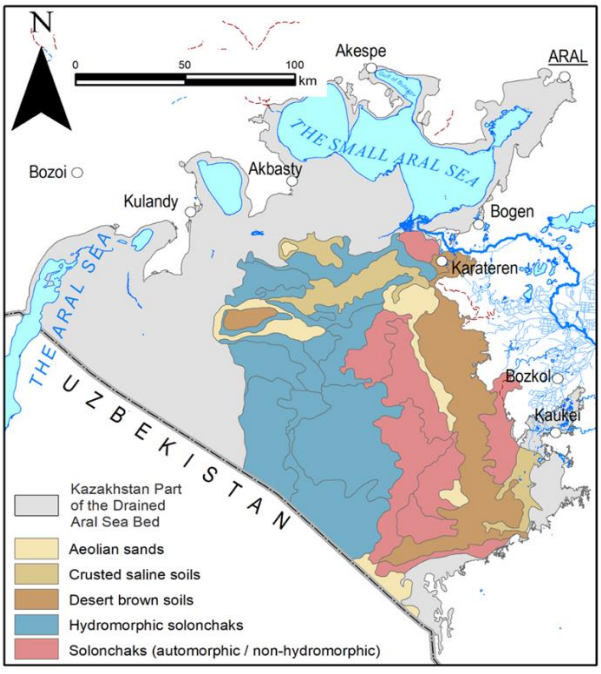

Fig. 4: Soil map of the DASB

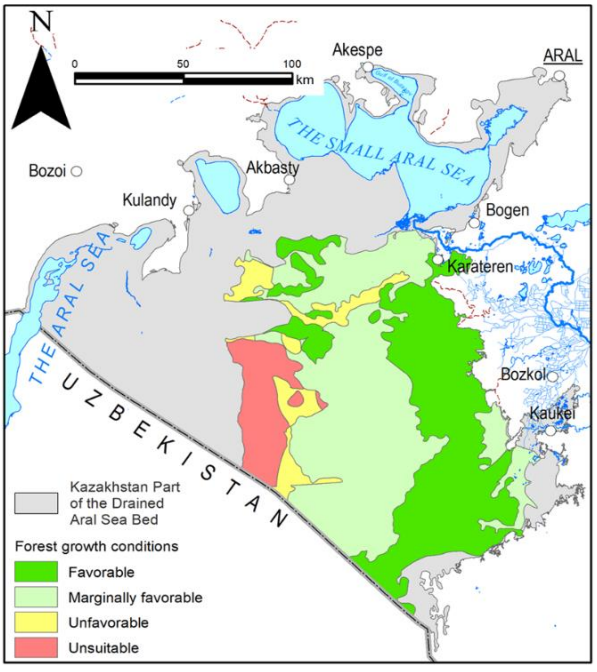

Fig. 5: Forest site conditions map of the DASB

of species enhances resistance to environmental stress and promotes a wider range of ecosystem function. Territories classified as unsuitable are not recommended for planting. As depicted in Fig. 5, the northwestern section of the study area, especially near the river delta influence zones, is characterized by favorable and marginally favorable forest site conditions, while the central and southern areas are predominantly unsuitable

Vegetation and saxaul plantations

A total of 93 plant surveys were conducted on 100 m² plots, recording species, cover, and community structure. The DASB flora has 368 plant species from 43 families and 178 genera. The main families are *Amaranthaceae, Asteraceae, Polygonaceae, Brassicaceae*, and *Poaceae*. Plant cover ranges from 0% to 70%, with most sites at 10-30%. *Atriplex pratovii* communities function as dependable indicators of favorable planting conditions, supporting previous concepts (Novitskiy, 2012). *Haloxylon aphyllum* was selected as the primary phytomelioration species due to its exceptional drought and salinity tolerance, its proven performance in large-scale plantations across the Aralkum (Novitskiy, 2012; Wucherer *et al.,* 2012b), and its sand-fixing capacity of up to 4 t per mature plant. In contrast to other indigenous halophytes found in the area, saxaul showed enhanced survival rates (22–100%) across diverse site conditions in this study. *Halocnemum strobilaceum*, while more salt-tolerant, showed significantly lower biomass production and sand-fixing capacity. Tamarix spp. exhibited strong performance in hydromorphic conditions, yet it is inappropriate for drier, higher regions. This species, classified as red-listed, flourishes in locations with moderate salinity and optimal groundwater conditions, exhibiting a natural ability to remove salt from the surface. Using indicator plants can substantially reduce survey costs. For large-scale planting programs (1.1 Mha by 2025) (Ministry of Ecology and Natural Resources of Kazakhstan, 2024), this approach has significant practical implications. Field data demonstrate that sites with mostly *A. pratovii* had

saxaul survival of 85-100%, while areas with mostly *Halocnemum strobilaceum* had survival below 25%. A total of ten saxaul plantation sites, ranging in age from 3 to 15 years, were analyzed. The stand density varied between 75 and 1,400 plants per hectare, survival rates ranged from 22% to 100%, and the average heights measured between 63 to 231 cm (Table 5 and Fig. 6). Natural seedling density between rows ranged from 1,400 to 52,000 plants/ha. In older plantations, sand mounds 20-40 cm high had formed around plants. Fig. 6 shows that existing saxaul plantations are predominantly located in the northwestern sector, corresponding to areas classified as favorable or marginally favorable in the forest site condition assessment.

Ecological risk zoning

The results significantly enhance the existing knowledge regarding the conditions in the Kazakhstan DASB and offer a scientific foundation for more effective phytomelioration planning. The link identified between saxaul survival and soil-groundwater factors matches what other researchers have reported (Salmukhanbetova *et al*., 2021; Matsui *et al*., 2019) and enables establishment of quantitative criteria for choosing planting sites. Results showed that only 7% of the area has favorable forest site conditions – much less than the 25% reported for the Uzbekistan DASB (Bao *et al*., 2024; Novitskiy, 2012). This difference is attributable to the groundwater characteristics of the eastern sector: more heavy soils and higher salinity (37.6-104.6 g/L versus 25-60 g/L in the western sector). A significant methodological improvement in this research is the four-tier forest site rating system developed for the severe groundwater conditions of the eastern DASB. Unlike earlier rating schemes made for Uzbekistan (Novitskiy, 2012), the scoring system developed here handles groundwater salinity up to 104.6 g/L – far higher than values in past studies. This methodological improvement enables more precise site selection for planting in regions previously considered uniformly unsuitable. A comprehensive evaluation of the DASB territory was carried out using six parameters. The integrated assessment identified the following ecological risk zones within the DASB (Table 6 and Fig. 7): (1) Low risk zone (210,658 ha, 7%) - hydromorphic conditions, projective cover exceeding 30%; (2) Moderate risk zone (1,144,466 ha, 37%) - stabilized sands, degrading meadows; (3) Elevated risk zone (763,391 ha, 25%) - crusty solonchaks, weakly stabilized sands; (4) High risk zone (967,489 ha, 31%) - exposed solonchaks and dunes, principal sources of salt-dust storms. According to the risk zoning, 31% of the area is categorized within the high-risk class, which is the principal source of salt-dust storms. This corresponds with the zoning results for the overall Aral Sea (Bao *et al*., 2024), where 47% was classed as serious risk zones. The spatial correspondence between high-risk zones and known salt-dust emission hotspots is further confirmed by satellite-based aerosol optical depth (AOD) data, which consistently show the northeastern and eastern DASB as the most active dust source areas in the region (Liu *et al*., 2025; Banks *et al*., 2024). The reduced proportion of high-risk areas in this study is attributed to the examination of the eastern sector, which presents more favorable conditions compared to the central DASB. Long-term restoration is essential for high-risk zones, necessitating soil treatment before planting. Uzbekistan's experience shows that physical protection (reed screens) works during early planting stages on bare solonchaks (Micklin, 2016). In 2024, UNDP started testing hydrogel products (SAP) and root coating with clay-manure mixes, raising survival to 60-70% even under bad conditions (UNDP, 2024a). Fig. 7 illustrates the geographical distribution of four ecological risk zones, indicating that high-risk regions are predominantly found in the central and southern parts, characterized by bare solonchaks and mobile dunes, which are key sources of salt-dust storms that influence the broader area.

Table 5: Results of saxaul plantation monitoring

Parameter	Minimum	Maximum
Plantation age, years	3	15
Stand density, individuals/ha	75	1,400
Survival rate, %	22	100
Mean height, cm	63	231
Crown area, m²	0.3	7.0
Natural regeneration, individuals/ha	1,400	52,000

Table 6: Characteristics of ecological risk zones across the full Kazakhstan DASB (~3,086,004 ha)

Risk zone	Area (ha)	Area (%)	Characteristics
Low risk zone	210,658	7	wet conditions, plant cover over 30%
Moderate risk zone	1,144,466	37	stabilized sands, thinning meadows
Elevated risk zone	763,391	25	crusty solonchaks, weakly stabilized sands
High risk zone	967,489	31	bare solonchaks and dunes, main sources of salt-dust storms

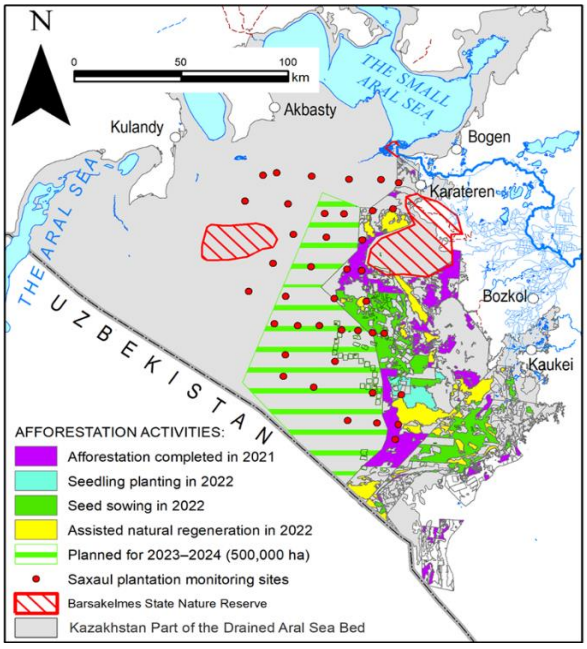

Fig. 6: Forest plantation areas in Kazakhstan's DASB

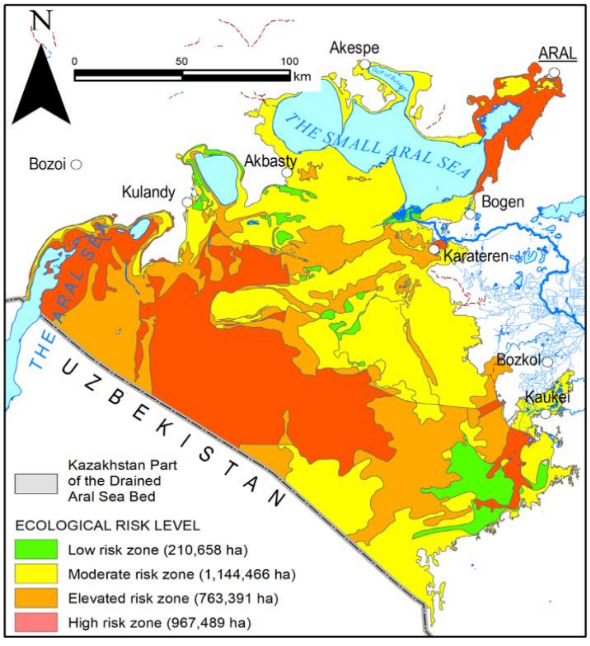

Fig. 7: Ecological risk zoning map of the DASB

Climate outlook and ecosystem services

Climate forecasts of 2.0-2.8°C warming by 2050 suggest that planting conditions will become harder. These projections were derived from CMIP-6 global climate models under SSP2-4.5 and SSP5-8.5 emission scenarios, as calculated by RSE Kazhydromet for the Eighth National Communication of Kazakhstan (Eighth National Communication, 2022; O'Neill *et al*., 2016). Under the SSP5-8.5 scenario, the humidification coefficient K is projected to decrease to 0.17–0.19 by 2050, indicating further intensification of moisture deficit. This modification will broaden the regions classified as high ecological risk zones, diminish the timeframe for favorable planting conditions, and heighten seedling mortality rates, particularly in soils with marginal groundwater salinity (50–60 g/L), which may fall into the unsuitable category under forecasted climate scenarios. According to Wang *et al*. (2023),

temperature rise will boost evaporation by 15-25% and further intensify regional aridity. Adaptation steps should include: 1) using the most drought-hardy saxaul types; 2) adding other desert shrubs (Calligonum spp., Salsola arbuscula); 3) using moisture-saving planting methods; and 4) timing planting based on expected changes. Saxaul plantations provide many benefits beyond stopping wind erosion. According to UNDP (2024a), a single mature saxaul bush has the capacity to capture as much as 4 t of blowing sand, and each hectare of plantation sequesters 1.1 t of carbon dioxide (CO_2) annually while emitting 0.8 t of oxygen. For global carbon storage efforts, DASB planting has great potential. Economic losses from dust storms in Karakalpakstan alone total 44.2 million United States dollar (USD) yearly (2.1% of GRP), with 20-year damage possibly topping 844 million USD (World Bank, 2024). Planting investments thus demonstrate clear economic justification. Additional advantages encompass beekeeping, which can yield up to 50 kilograms (kg) of honey per hectare of flowering tamarisk, as well as livestock grazing.

Future research needs

Further research is required in several areas: long-term tracking of groundwater-vegetation interactions using automated sensors; testing survival of other species under high-salt conditions (Halocnemum strobilaceum, Halostachys belangeriana, Kalidium caspicum); measuring ecosystem services from plantations of different ages using natural capital methods; and field testing of new planting techniques like hydrogels, mycorrhiza, and mulching in the Kazakhstan DASB. The possible effects of extensive phytomelioration on groundwater dynamics necessitate consideration. Large saxaul plantations could enhance evapotranspiration, which may lead to a decrease in shallow water tables in regions with depths ranging from 1 to 2 m, potentially diminishing the capillary salt supply to the surface — an effect that could be advantageous. Monitoring of groundwater levels within plantation areas is recommended through a network of regime observation wells measuring water level, salinity, and chemical composition at regular intervals. The multi-species planting recommendations developed in this study (*Haloxylon aphyllum*, *Atriplex pratovii*, *Halocnemum strobilaceum*, *Tamarix* spp.) are designed to support habitat diversity rather than monoculture dominance. Furthermore, collaboration with the Barsakelmes State Nature Reserve buffer zone strategy is suggested to ensure the maintenance of native species corridors while minimizing the potential for dominant species proliferation. The ecological risk zoning map should be updated every 3–5 years using new Sentinel-2 and Landsat imagery, NDVI time-series analysis, and groundwater monitoring data to account for dynamic changes in soil salinity, vegetation cover, and climate conditions across the DASB. The execution of extensive phytomelioration throughout the DASB is projected to require approximately 15,000–20,000 USD per hectare for manual planting in isolated regions, along with annual maintenance expenses ranging from 2,000 to 3,000 USD per hectare during the initial three years. Engagement with the community and adherence to local land-use practices are crucial for the sustained success of afforestation initiatives. A long-term monitoring framework should include: 1) restoration of the Barsakelmes meteorological station and installation of additional automated weather stations on the DASB; 2) monthly NDVI mapping from Sentinel-2 and Landsat imagery for desertification tracking; 3) a network of groundwater regime wells monitoring water level, salinity, and chemical composition; 4) saxaul survival assessments every 3 years; and 5) dust storm frequency tracking as an early warning indicator of restoration effectiveness. The study did not directly measure the long-term survival and growth dynamics of saxaul after the initial establishment phase, focusing instead on plantations that were 3 to 15 years old. Based on

regional studies, saxaul plantations typically reach structural maturity at 7–10 years, with wind speed reduction to near-zero and sand-fixing capacity maximized (UNDP, 2024a). Under projected warming of 2.0–2.8°C by 2050, increased evapotranspiration may reduce survival rates in marginal sites, particularly those with groundwater salinity of 50–60 g/L. It is advised that long-term observation of plantation dynamics in the context of climate change be prioritized as a critical area of research.

Study limitations

This study has multiple limitations that must be taken into account when analyzing the findings. First, the fieldwork was performed within a single season (April-May 2023), which restricts the capacity to observe seasonal and inter-annual fluctuations in groundwater levels and vegetation dynamics. Second, the sampling density (27 wells and 68 soil pits across 1,071,967 ha) may not fully represent the spatial heterogeneity of this extensive area. Third, the weights assigned to the six parameters in the ecological risk zoning were established based on expert opinion and literature review instead of empirical optimization; future studies could apply sensitivity analysis to validate these weights. Fourth, saxaul survival data were collected from existing plantations of varying ages and management histories, which introduces potential confounding factors. Notwithstanding these constraints, the results offer a significant foundation for phytomelioration strategy development within the Kazakhstan DASB sector. Process-based modeling of salt transport, including capillary rise dynamics and evaporation-driven salt accumulation, was not conducted in this study, as the primary objective was field-based ecological assessment rather than hydrological process simulation. The detected surface salt levels (0.157–35.867%) are regarded as the combined outcome of extended capillary rise and evaporation activities, in accordance with patterns outlined in the literature for comparable hyperarid environments (An *et al.,* 2022). Future studies should incorporate numerical salt transport models to quantify these processes and improve predictions of root-zone salinity under changing climate conditions.

CONCLUSION

This study offers the first field-oriented comprehensive ecological evaluation covering 1,071,967 ha of the Kazakhstan DASB, synthesizing hydrogeological, pedological, and geobotanical data within a unified GIS framework. The key findings are as follows: 1) Harsh desert conditions (120 mm yearly rainfall, K = 0.20, HTC = 0.12, 150 days of hot dry winds) and predicted warming of 2.0-2.8°C by 2050 mean drought- and salt-tolerant species should be prioritized for afforestation efforts. 2) High groundwater salinity (37.6-104.6 g/L, mean 65.4 g/L) and widespread salty soils (surface salt up to 35.9%) limit favorable forest site conditions to just 7% of the study area – significantly lower than the 25% reported for the Uzbekistan sector. 3) The survival rate of saxaul (22-100%) is contingent upon the interplay of soil texture, soil salinity, and groundwater depth. Atriplex pratovii communities function as trustworthy bioindicators of optimal planting sites, with survival rates of 85-100% where this species dominates. 4) High-risk zones (31% of the area, 967,489 ha) correspond to bare solonchaks and moving dunes – the principal sources of salt-dust storms affecting the wider Central Asian region. The significant scientific contributions of this study encompass: (a) the development of a four-tier forest site classification system specifically calibrated for extreme groundwater salinity levels (up to 104.6 g/L) not addressed in previous classification schemes; (b) quantitative criteria for site selection based on integrated soil-groundwater-vegetation parameters; and (c) the first ecological risk zoning map of the Kazakhstan DASB sector. For lasting phytomelioration, the following recommendations are made: establishing long-term monitoring networks with automated groundwater loggers; prioritizing

afforestation in areas dominated by Atriplex pratovii communities; creating vegetation corridors between Barsakelmes Reserve clusters to enhance habitat connectivity; and implementing monthly NDVI tracking for early detection of vegetation stress. The integrated assessment established in this study – associating groundwater, soil, and vegetation data in a GIS framework – provides a transferable strategy suitable for other degraded drylands in Central Asia encountering comparable environmental issues. The findings offer a scientific foundation for phytomelioration planning, acknowledging the need for further validation of sampling adequacy and expert-based weighting. The outcomes aid in the advancement of Kazakhstan's National Afforestation Program spanning 2021 to 2025, in addition to regional strategies to fight desertification and reducing cross-border effects of salt-dust storms from the Aralkum desert. The salinity thresholds and forest site classification criteria established here are directly applicable to analogous environments in the Aral-Caspian basin, Iranian Plateau, and Central Asian deserts where extreme groundwater salinity (>60 g/L) limits conventional afforestation approaches.

AUTHOR CONTRIBUTIONS

N. Zinabdin, the corresponding author, contributed to data analysis, GIS mapping, interpretation of the results, and preparation of the original draft of the manuscript. B. Bekniyaz contributed to the conceptualization of the study, development of the methodology, field investigation, project administration, and funding acquisition. S. Baisholanov contributed to methodology development, data analysis, and manuscript review and editing. G. Vakassova participated in field investigation and collection and organization of research materials. I. Rakhmetov contributed to methodology development, interpretation of the results, and manuscript review and editing. D. Ussenov participated in field investigation and collection of field data.

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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
AHP	Analytic hierarchy process
AOD	Aerosol optical depth
cm	Centimeters
Gha	Billion hectares
CMIP	Coupled model intercomparison project
DASB	Dried Aral Sea-bed
g/L	Grams per liter
GIS	Geographic information system
GNSS	Global navigation satellite system
GOST	State standard
GWP	Global water partnership
ha	Hectares
hPa	Hectopascal
HTC	Hydrothermal coefficient
IDMP	Integrated drought management programme
IPCC	Intergovernmental panel on climate change
K	Humidification coefficient during the growing season
kg	Kilograms
km	Kilometers
km²	Square kilometers
km³	Cubic kilometers
m	Meters
m²	Square meters
m/s	Meters per second
mg-eq/L	Milligram equivalents per liter
MGCAO	Models of the General circulation of the atmosphere and ocean
Mha	Million hectares
mm	Millimeters
NDVI	Normalized difference vegetation index
pH	Potential of hydrogen
RCP	Representative concentration pathway
RGB	Red, green and blue
RSE	Republican state enterprise
SAP	Superabsorbent polymer
SP60	Spectra Precision SP60
SSP	Shared socio-economic pathway
UNDP	United Nations development programme
USD	United States dollar
WMO	World meteorological organization
W/m²	Watts per square meters

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ORIGINAL RESEARCH ARTICLE

Temporal and seasonal influences concerning the carbon footprint of pelagic fisheries

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ABSTRACT

BACKGROUND AND OBJECTIVES: Pelagic fisheries play a vital role in sustaining coastal livelihoods and food security in the Eastern Indian Ocean, yet they also contribute to greenhouse gas emissions due to fuel-intensive operations. Notwithstanding their significance, there is a lack of empirical evidence concerning the carbon footprint associated with small-scale pelagic fisheries in Indonesia. The study aimed to quantify the carbon footprint associated with pelagic fisheries and to investigate variations related to fishing gear and target species, while examining temporal, seasonal, and catch per unit effort influences to enhance climate-resilient fisheries management in the Eastern Indian Ocean.

METHODS: A five-year dataset from fuel records, logbooks, landings, and interviews was used to estimate carbon footprints using the Intergovernmental Panel on Climate Change Tier 1 method (2.68 kilograms carbon dioxide per litre diesel). Trends and relationships concerning gear-specific intensity and catch per unit effort were also analysed.

FINDINGS: The average carbon footprints per vessel during 2019–2023 was 2.22 tons of carbon dioxide equivalent per ton fish. Monthly emissions ranged from 1.35 to 4.94 tons of carbon dioxide equivalent per ton fish, with levels 30 to 40 percent higher during peak fishing months (March–June), highlighting the strong influence of seasonal fishing intensity on emission variability. Longline fisheries exhibited the greatest carbon footprint, succeeded by gillnet and handline, while purse seine demonstrated the least cumulative emissions. Monthly catch per unit effort fluctuated from 0.56 to 2.52 ton per trip, demonstrating an inverse correlation that suggests greater stock abundance improves fuel efficiency per unit catch. At the species level, Yellowfin Tuna and Scad had the highest carbon footprint intensity, whereas Skipjack Tuna consistently showed the lowest emission levels.

CONCLUSION: Although emission intensity remains moderate compared to industrial fleets, cumulative emissions from small-scale pelagic fisheries are significant and strongly effort driven. Re-revitalizing fish populations, boosting fuel efficiency, and embedding routine carbon accounting into fisheries governance are vital for ensuring that pelagic fisheries are in harmony with Indonesia's sustainable and low-emission blue economy objectives.

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INTRODUCTION

Pelagic fisheries are a cornerstone of coastal economies in the Eastern Indian Ocean, providing essential protein, employment, and income for millions of people. In a global context, fisheries play a significant role in ensuring food security and alleviating poverty, yet they also exert growing pressure on marine ecosystems through overexploitation and operations that depend heavily on fuel (Andersen *et al.,* 2024). The dual role of fisheries—as both vital economic sectors and sources of greenhouse gas (GHG) emissions—underscores the urgency of quantifying their carbon footprint to support climate-resilient management (Morales *et al.,* 2026; Mariani *et al.,* 2020). The predominant source of GHG emissions in capture fisheries is fuel consumption, which accounts for over 90 percent (%) of total emissions during the fishing phase (Parker *et al.,* 2018). Global estimates suggest that fishing activities emit about 168 million tonnes (Mt) of carbon dioxide (CO_2) annually, corresponding to roughly 4% of total emissions from global food production (Nath *et al.,* 2025). Although pelagic fisheries typically exhibit greater fuel efficiency compared to demersal or crustacean fisheries, their total emissions are still considerable owing to substantial catch volumes and escalating fishing effort (Sandison *et al.,* 2021). This makes them an important focus for carbon accounting and emission reduction studies. In the Indian Ocean, pelagic fisheries, particularly those targeting tuna, mackerel, and other migratory species play a major role in national economies but also represent a growing source of GHG emissions. A recent study estimated that the purse seine fishery in the western Indian Ocean consumed about 160,000 tonnes of fuel annually, producing 590,000 tonnes of CO_2-equivalent (t CO_2-eq) emissions between 2015 and 2019 (Chassot *et al.,* 2021). These emissions exhibit significant variation among different fleets and seasons, influenced by factors such as fuel prices, fishing strategies, and stock availability. The geographical allocation of fishing activities, especially the differentiation between nearshore and offshore operations, is crucial in influencing fuel consumption and associated greenhouse gas emissions. Offshore fishing generally necessitates longer travel distances, higher engine loads, and prolonged operational periods in comparison to nearshore activities, which consequently elevates total fuel usage and emissions intensity (Chassot *et al.,* 2021). In contrast, nearshore fisheries often benefit from shorter trip durations and lower fuel requirements, although their efficiency can still vary depending on resource availability and fishing strategies, highlighting the importance of spatial dynamics in shaping the carbon footprint of fisheries (Scherrer *et al.,* 2024). Nonetheless, thorough evaluations of small-scale pelagic fisheries in the eastern Indian Ocean are still scarce (Nath *et al.,* 2025; Jenish *et al.,* 2024; Asokan *et al.,* 2023). Strengthening sustainability through innovation in blue economy approaches, such as energy-efficient technologies and integrated marine resource governance has been identified as a key strategy to reduce environmental impacts while maintaining economic productivity in this sector (Trenggono *et al.,* 2025). Small-scale fleets, which dominate most coastal fisheries in Southeast Asia, exhibit diverse gear types—gill net, hand line, long line, and purse seine each with distinct energy demands. This diversity may result in significant variations in emission intensity among different gears and operations (Jenish *et al.,* 2024). Vessel size, engine type, and maintenance practices significantly influence carbon footprints in small-scale fleets, as larger or more powerful vessels generally require higher energy input while fuel efficiency varies depending on operational patterns, engine performance, and technical condition, with improvements in propulsion systems and vessel design shown to reduce fuel consumption and emissions (Parker and Tyedmers, 2015). However, most current analyses concentrate on industrial fleets, resulting in a considerable knowledge gap regarding the contributions of artisanal and semi-industrial pelagic fisheries contribute to regional

carbon budgets (Ferrer *et al.,* 2021; Tassetti *et al.,* 2022; Castello, 2023; Mouillot *et al.,* 2023). Quantifying these emissions is essential to formulate realistic mitigation strategies for small-scale operations that balance productivity and environmental responsibility (de Cadenet *et al.,* 2025). Recent studies underscore that efficient fisheries management is inherently connected to carbon management. Overfishing, inefficient gear use, and poor stock status not only threaten biodiversity but also elevate emissions due to increased fuel consumption per unit catch (Andersen *et al.,* 2024). Conversely, rebuilding fish stocks and promoting energy-efficient practices can reduce the fuel use intensity (FUI) and carbon footprints from fishing operations (Bastardie *et al.,* 2022). Integrating such principles into pelagic fisheries governance is central to advancing a low carbon "blue economy" in the Indian Ocean. The Eastern Indian Ocean offers a notably dynamic setting, where monsoonal cycles, market demand, and fuel availability significantly impact fishing effort and carbon emissions. Fluctuations in sea conditions affect catch rates and travel distances, which in turn determine fuel consumption and emissions. Studies in comparable tropical fisheries have demonstrated that these seasonal variations can produce emission differences of up to 40% annually (Basurko *et al.,* 2022). Understanding these temporal patterns is crucial to designing adaptive and sustainable management frameworks. Temporal trends in fisheries indicate that improvements in fuel efficiency and reductions in emissions can be achieved through technological adoption and optimized operational practices, such as the use of more efficient fishing techniques, better stock management, and adaptive fishing strategies, which reduce fuel use intensity over time (Bastardie *et al.,* 2022). Simultaneously, environmental elements, such as weather patterns, ocean currents, sea state, and seasonal variability significantly affect fuel consumption and carbon footprint associated with each fishing trip. The alteration of oceanographic conditions affects vessel speed, travel distance, and catch efficiency, resulting in considerable temporal fluctuations in emissions across fishing seasons (Basurko *et al.,* 2022). Given the growing importance of climate considerations in fisheries policy, countries bordering the Indian Ocean are beginning to incorporate emission monitoring into management decisions. As an illustration, enhanced fuel efficiency standards and vessel modernization programs have been acknowledged as practical approaches to lower emissions without jeopardizing livelihoods (Kim *et al.,* 2021). However, data scarcity remains a major barrier to implementing such measures effectively in small-scale contexts. By combining emission estimates with operational data, the study provides empirical insights into the scale, variability, and drivers of carbon footprints in small-scale pelagic fisheries. The results are anticipated to guide policy measures, encourage fuel-efficient practices, and facilitate the shift towards low-emission and climate-resilient fisheries management in the region. This study aims to quantify and assess the carbon footprint of pelagic fisheries in the Eastern Indian Ocean from 2019 to 2023, focusing on temporal trends and gear-specific differences.

MATERIALS AND METHODS

This study was undertaken in the pelagic fishing areas of the Eastern Indian Ocean, characterized by significant biological productivity and powerful seasonal monsoon influences that shape fishing activity and fuel use. The region supports many artisanal and semi-industrial vessels operating within 50–100 nautical miles from shore using gill nets, hand lines, long lines, and purse seines to target tuna (*Thunnus* spp.), mackerel (*Rastrelliger* spp.), and sardines (*Sardinella* spp.). These fisheries constitute an essential element of Indonesia's small-scale sector, where variations in fishing effort, vessel power, and sea conditions have a profound impact on operational efficiency and carbon footprints (Chassot *et al.,* 2021; Basurko *et al.,* 2022). The study area was selected

to capture diverse operational strategies representative of pelagic fleets in the Indian Ocean's eastern margin, where fuel dependency and emission variability remain poorly quantified (Jenish *et al.,* 2024). Data collection covered the period 2019–2023, combining primary and secondary data from fishing logbooks, fuel purchase records, and structured interviews with vessel operators. Monthly data were gathered for each type of fishing gear, encompassing the number of trips, fuel consumption (L), days at sea, engine capacity (HP), and landed catch (kg). Fuel consumption was validated by comparing it with port fuel-supply records to minimize reporting bias (Sala *et al.,* 2022). The method used to calculate carbon footprints follows the Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Carbon emissions (CO_2)

Carbon emissions from fishing vessels refer to greenhouse gases (GHGs) produced during vessel operations, primarily because of burning fossil fuels such as marine diesel or diesel oil. The fuel combustion process in ship engines produces CO_2. Methane (CH_4) and nitrous oxide (N_2O) emissions were included in the calculation but contributed negligibly (<1–2%) to total emissions and are therefore not presented separately. Each of these gases has a different Global Warming Potential (GWP). To simplify the calculation of their impact on climate change, emissions from all gases are commonly expressed in units of CO_2 equivalent (CO_2eq). This unit denotes the volume of CO_2 that has a comparable global warming impact to that of other greenhouse gases.

Carbon footprints are calculated using Eq. 1 (IPCC, 2006):

Carbon footprints of fishing vessels = CO_2 Emissions + CH_4 Emissions + N_2O Emissions (1)

where:

CO_2 Emissions = Fuel consumption × emission factor. Total carbon emissions released by the vessel during one year of operation in tonne of t-CO_2eq.

Fuel Consumption = Energy produced from fuel in terajoule (TJ)

CH_4 Emissions = Fuel consumption × emission factor × AR5

N_2O Emissions = Fuel consumption × emission factor × AR5

Emission factors

CO_2 emission factor for fossil fuel: 73.28 tons/TJ

CO_2 emission factor for biodiesel: 70.8 tons/TJ

CH_4 emission factor: 7 tons/TJ

N_2O emission factor: 2 tons/TJ

AR5: Conversion factors for CH_4 and N_2O emissions according to the IPCC Fifth Assessment Report (AR5), with conversion ratios of CH_4 = 28 and N_2O = 265.

To ensure consistency with the IPCC Tier 1 methodology, all emission calculations are fundamentally based on energy units (TJ) using standard emission factors. Fuel consumption figures documented in litres were transformed into energy units utilizing standard calorific values before estimating emissions. The commonly used emission factor of 2.68 kilograms carbon dioxide per liter (kg CO_2/L) is applied as an equivalent representation derived from these energy-based calculations. This approach ensures consistency between volume-based fuel data and energy-based emission factors while maintaining transparency in the calculation process. The assessment of carbon footprints is also impacted by the fuel composition employed by fishing vessels, as demonstrated in Table 1, which is derived from fuel composition data collected from 2019 to 2023 for vessels under 30 gross tonnages (GT).

Table 1: Fuel composition of fishing vessels based on biodiesel blending

Year	Biodiesel blend	Vessels <30 GT	Vessels >30 GT
2019	B20	80% fossil, 20% biofuel	100% fossil
2020	B30	70% fossil, 30% biofuel	100% fossil
2021	B30	70% fossil, 30% biofuel	100% fossil
2022	B30	70% fossil, 30% biofuel	100% fossil
2023 (Jan–July)	B30	70% fossil, 30% biofuel	100% fossil
2023 (Aug–Dec)	B35	65% fossil, 35% biofuel	100% fossil

Carbon footprint

The carbon footprint of fishing vessels is a measure of the environmental impact of fishing activities in terms of greenhouse gas (GHG) emissions, expressed in tons of t CO_2eq per tons of fish caught. This figure indicates the amount of carbon footprint generated for every ton of fish landed. The resulting value serves as an indicator of carbon efficiency in fishing vessel operations. The smaller the value, the more environmentally friendly the vessel operation, using Eq. 2 (IPCC, 2006):

$$\text{Carbon footprint (ton } CO_2\text{eq/ton fish)} = \frac{\text{Total carbon footprints (ton } CO_2\text{eq)}}{\text{Total catch (ton)}} \quad (2)$$

where:

Carbon footprint: Amount of carbon footprint produced per ton of fish landed (t CO_2-eq/ton fish).

Total carbon footprints: Total carbon footprints released by the vessel during one year of operation (ton CO_2eq).

Total catch: Total annual catch (ton).

Statistical analyses

Statistical analyses were conducted to identify differences and trends in carbon footprints. Descriptive statistics were used to summarize fuel consumption and emission characteristics, while Analysis of variance (ANOVA) and Kruskal–Wallis tests evaluated differences among gear types. Temporal variations were assessed through linear regression to ascertain annual emission trends, and time-series decomposition was employed to highlight seasonal peaks connected to fishing patterns influenced by the monsoon (Parker *et al.,* 2018; Bastardie *et al.,* 2022). ANOVA was employed to test for significant differences in carbon footprints between different fish species. This method helps in comparing means across multiple groups (species in this case). The null hypothesis posits that there is no variation in emissions among species, whereas the alternative hypothesis indicates that at least one species exhibits a significant difference from the others. The ANOVA model is given using Eq. 3 (Silva *et al.,* 2023):

$$Y_{ij} = \mu + \tau_i + \epsilon_{ij} \quad (3)$$

where:

Y_{ij} is the carbon footprint observed for the ith species and j^{th} observation.

μ is the overall mean of the data.

τ_i is the effect of the ith species.

ϵ_{ij} is the error term.

The F-value is used to assess whether there are significant differences between groups using Eq. 4 (Silva *et al.,* 2023):

$$F = \frac{\text{Mean Square between Groups}}{\text{Mean Square within Groups}} \quad (4)$$

A significant p-value (typically p<0.05) indicates that at least one species has a significantly different carbon footprint. Given that the data did not always meet the assumptions of normality, the Kruskal-Wallis test was used as a non-parametric alternative to ANOVA. This assessment evaluates the median ranks among various species and is appropriate for data that does not follow a

normal distribution. The test statistic for Kruskal-Wallis is calculated, using Eq. 5 (Zhang *et al.,* 2024):

$$H = \frac{12}{N\,(N+1)} \sum_{i=1}^{k} \frac{n_i(R_i-\overline{R})^2}{n_i} \quad (5)$$

where:

H = The test statistic (H) represents the degree of difference in median ranks among species

N is the total number of observations.

n_i is the number of observations in the ith group

R_i is the sum of ranks in the

$\overline{R}$ is the overall mean rank

The null hypothesis of this test is that all species have the same distribution of carbon footprint, and a *p-value* less than 0.05 indicates a significant difference between at least one group. To assess the trend in carbon footprints over time, linear regression was applied. The dependent variable was the carbon footprint, and the independent variable was the year. The model posits that the carbon footprint has a linear relationship with the year of observation. The linear regression, using Eq. 6 (Zhang *et al.,* 2024):

$$Y = \beta_0 + \beta_1 . X + \epsilon \quad (6)$$

where:

Y is the carbon footprint (dependent variable),

X is the year (independent variable),

β_0 is the intercept (constant),

β_1 is the slope (rate of change per year),

ϵ is the error term.

The regression results provide a coefficient for the year (β_1), which indicates whether there is a significant increase or decrease in emissions over time. To examine the seasonal variations in carbon footprints, time-series decomposition was applied. This technique decomposes the time series into its components: trend, seasonality, and residuals. The model assumes that the data follows an additive model, using Eq. 7 (Zhang *et al.,* 2024):

$$Y_t = T_t + S_t + R_t \quad (7)$$

where:

Y_t is the observed value at time

T_t is the trend component,

S_t is the seasonal component,

R_t is the residual component.

The trend illustrates the enduring changes in emissions, whereas the seasonality indicates periodic variations (for instance, increased emissions during specific months attributed to fishing activities), and the residuals signify random noise. This decomposition helps in identifying seasonal peaks linked to fishing activity, especially during monsoon seasons. All analyses were performed using R software (v.4.3.1), and significance was set at $p < 0.05$. Limitations of this study include its focus on direct fuel-combustion emissions (scope 1) without incorporating upstream or post-harvest processes; however, this scope aligns with established methodologies for carbon footprint assessment in capture fisheries (Chassot *et al.,* 2021; Sala *et al.,* 2022). This scope does not encompass wider ecosystem-level effects, including trophic interactions and habitat disturbance associated with fishing activities.

RESULTS ANS DISCUSSION

The average carbon footprint per vessel during 2019–2023 is 2.22 ranged between 1.70 and 2.90 t CO_2-eq/ton fish, as presented in Table 2. Annual values show clear temporal variation, decreasing from 2.47 t CO_2-eq/ton fish in 2019 to 1.70 t CO_2-eq/ton fish in 2020, followed by a gradual increase to 1.88 t CO_2-eq/ton fish in 2021 and 2.15 t CO_2-eq/ton fish in 2022, before rising markedly to 2.90 t CO_2-eq/ton fish in 2023, the highest average level recorded during the study period. The reduction in carbon emissions noted in 2020 could be linked to

Table 2: Yearly carbon footprint per vessel and gear type (2019–2023)

Year	Average carbon footprint (t CO_2-eq/ton fish)	Number of vessel (unit)	Average of gillnet footprint (t CO_2-eq/ton fish)	Average of handline footprint (t CO_2-eq/ton fish)	Average of longline footprint (t CO_2-eq/ton fish)	Average of purse seine footprint (t CO_2-eq/ton fish)
2019	2.47	6,211	2.05	1.18	2.36	1.10
2020	1.7	7,683	1.52	1.36	1.74	1.06
2021	1.88	9,905	2.00	1.72	2.06	1.42
2022	2.15	13,473	2.27	1.73	2.21	1.41
2023	2.90	14,962	2.33	1.97	2.69	1.23

operational interruptions caused by the COVID-19 pandemic, which impacted fishing operations in numerous areas. However, unlike the decline in emission intensity, the number of vessels landing catches at Cilacap Ocean Fishing Port increased consistently over the study period, rising from 6,211 units in 2019 to 14,962 units in 2023. This implies that even though there was a short-term reduction in emissions per vessel in 2020, the simultaneous expansion of the fleet could have resulted in higher cumulative emissions in the subsequent years. Time-series decomposition reveals clear seasonal patterns, with peak emissions generally occurring during mid-year months (March–July), likely reflecting intensified fishing activity associated with monsoonal cycles in the Indian Ocean. Residual fluctuations indicate variability in emissions that cannot be fully explained by trend or seasonal components alone. Ultimately, the findings concludes that carbon footprints are shaped by a combination of operational intensity, fishing gear attributes, and seasonal factors that influence both fishing effort and the availability of various species.

Monthly carbon footprint estimates from the pelagic fishery operating out of Cilacap Ocean Fishing Port exhibited pronounced seasonal variability, indicating a strong association between temporal fluctuations in fishing effort and emission intensity. The highest monthly emission during the study period was recorded in March 2023 (4.94 t CO_2-eq/ton fish), followed by April 2019 (4.29 t CO_2-eq/ton fish) and January 2019 (3.97 t CO_2-eq/ton fish) (Fig. 1). These heightened figures align with times of increased fishing efforts, during which extended fishing trips and greater fuel usage probably led to a rise in greenhouse gas emissions. Previous studies have demonstrated that fuel use constitutes the dominant source of emissions in capture fisheries and is closely linked to fishing effort and vessel activity levels (Tyedmers *et al.,* 2005; Parker *et al.,* 2018). Consequently, seasonal increases in fishing intensity directly translate into higher carbon outputs. In contrast, substantially lower emissions were observed in January 2020 (1.39 t CO_2-eq/ton fish) and August 2020 (1.39 t CO_2-eq/ton fish), as well as May 2022 (1.44 t CO_2-eq/ton fish). These troughs probably indicate seasonal reductions in fishing activity linked to monsoonal shifts and oceanographic fluctuations in the Indian Ocean. The regional monsoon system has a significant impact sea surface conditions, primary productivity, and fish distribution patterns, thereby influencing the timing and intensity of fishing endeavors (Schott and McCreary, 2001; Wyrtki, 1961). Adverse weather conditions or lower catch rates during transitional monsoon phases may constrain vessel operations, resulting in reduced fuel consumption and lower carbon footprints. Ultimately, the consistent fluctuations in monthly emissions highlight the responsiveness of the pelagic fishery's carbon footprint to seasonal variations in both operational intensity and environmental influences. The sharp increase observed in early 2023, particularly in March, suggests intensified fishing activity during that

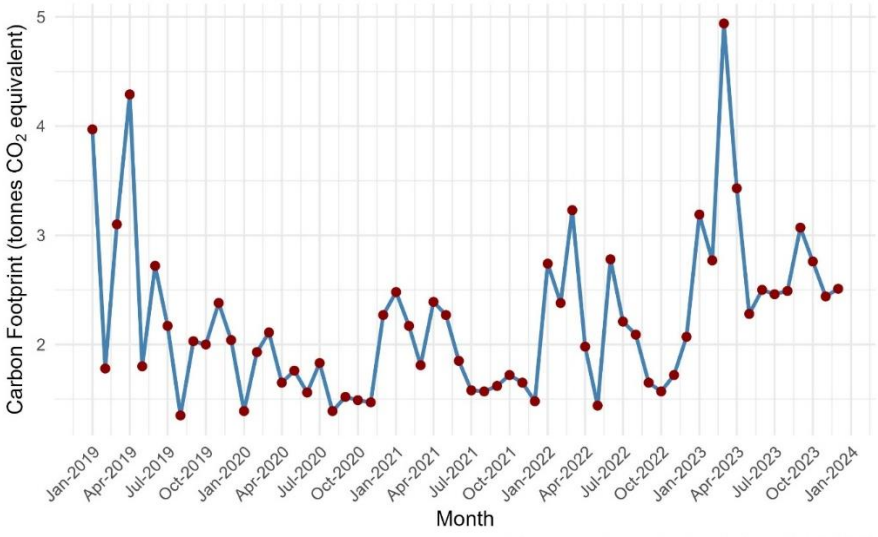

Fig. 1: Monthly carbon footprint of pelagic fishing gear landed at Cilacap fishing port

period. This pattern corresponds with extensive evidence indicating that greenhouse gas emissions related to fisheries are mainly driven by effort and influenced by environmental factors, especially in marine systems affected by monsoons (Parker *et al.,* 2018; FAO, 2020).

The temporal relationship between catch per unit effort (CPUE) and carbon footprint intensity represents a key dimension of environmental performance in small-scale pelagic fisheries. As shown in Fig. 2, carbon footprints ranged from 1.35 to 4.94 t CO_2-eq/ton fish, while CPUE varied between 0.56 and 2.52 ton/trip during 2019–2023. A clear inverse relationship was observed, supported by a strong negative Spearman correlation ($r = -0.63$, $p < 0.001$), indicating that higher catch efficiency is associated with lower emission intensity. While this relationship does not imply causation, it indicates that a lower CPUE could result in heightened fishing effort and fuel consumption. These findings highlight a structural linkage between stock availability and energy use, reinforcing that fisheries sustainability and climate mitigation are intrinsically aligned. Accordingly, maintaining stock biomass through effective management may reduce fuel use intensity and provide a direct pathway for emissions mitigation in small-scale fisheries.

Fig. 3 presents the monthly carbon footprint per tons of landed fish (ton CO_2-eq per ton fish) by fishing gear type from January 2019 to December 2023. Throughout the duration of the study, long line fisheries demonstrated the greatest average carbon footprint, accounting for roughly 30% of the total carbon footprint per unit of catch across different gear types. Gill net fisheries followed closely (around 28%), while hand line operations accounted for approximately 23%. Purse seine fisheries showed the lowest overall contribution, representing about 19% of the cumulative carbon footprint over the five-year period. Monthly carbon footprint values were estimated to be between 4 and 12 t CO_2-eq/ton fish when combined across gear types. The highest combined monthly intensity occurred in early 2023, approaching 12 t CO_2-eq/ton fish, whereas several months in 2020 recorded lower combined values below 6 t CO_2-eq/ton fish. Long line fisheries have regularly demonstrated a higher monthly carbon footprint in comparison to other gears, typically falling between approximately 1.8 and 2.8 t CO_2-eq per ton fish. Gill net values

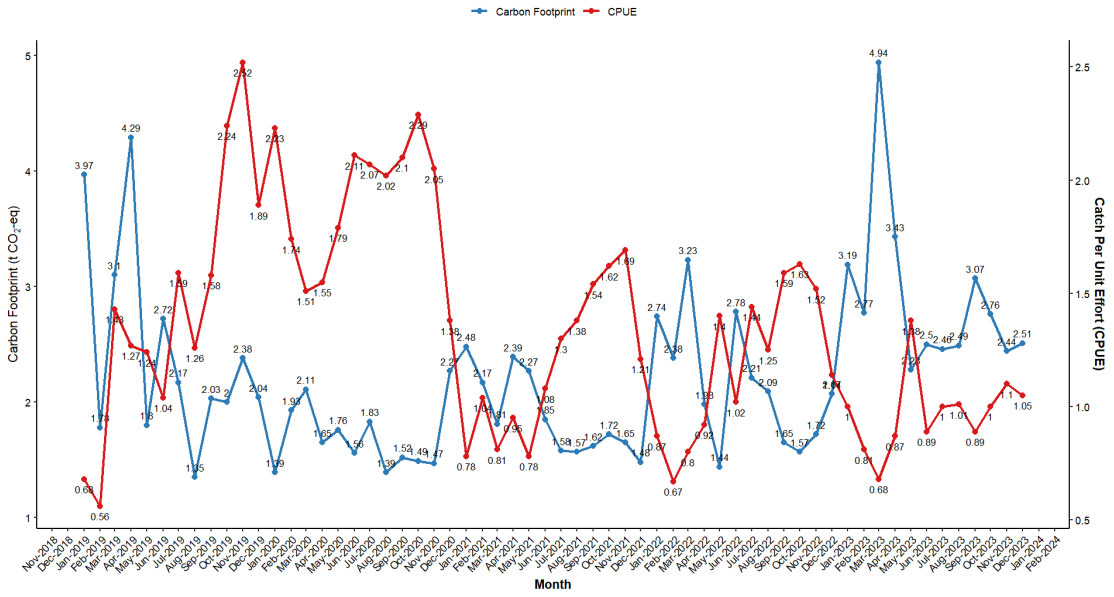

Fig. 2: Monthly carbon footprint compared to the CPUE (catch per unit effort) combined from handline, longline, gillnet, and purse seine

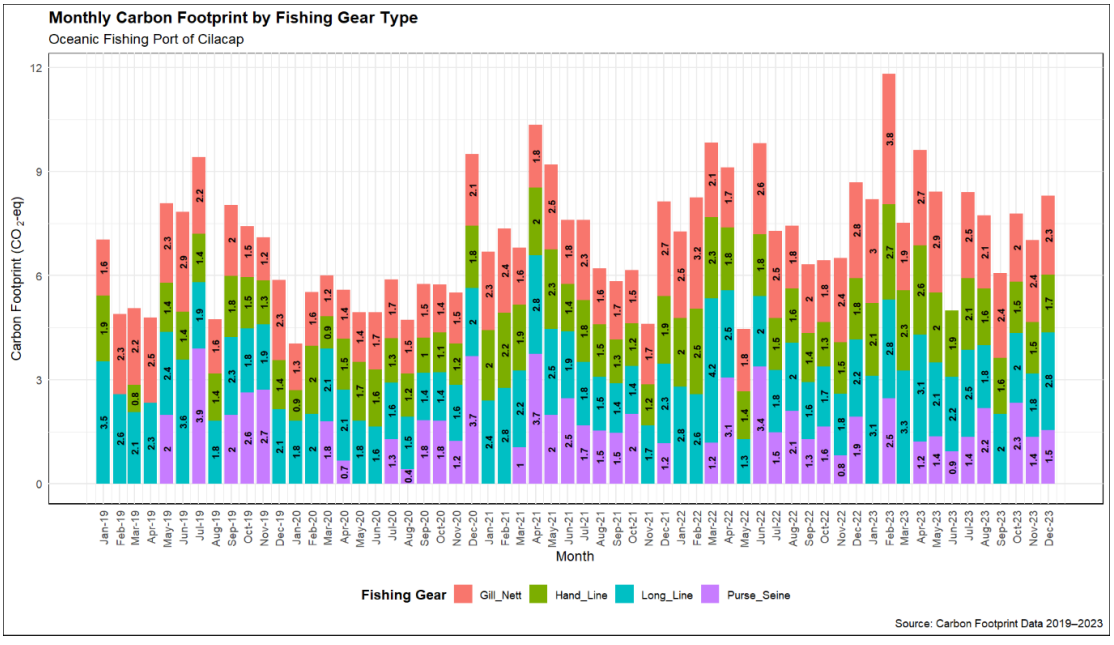

Fig. 3: Monthly carbon footprint by fishing gear type during the period of 2019-2023

typically ranged from about 1.5 to 3.8 t CO_2-eq/ton fish, while hand line fisheries remained mostly between 1.2 and 2.9 t CO_2-eq/ton fish. Purse seine operations exhibited increased variability from month to month, with multiple peaks surpassing 3 t CO_2-eq/ton fish during certain months (for instance, mid-2019, late-2020, mid-2022, and early-2023). Across years, carbon footprint declined during 2020 compared to 2019, increased during 2021–2022, and reached its

highest levels in 2023. Between March and July, seasonal increases were regularly noted in multiple years, whereas relatively lower carbon footprint values were recorded toward the final quarter of several years.

These variations in carbon footprint per ton of landed fish are consistent with the operational features of each gear type, which encompass fishing range, engine capacity, trip duration, and gear deployment intensity, as outlined in Table 3 (Chassot *et al.,* 2021; Nath *et al.,* 2025), and visualized in Fig. 4 and Fig. 5. Long line fisheries, which demonstrated the greatest average carbon footprint during the 2019–2023 timeframe, are linked to comparatively larger vessel sizes, longer fishing distances, and continuous operational activity. Gill net and hand line fisheries showed moderate carbon footprint values, reflecting comparatively smaller vessels and lower fuel demand per unit catch. Purse seine fisheries, although occasionally exhibiting short-term peaks, maintained the lowest cumulative carbon footprint per kilogram of catch across the study period. The monthly analysis provided additional confirmation of distinct seasonal variation. Carbon footprint values during peak fishing months—particularly between March and July—were up to approximately 35–40% higher than during lower-activity periods, indicating strong temporal fluctuations in fuel use relative to catch volume. A significant reduction in carbon emissions was noted in 2020, succeeded by a steady rise from 2021 to 2023, culminating in the peak monthly combined intensity documented in early 2023. Overall, while the carbon footprint per kilogram of fish produced by these small- to medium-scale pelagic fisheries remains moderate compared to industrial fleets, the sustained and cumulative nature of their operations results in a substantial carbon contribution over time. Due to their essential function in the regional fishing economy, a relatively small carbon footprint per unit catch can lead to considerable overall emissions (Basurko *et al.,* 2022; Jenish *et al.,* 2024). In addition to operational characteristics, differences in carbon footprint across gear types may also be influenced by bycatch rates, discards, and unutilized catch, although these factors were not explicitly quantified in the present study. Fishing equipment that results in higher bycatch or discard rates may demonstrate diminished emission efficiency, since fuel is consumed for biomass that is neither retained nor utilized, thereby effectively raising emissions per unit of landed catch. Conversely, more selective gears that minimize unwanted catch can improve carbon efficiency by maximizing the proportion of retained biomass relative to fuel use. Because the available dataset did not include detailed information on bycatch or discard composition at the trip level, these effects could not be directly assessed. Furthermore, this highlights a significant aspect for future studies, especially in analyzing the ecological efficacy of diverse fishing methods in a low-emission fishery setting. Overall statistical analysis revealed significant differences in carbon footprint among fish species, as indicated by both ANOVA ($F = 30.14$, $p < 0.001$) and the Kruskal–Wallis test ($\chi^2 = 145.02$, $p < 0.001$). However, due to violations of normality and homogeneity of variance, the non-parametric results are considered more robust. Post-hoc analyses using Dunn's test (Table 4) and Tukey's HSD (Table 5) and showed largely consistent patterns of pairwise differences. Specifically, Skipjack tuna, Scad, and Yellowfin tuna differed significantly from most other species ($p < 0.001$), with Scad exhibiting the most distinct carbon footprint profile across comparisons. Conversely, specific pairs of species, including Skipjack tuna versus (vs.) Bigeye tuna and Squid vs. Yellowfin tuna, showed no significant differences in either analysis, suggesting that their distributions are overlapping. A minor discrepancy was observed for the Squid vs. Bigeye tuna comparison, which was significant in the Dunn test but not in the Tukey HSD results, likely reflecting the non-normal distribution of the data in the analyzed data set and unequal variances.

Table 3: Characteristics of fishing fleets by gear type, including capacity, effort, fuel consumption, and fishing distance

Gear Type	Total GT	Number of Vessel	Average CPUE per day (ton)	Total fuel Consumption (ton)	Total distance from main port (km)
Hand Line	27,435	1,007	0.19	75,428	168,469
Long Line	26,815	788	0.23	65,712	65,712
Gill Net	10,797	473	0.16	15,164	56,943
Purse Seine	1,375	16	0.31	1,918	1,918

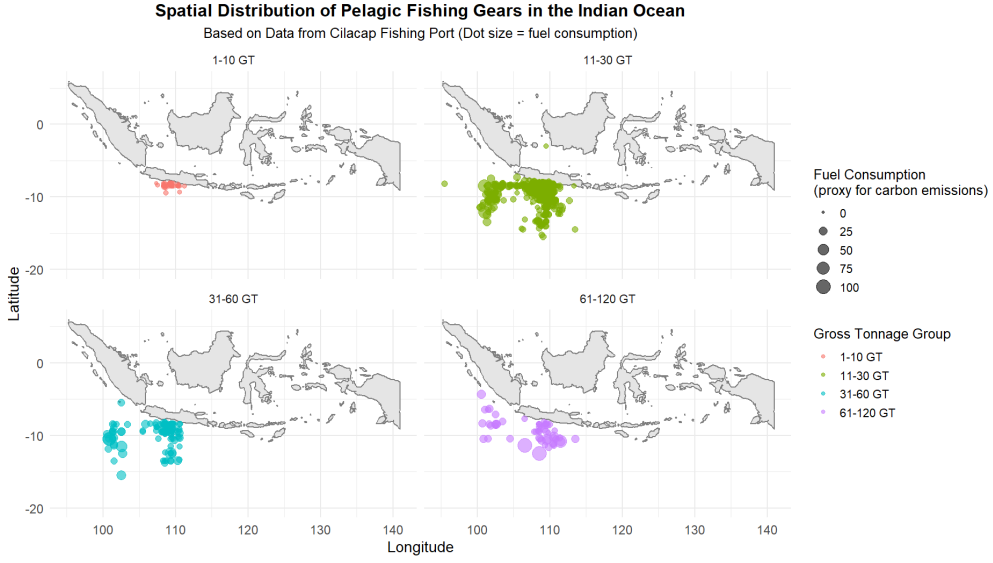

Fig. 4: Spatial distribution of pelagic fishing gear in the Indian Ocean based on Cilacap Fishing Port

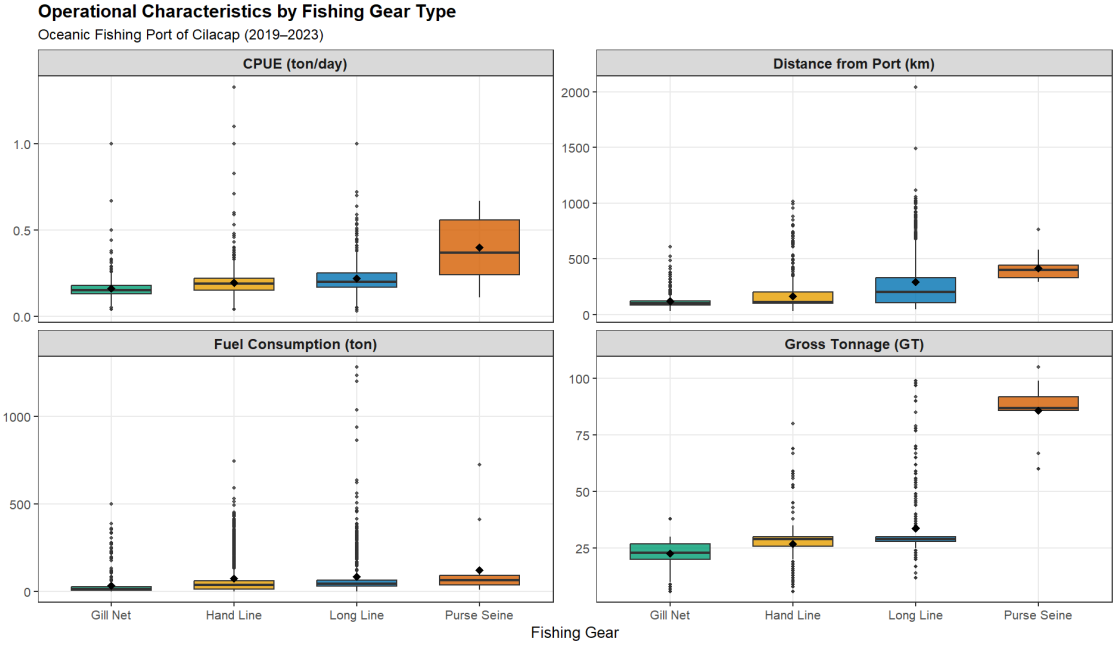

Fig. 5: Operational characteristics of fishing gear type

In summary, the results indicate that variations in carbon footprints are significantly affected by differences among species, with reliable evidence observed in both parametric and non-parametric methods. Linear regression analysis revealed a minor yet statistically significant positive temporal trend in carbon footprint ($\beta = 2.41$, $p = 0.004$), despite the low explanatory power ($R^2 = 0.027$). Including species substantially improved the model ($R^2 = 0.317$, $p < 0.001$), indicating that species identity explains more variation than time alone. The interaction model further augmented explanatory power ($R^2 = 0.371$, $p < 0.001$), implying that temporal trends differ among species. Ultimately, the differences in carbon footprints are primarily determined by the unique characteristics of each species rather than by a standardized time trend. From 2019 to 2023, the monthly carbon footprint statistics depicted in Fig. 6 highlight significant differences in emission intensity among the various species of fish. Yellowfin Tuna exhibited the highest average carbon footprint, with a mean value of approximately 3.40 t CO_2-eq/ton fish, and several months showing substantially higher peaks. For instance, emissions reached 9.76 t CO_2-eq/ton fish in June 2020 and 9.04 t CO_2-eq/ton fish in December 2021, indicating periods of particularly high fuel intensity in fishing operations targeting this species. Scad showed a similarly high emission intensity, with an average of 3.32 t CO_2-eq/ton fish, although its monthly values were highly variable, ranging from below 1 t CO_2-eq/ton fish to peaks above 9 t CO_2-eq/ton fish (for instance, 9.17 t CO_2-eq/ton fish in March 2019). Bigeye Tuna and Squid displayed more moderate emission levels, with average carbon footprints of 1.99 t CO_2-eq/ton fish and 1.84 t CO_2-eq/ton fish, respectively. While these species experienced sporadic short-term growth, their monthly figures typically stayed within a more limited range in comparison to Yellowfin Tuna and Scad. In contrast, Skipjack Tuna consistently recorded the lowest carbon footprint intensity, with an average of only 0.94 t CO_2-eq/ton fish and most monthly values remaining below 1 t CO_2-eq/ton fish throughout the study period.

In proportional terms as illustrated in Fig. 6 regarding the mean monthly carbon footprint, Yellowfin Tuna represented the highest proportion of average emissions (approximately 29–30%), closely followed by Scad (about 28–29%). Collectively, these two species accounted for almost 60% of the average carbon footprint intensity among all species throughout the study period. Bigeye Tuna represented around 17%, while Squid contributed approximately 16% of the mean emissions. In contrast, Skipjack Tuna accounted for only about 8%, reflecting its consistently lower carbon footprint values across most months in the dataset. While distinct species-level variations in carbon footprint were noted, this study did not specifically evaluate multi-species targeting behavior or the transition between high- and low-value species as an independent factor influencing emission efficiency.

Table 4: Dunn's post-hoc pairwise comparisons of carbon footprint among fish

Comparison	Z-value	Adjusted p-value	Significance
Skipjack Tuna – Squid	4.1	0.0004	***
Skipjack Tuna – Scad	10.75	<0.0001	***
Squid – Scad	6.65	<0.0001	***
Skipjack Tuna – Yellowfin Tuna	4.91	<0.0001	***
Squid – Yellowfin Tuna	0.81	1	ns
Scad – Yellowfin Tuna	-5.84	<0.0001	***
Skipjack Tuna – Bigeye Tuna	0.81	1	ns
Squid – Bigeye Tuna	-3.29	0.01	*
Scad – Bigeye Tuna	-9.94	<0.0001	***
Yellowfin Tuna – Bigeye Tuna	-4.09	0.0004	***

Table 5: Tukey HSD post-hoc pairwise comparisons of carbon footprint among fish species

Comparison	Mean Difference	Lower CI	Upper CI	Adjusted p-value	Significance
Skipjack Tuna – Squid	-175.45	-283.53	-67.38	0.0001	***
Skipjack Tuna – Scad	-401.00	-509.08	-292.92	<0.0001	***
Skipjack Tuna – Yellowfin Tuna	-255.92	-364.00	-147.84	<0.0001	***
Skipjack Tuna – Bigeye Tuna	-98.66	-206.74	9.41	0.092	ns
Squid – Scad	-225.55	-333.62	-117.47	<0.0001	***
Squid – Yellowfin Tuna	-80.46	-188.54	27.61	0.248	ns
Squid – Bigeye Tuna	76.79	-31.29	184.87	0.293	ns
Scad – Yellowfin Tuna	145.08	37.01	253.16	0.0025	**
Scad – Bigeye Tuna	302.34	194.26	410.41	<0.0001	***
Yellowfin Tuna – Bigeye Tuna	157.25	49.18	265.33	0.0008	***

Significance levels: ns = not significant (p ≥ 0.05); p < 0.05; ** p < 0.01; *** p < 0.001

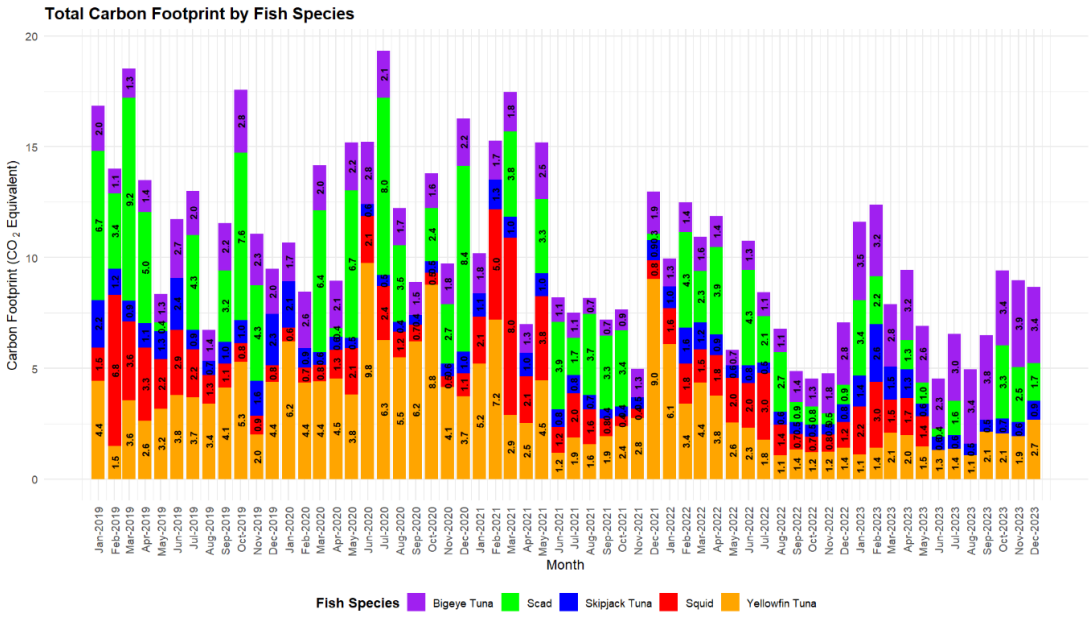

Fig. 6: Monthly carbon footprint of fishing activities by fish species

Although the absolute emission figures could be impacted by uncertainties in fuel-use reporting, emission factors, and catch allocation, it is unlikely that these uncertainties will modify the key comparative trends noted in the study, particularly those concerning temporal, gear-related, and species-level distinctions. Future studies should incorporate formal uncertainty propagation or Monte Carlo simulation to better quantify confidence ranges around carbon footprint estimates. Because the available dataset was not organized at the trip level, fuel use could not be allocated among multiple species caught within the same fishing operation. Nonetheless, the variation noted among species indicates that the composition of the catch could indirectly affect emission efficiency due to variations in catchability, fishing range, and operational effort. This continues to be a significant area for future investigation. The findings demonstrate that carbon footprints from pelagic fisheries operating out of Cilacap Ocean Fishing Port are strongly effort-driven and temporally dynamic. The five-year annual average carbon footprint per vessel ranged from 1.70 to 2.90 t CO_2-eq/ton fish, with an overall mean of approximately 2.22 t CO_2-

eq/ton fish during 2019–2023. Rather than exhibiting a consistent rise, emissions experienced fluctuations throughout the period. Average annual emissions declined from 2.47 t CO_2-eq/ton fish in 2019 to 1.70 t CO_2-eq/ton fish in 2020, followed by a gradual increase to 1.88 t CO_2-eq/ton fish in 2021, 2.15 t CO_2-eq/ton fish in 2022, and peaking at 2.90 t CO_2-eq/ton fish in 2023. The decline noted in 2020, followed by the increase observed through 2023, aligns with the disruption and recovery stages of fisheries operations during and after the COVID-19 pandemic. Globally, capture fisheries experienced reduced fuel consumption and landings during pandemic-related mobility restrictions, followed by a rebound phase marked by intensified effort (FAO, 2020). The marked increase in 2023 therefore likely reflects restored fishing mobility and expanded operational intensity rather than structural inefficiency alone. This study's primary contribution is the evidenced inverse correlation between CPUE and carbon footprints. Across the study period, monthly emissions ranged from 1.35 to 4.94 t CO_2-eq/ton fish, while CPUE varied between 0.56 and 2.52 ton/trip. Months characterized by elevated CPUE typically aligned with reduced emission levels. For example, January 2020 (CPUE = 2.23 ton/trip) and October 2020 (CPUE = 2.29 ton/trip) were associated with relatively low emissions (1.39 and 1.49 t CO_2-eq/ton fish, respectively). In contrast, the highest emission observed—March 2023 (4.94 t CO_2-eq/ton fish), coincided with one of the lowest CPUE values (0.68 ton/trip). This confirms that carbon footprint in small-scale fisheries is fundamentally biomass-dependent. When stock availability and catchability are high, vessels require less search time and consume less fuel per unit catch. On the contrary, a decrease in biomass raises the marginal effort needed, thereby increasing FUI (Hornborg and Smith, 2020). Similar negative relationships between biomass status and fuel intensity have been documented in Mexican and European fisheries (Ferrer *et al.,* 2022; Martin *et al.,* 2022), as well as globally (Parker and Tyedmers, 2015). Fluctuations in CPUE among different species and throughout time significantly influence fuel efficiency and carbon emissions in small-scale pelagic fisheries. Periods and species characterized by higher CPUE generally reflect greater stock availability and catchability, allowing vessels to achieve target catches with reduced search time and fuel consumption, thereby lowering carbon footprint per unit catch (Parker *et al.,* 2018; Hilborn *et al.,* 2026). Conversely, conditions of lower CPUE—whether influenced by species distribution, environmental fluctuations, or localized stock depletion—necessitate heightened fishing effort, extended trip durations, and increased fuel consumption, leading to a rise in emission intensity (Hornborg and Smith, 2020; Park *et al.,* 2015). The temporal consistency of this inverse relationship observed throughout the 2019–2023 period suggests that carbon efficiency is closely linked to ecological conditions and stock dynamics rather than short-term operational factors alone (Parker and Tyedmers, 2015). These results emphasize the necessity of upholding stable stock conditions and implementing adaptive fishing strategies to sustain both fuel efficiency and emission performance over time. Seasonal variability further demonstrates how environmental influences shapes emission patterns. Emission peaks were frequently observed during March–June, including April 2019 (4.29 t CO_2-eq/ton fish) and March 2023 (4.94 t CO_2-eq/ton fish). These months likely correspond to intensified fishing activity during productive monsoonal phases in the Indian Ocean. Monsoon-induced oceanographic activities change primary productivity and the clustering of pelagic species, thereby directly impacting fleet deployment and the distribution of effort (Schott and McCreary, 2001). The notable intra-annual fluctuations identified in this study underscores the importance of implementing temporally adaptive carbon accounting frameworks rather than reliance on static annual averages. The concentration of emissions during peak fishing months (March–June) also has important implications for interpreting annual carbon

footprint estimates and designing management interventions. Since a significant portion of overall emissions occurs within a limited seasonal timeframe, annual averages might mask intervals of exceptionally high carbon output. This temporal clustering suggests that mitigation efforts targeted during peak months—such as optimizing trip planning, improving fuel efficiency, or implementing seasonal effort controls—could yield more effective emission reductions compared to uniform year-round measures. Moreover, identifying these seasonal emission hotspots offers a more refined foundation for adaptive fisheries management, ensuring that operational intensity is in harmony with both ecological conditions and climate mitigation objectives. In addition to the factors discussed above, fuel consumption and associated CO_2 emissions in small-scale pelagic fisheries are influenced by an interaction of vessel characteristics, fishing gear, trip duration, and environmental conditions. Differences in vessel dimensions, engine power, and propulsion efficiency establish the fundamental fuel requirements, whereas the type of gear influences operational behaviors including fishing range, deployment duration, and effort intensity (Sala *et al.,* 2022; Parker and Tyedmers, 2015). Longer trip durations and extended search time—often associated with lower CPUE—directly increase fuel consumption and emissions (Parker, *et al.,* 2018; Hornborg and Smith, 2020). Environmental conditions, including ocean currents, sea state, and seasonal monsoon variability, further affect vessel speed, navigational efficiency, and access to fishing grounds, thereby influencing overall fuel use (Colombelli *et al.,* 2022). For instance, unfavorable sea conditions or heightened currents may elevate engine load and prolong travel time, whereas favorable conditions can enhance fuel efficiency (Yaqin *et al.,* 2024). Furthermore, it is important to recognize that the carbon footprint in small-scale fisheries is shaped by a combination of technological advancements and the varying environmental and operational contexts (Chassot *et al.,* 2021). Gear-specific analysis reveals clear differences in emission intensity. Based on annual averages, longline fisheries exhibited the highest carbon footprint per unit catch, increasing from 2.36 t CO_2-eq/ton fish in 2019 to 2.69 t CO_2-eq/ton fish in 2023. Gillnet fisheries showed moderate values (2.05–2.33 t CO_2-eq/ton fish), while handline fisheries increased from 1.18 to 1.97 t CO_2-eq/ton fish over the study period. Purse seine operations consistently recorded the lowest footprint (1.06–1.42 t CO_2-eq/ton fish). These distinctions illustrate operational features including vessel dimensions, the extent of offshore operations, journey length, and engine capacity. The comparatively greater intensity noted in longline fisheries is probably associated with prolonged offshore deployment and continuous engine operation. The relatively higher carbon footprint in longline fisheries is largely driven by their operational characteristics, including wider fishing ranges, longer trip durations, and continuous engine use during gear setting and hauling. Compared to more spatially concentrated gears such as gillnets or purse seines, longline vessels typically must cover larger distances to locate target species, leading to longer search times and higher fuel usage. In addition, periods of lower catch per unit effort (CPUE) can further increase fuel use per unit of catch. These factors collectively contribute to higher emissions intensity in longline fisheries (Park *et al.,* 2015). Improving efficiency in this sector may involve optimizing fishing routes, reducing unnecessary steaming, enhancing target detection, and utilizing more fuel-efficient technologies. Furthermore, aligning fishing effort with periods of increased stock availability can help to reduce the carbon footprint per unit catch. Importantly, the reduction in 2020 was temporary. Without structural efficiency improvements, emissions rebounded steadily through 2023 alongside expanding fishing effort and fleet growth (from 6,211 vessels in 2019 to 14,962 vessels in 2023). This pattern indicates that passive reductions resulting from external shocks are inadequate for achieving long-term decarbonization. Emission trajectories appear

closely intertwined with operational intensity. From a mitigation perspective, improving stock health appears to be the most structurally effective intervention. The inverse CPUE–emission relationship observed here indicates that higher catch efficiency directly reduces fuel intensity per unit catch. Data from other areas also shows that rebuilding stocks leads to a reduction in search time and a decrease in fuel consumption (Martin *et al.,* 2022; Ferrer *et al.,* 2022). To enhance ecological sustainability and decrease carbon footprint in the Eastern Indian Ocean, it is crucial to strengthen stock assessment, regulate fishing efforts, and enforce precautionary catch limits. Technological improvements offer additional mitigation potential. Energy audits in global fleets have identified fuel savings of up to 20% through propeller optimization, hull maintenance, and engine upgrades (Li *et al.,* 2024; Sala *et al.,* 2022). Given that small-scale fleets often operate aging engines (Parker *et al.,* 2018), modernization of propulsion systems and improved route planning could yield measurable emission reductions. Furthermore, in the absence of simultaneous enhancements in biomass management, the gains in efficiency could be negated by an escalation in fishing activities. Reducing carbon footprint in small-scale pelagic fisheries requires a combination of operational, technological, and management-based approaches that do not compromise fisher livelihoods. Furthermore, beyond enhancements in fuel efficiency, adaptive effort management such as optimizing fishing schedules and locations according to times of greater stock availability improve catch efficiency while reducing fuel consumption. In parallel, gradual adoption of low-carbon technologies, including hybrid propulsion systems or alternative fuels, may provide additional emission reductions, particularly if supported by targeted incentives and capacity-building programs. Importantly, mitigation strategies should be context-specific and economically viable, guaranteeing that efficiency improvements lead to both lower emissions and either sustained or enhanced income for fishers. Integrating these approaches within fisheries governance frameworks can support a transition toward low emission yet productive small-scale fisheries systems (Bastardie *et al.,* 2022). Incorporating carbon monitoring and reporting into fisheries governance can further strengthen management decisions by offering regular evidence on the interactions between fuel use, fishing effort, catch efficiency, and stock dynamics that influence emission patterns. By systematically tracking these indicators, managers can identify periods or fishing practices associated with higher carbon footprint, improve the targeting of fuel-efficiency measures, and support adaptive regulations that align fishing effort with periods of greater stock availability. Furthermore, it plays a significant role in assessing the balance between productivity, livelihoods, and environmental performance, aiding small-scale fisheries in their shift towards blue economy pathways that are both economically feasible and adaptable to climate considerations. Embedding carbon metrics into governance frameworks therefore offers a practical basis for linking fisheries sustainability objectives with low-emission development strategies in coastal sectors (Bastardie *et al.,* 2022). The carbon footprint values estimated in this study can be further contextualized by comparison with life cycle assessment (LCA)-based studies (Almeida *et al.,* 2014). LCA methodologies generally indicate elevated emission figures as they encompass a wider system boundary, which includes upstream fuel production as well as downstream activities like handling, processing, storage, and transportation. As an illustration, prior LCA studies on capture fisheries has shown significantly increased total emissions when post-harvest stages are included (Parker and Tyedmers, 2015; Parker *et al.,* 2018). In contrast, the present study focuses on operational (on-vessel) emissions, which represent the dominant emission source but do not capture the full life-cycle impacts. Despite this narrower scope, the estimated carbon footprint values are broadly consistent with the lower range of LCA-based results, indicating that operational emissions

provide a robust basis for comparative analysis across time, gear types, and species. This differentiation emphasizes the significance of defining system boundaries when analyzing and contrasting carbon footprint estimates across studies. Overall, this study provides empirical evidence that emissions in small-scale pelagic fisheries are effort-driven, seasonally mediated, biomass-dependent, and gear-specific. The identified inverse relationship between CPUE and emissions validates that the restoration of fish stocks serves as both a conservation imperative and a strategy for climate mitigation. Without structural improvements in stock management and energy efficiency, emission levels are likely to continue increasing alongside fishing intensification. Integrating carbon accounting into fisheries governance is therefore essential to align regional fisheries development with global climate objectives. While this analysis primarily examines direct emissions from fuel combustion, it is important to note that indirect sources linked to post-catch activities—such as ice production, cold storage, processing, and transportation—can significantly impact the overall carbon footprint of fisheries systems. These downstream processes can increase overall emissions beyond those generated during fishing operations, particularly in supply chains requiring extended preservation and distribution. Furthermore, the absence of quantification in this study suggests that their inclusion could notably modify the balance between operational and post-harvest emissions, emphasizing the importance of integrated life-cycle approaches in future assessments. In this broader context, the carbon footprint levels estimated in this study fall within the range reported for small-scale pelagic fisheries globally, while highlighting clear operational differences among gear types. The relatively lower emission intensity observed in purse seine fisheries aligns with findings that pelagic fisheries typically demonstrate enhanced fuel efficiency due to schooling behavior of target species and increased catch rates. In contrast, the heightened carbon footprint observed in longline fisheries is indicative of a greater fuel requirement linked to broader fishing ranges and extended longer trip durations (Parker and Tyedmers, 2015). Although per-vessel emissions remain lower than those of industrial fleets, the strong linkage between emissions and fishing effort, combined with rapid fleet expansion, indicates increasing cumulative emissions, consistent with patterns observed in regional pelagic fisheries (Chassot *et al.,* 2021). Furthermore, the inverse relationship between CPUE and emissions emphasizes that fuel efficiency is intricately linked to stock availability, as increased biomass leads to a reduction in search time and fuel consumption. Overall, these comparisons suggest that while emission magnitudes are broadly comparable across small-scale fisheries, carbon performance is primarily shaped by stock dynamics, operational strategies, and temporal variability.

CONCLUSION

This study assesses the carbon footprint of small- to medium-scale pelagic fisheries operating from Cilacap Ocean Fishing Port in the Eastern Indian Ocean during 2019–2023 by integrating emission estimates, CPUE dynamics, seasonal variability, and gear-specific characteristics. The findings indicate that greenhouse gas emissions are mainly influenced by fishing effort, stock availability, and operational variations among gear types. The annual average carbon footprint per vessel ranged from 1.70 to 2.90 t CO_2-eq/ton fish, with a mean of 2.22 t CO_2-eq/ton fish. Although relatively moderate compared to industrial fleets, the rapid increase in fleet size—from 6,211 vessels in 2019 to 14,962 in 2023—indicates a growing cumulative carbon contribution at the regional scale. Emission trends exhibited a non-linear pattern, characterized by a decrease in 2020 linked to diminished fishing activities due to the COVID-19 pandemic. This was succeeded by a consistent rise from 2021 to 2023, indicating a recovery and an escalation in fishing effort. A strong inverse relationship between catch per unit effort (CPUE) and emissions was observed, confirming that carbon footprint is fundamentally biomass-

dependent. Periods of high CPUE were consistently associated with lower emissions, while low CPUE corresponded to higher emission levels. This implies that an abundance of fish stocks allows vessels to minimize their search time and fuel expenditure per unit catch, while a decline in biomass results in heightened effort and fuel usage intensity. This finding highlights an important linkage between fisheries sustainability and climate mitigation, where maintaining healthy fish stocks not only supports ecological resilience but also reduces emission intensity. Seasonal fluctuations further highlight the effort-based characteristics of emissions. Higher carbon outputs were recorded during peak fishing periods, particularly between March and June, with increases of up to 30–40% compared to low-emission months. These variations are probably affected by oceanographic processes driven by the monsoon, which in turn influence fish distribution and fleet activity. As a result, static annual emission estimates may overlook important temporal dynamics, underscoring the need to incorporate seasonal variability into carbon accounting frameworks. Considerable distinctions in carbon footprint were likewise recognized across various gear types. Longline fisheries showed the highest emission levels, followed by gillnets and handlines, while purse seine fisheries consistently exhibited the lowest carbon footprint. These variations illustrate distinctions in operational range, trip duration, engine utilization, and fishing strategies. Species composition further contributed to emission variability, with fisheries targeting widely distributed or lower-efficiency species requiring greater effort and fuel consumption. This suggests that both technological and ecological elements collaboratively influence carbon performance in fisheries. Despite moderate per-vessel emissions, the combination of increasing fleet size and rising operational intensity suggests that total emissions are likely increasing. Without improvements in efficiency or effective effort regulation, emission trajectories may continue to rise alongside fishing expansion. These results underscore various implications for fisheries governance. Strengthening stock management may lead to improved CPUE and a reduction in fuel intensity, whereas incorporating fuel-use monitoring into fisheries data systems can facilitate better emission evaluations. Technological measures, such as engine optimization and improved navigation, offer mitigation potential, but are insufficient if not accompanied by effort control. In summary, this study illustrates that the carbon footprint associated with small-scale fisheries is fundamentally connected to ecological conditions and fishing effort. Effective decarbonization therefore requires an integrated approach combining ecosystem-based management, technological efficiency, and policy interventions. The strong relationship between CPUE and emissions provides clear evidence that sustainable fisheries management is inherently aligned with climate mitigation objectives.

AUTHOR CONTRIBUTIONS

Syamdidi contributed to the conceptualization, conducted data interpretation, prepared the original manuscript draft, and led the literature review. M.R. Putri provided supervision of the writing process and contributed to critical review of the manuscript. L. Bernawis provided supervision and contributed to refinement of the manuscript. S.W. Trenggono contributed to critical review of the manuscript. R.A. Wahyudin contributed to critical review and final editing of the manuscript. S.D. Diantara contributed to the literature review. T. Yuwono contributed to data analysis and strengthened the literature review. W.I. Sakti contributed to revising the manuscript. F.Y. Arthatiani assisted with data collection and interpretation. D.C. Simamora supported data compilation. A. Sabina supported data verification. L.O.M.A. Wahid contributed to data validation and analytical review. I.N. Radiarta contributed to conceptualization and the literature review. K. Kasim contributed to manuscript preparation, data analysis, and interpretation. All authors have reviewed and approved the final version of the manuscript for 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, 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
ANOVA	Analysis of variance
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
B/BMSY	Biomass relative to Biomass at Maximum Sustainable Yield
B20	Biodiesel blend containing 20% biofuel and 80% fossil diesel
B30	Biodiesel blend containing 30% biofuel and 70% fossil diesel
B35	Biodiesel blend containing 35% biofuel and 65% fossil diesel
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalent
COVID-19	Coronavirus disease 2019
CPUE	Catch per unit effort
FAO	Food and Agriculture Organization of the United Nations
FUI	Fuel use intensity
GHG	Greenhouse gas
GT	Gross tonnage
GWP	Global Warming Potential
HP	Horsepower
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kg CO_2/L	kilograms carbon dioxide per liter
km	Kilometre
L	Litre
LCA	Life cycle assessment
LNG	Liquefied natural gas
MMAF	Ministry of Marine Affairs and Fisheries
N_2O	Nitrous oxide

p	Probability value (statistical significance level)
R	Statistical computing software (R programming language)
Spp.	Species (plural; used in scientific names)
t CO_2eq	Ton of carbon dioxide equivalent
TJ	Terajoule
v	Version

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ORIGINAL RESEARCH ARTICLE

Mangrove ecosystem integrity on environmental sustainability, fisheries performance, and food security in small island systems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Mangrove ecosystems are fundamental to coastal fisheries and food systems. Despite their importance, a critical knowledge gap remains regarding their precise impact on fisheries productivity and multidimensional food security in small island socio-ecological systems. The study objectives were to investigate how mangrove ecosystem integrity regulates environmental stability, trophic productivity, fisheries performance, livelihood resilience, and household food security in Tanakeke Island, Indonesia.

METHODS: The study integrated mangrove vegetation analysis, soil and water quality measurements, plankton-benthos assessments, fisheries observations. It also included governance analysis, rapid appraisal for fisheries multidimensional scaling and dynamic systems modelling. The household dietary diversity score and household food insecurity access scale were utilized to conduct food security surveys among 336 households.

FINDINGS: The results revealed a strong ecological gradient from intact mangrove ecosystems to pond-dominated degraded landscapes. Healthy mangrove systems exhibited higher biodiversity, more stable trophic structures, improved environmental regulation, and greater plankton, benthos, and fisheries productivity. Conversely, degraded systems demonstrated a clear trend toward trophic simplification and nutrient imbalance, which directly correlated with declining fisheries productivity and rising livelihood vulnerability. Tanakeke Island currently consists of approximately 40 percent mangrove and 60 percent aquaculture ponds, suggesting that the current landscape composition may be approaching ecological carrying capacity limits. This condition compromises the ecosystem's capacity to regulate nutrient cycling, maintain habitat stability, and sustain fisheries productivity. Despite continued fish availability, low dietary diversity (4.0-4.7) and 92.85 percent of households experienced food insecurity. These data suggest that food insecurity is driven by systemic vulnerabilities—specifically ecological degradation, livelihood instability, and restricted socio-economic resilience—rather than being solely a function of agricultural yields.

CONCLUSION: This study demonstrates that mangrove ecosystem integrity regulates fisheries productivity and food security through cascading socio-ecological pathways linking environmental regulation, trophic productivity, livelihoods, and food access. The study integrates ecological integrity, trophic dynamics, fisheries productivity, and livelihood resilience into a socio-ecological framework for small island systems. The framework also incorporates multidimensional food security, and ecological carrying capacity. The findings emphasize that achieving sustainable food systems in small island contexts relies fundamentally on preserving ecological integrity across the landscape. The study also emphasizes the urgent need for ecosystem-based mangrove-fisheries management to restore resilience and long-term sustainability.

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70	10	5

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INTRODUCTION

Small island systems are widely recognised as among the most climate-exposed and resource-dependent social-ecological systems (SES) globally. Within these systems, ecological degradation functions as a direct catalyst for economic instability and systemic food insecurity. Limited land availability, restricted livelihood diversification systems, high dependence on coastal ecosystems increase the vulnerability of small island systems to environmental (Yetein *et al.,* 2025), household nutrition (Ickowitz *et al*., 2023), and income stability (Das *et al*., 2026). Mangroves regulate nutrient cycling, stabilise hydrological processes (Feng *et al*., 2026), and function as critical nursery habitats for commercially important fish and crustacean species (Cure *et al*., 2026). Given that small island communities depend heavily on fisheries for both household income and dietary protein, maintaining these underlying ecological processes is paramount (Yamamoto, 2023). However, across Southeast Asia, mangrove landscapes have experienced significant transformation due to aquaculture expansion, pond conversion, and coastal development (Sofue *et al.,* 2024; Pettigrew and McCauley, 2026). Consequently, these alterations can compromise habitat complexity, thereby undermining the trophic functions critical to sustaining fisheries productivity (Yan *et al*., 2026). Despite extensive research on mangrove ecosystem services, much of the literature treats ecological functions and food security outcomes as separate analytical domains (Afifah *et al*., 2026). Most mangrove studies emphasize ecosystem services such as biomass (Huang *et al*., 2026), carbon storage, (Deng *et al*., 2026), habitat provision, and shoreline stabilization (Morris *et al*., 2023). Despite a tendency in traditional food security literature to overlook ecosystem integrity within socio-ecological systems, these factors remain intrinsically linked (Chi *et al*., 2026). In fisheries-dependent small islands, ecosystem integrity may be closely associated with long-term food system stability under climate stress (Omokaro, 2025). Mangrove ecosystem integrity includes vegetation structure, nutrient balance, hydrological exchange, and habitat complexity (Yan *et al*., 2026). Declining ecosystem integrity is often associated with reduced fisheries productivity (Analuddin *et al*., 2025), unstable livelihoods, and lower dietary diversity income variability may rise (Daw *et al*., 2023). Despite their importance, few empirical studies have mapped these cascading linkages within a unified SES framework, leaving a critical knowledge gap in tropical small island contexts (Otieno *et al.,* 2026). In small island socio-ecological systems, mangrove ecosystem integrity appears to function as an important ecological foundation linking environmental regulation with fisheries productivity and household food security (Chi *et al.,* 2006). Through processes such as nutrient retention, hydrological stabilization, habitat provision, carbon storage, and coastal buffering, mangrove ecosystems may help sustain trophic productivity and ecological resilience, which are closely associated with livelihood stability and long-term food system resilience (Qiu *et al.,* 2026). The socio-ecological vulnerability of tropical small islands is clearly demonstrated on Tanakeke Island in South Sulawesi, where mangrove conversion to aquaculture, unstable fisheries yield, and intensifying climate variability threaten local sustainability (Serdar *et al.,* 2024; Malik *et al*., 2025). Nevertheless, local communities remain heavily dependent on capture fisheries and pond-based aquaculture, while dietary diversity indicators suggest persistent vulnerability (Stacey *et al*., 2021). Unlike previous studies thet primarily examined mangroves (Yap *et al*., 2025), household income (Arifanti *et al*., 2022), fisheries production (Kolapo *et al*., 2025). This study aims to examine how mangrove ecosystem integrity is associated with environmental regulation, fisheries productivity, livelihood resilience, and food security in small island systems. The study was carried out in Tanakeke Island, Takalar District, South Sulawesi, Indonesia during the years of 2024 and 2025.

MATERIALS AND METHODS

This study employs a mixed-methods approach integrating ecological measurements, socio-economic surveys, fisheries monitoring, and governance analysis. Grounded in SES frameworks, this methodology centers on the complex socio-ecological dynamic interactions occurring among ecological subsystems, resource users, and governance structures.

The study area

This research was conducted on Tanakeke Island, located in Takalar Regency, South Sulawesi Province, Indonesia. Administratively, Tanakeke is part of the Spermonde Islands. This island is located on the southwestern side of the mainland of south Sulawesi Province and borders directly on the waters of the Geographically, the island is situated at 119° 14' 22" – 119° 20' 29" east (E) and 5° 26' 43" – 5° 32' 34" south (S). There are six villages, namely Minasa Baji Village, Tompo Tanah Village, Maccini Baji Village, Rewataya Village, Balandatu Village, and Mattiro Baji Village, scattered across several small low-lying islands. The island has an area of approximately 43 square kilometers (km²) and is dominated by mangrove forests, tidal flats, seagrass beds, and shallow marine ecosystems, which play an important role in supporting fisheries productivity and coastal livelihoods (Fig. 1).

Study design and sampling framework

This study applied an integrated SES approach to examine relationships between mangrove ecosystem integrity, environmental regulation, fisheries productivity, and household food security within small island socio-ecological systems under varying environmental and livelihood conditions (Prayunita *et al.,* 2026; Kashif *et al.,* 2026). To effectively map local environmental gradients, sampling was stratified by ecosystem type—including dense, moderate, and sparse mangroves, as well as aquaculture ponds—across six villages in Tanakeke Island.

Mangrove vegetation analysis

Mangrove vegetation sampling employed a stratified ecological design across four ecosystem zones: dense mangrove, moderate mangrove, sparse mangrove, and pond systems. To establish the sampling framework, the target number of plots was calculated using Slovin's formula, after which a disproportionate stratified sampling design was employed to distribute plots equally among the strata. Plot distribution was further adjusted proportionally based on mangrove areas within each village, resulting in 108 observation plots across the study area. Sampling locations were randomly assigned within each stratum to reduce spatial bias. To ensure statistical validity across ecosystem gradients, field observations were standardized by season and tide; the resulting replication level was robust enough to permit principal component analysis (PCA) and rank abundance curve (RAC) evaluations (Kairoa *et al.,* 2008; Nyangoko *et al.,* 2022).

Soil sampling and laboratory analysis

Measurements of soil, water, and plankton were obtained from 6 villages, divided into 4 zones with 3 replicates each, resulting in a total of 72 sample plots. Soil samples were collected from each stratum using a stratified approach. Topsoil with 0-20 centimeters (cm) was sampled and analyzed for soil texture, pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium (Division, 2021; Zhang *et al.,* 2025).

Water sampling and laboratory analysis

To evaluate localized environmental regulation and aquatic habitat quality, water sampling was stratified across adjacent aquaculture ponds and varying mangrove density zones (dense, moderate, and sparse). To capture environmental gradients, water quality sampling was stratified across the study area based on variations in mangrove ecosystem integrity. At each sampling station, in situ measurements of temperature, pH, salinity, dissolved oxygen (DO), turbidity, and

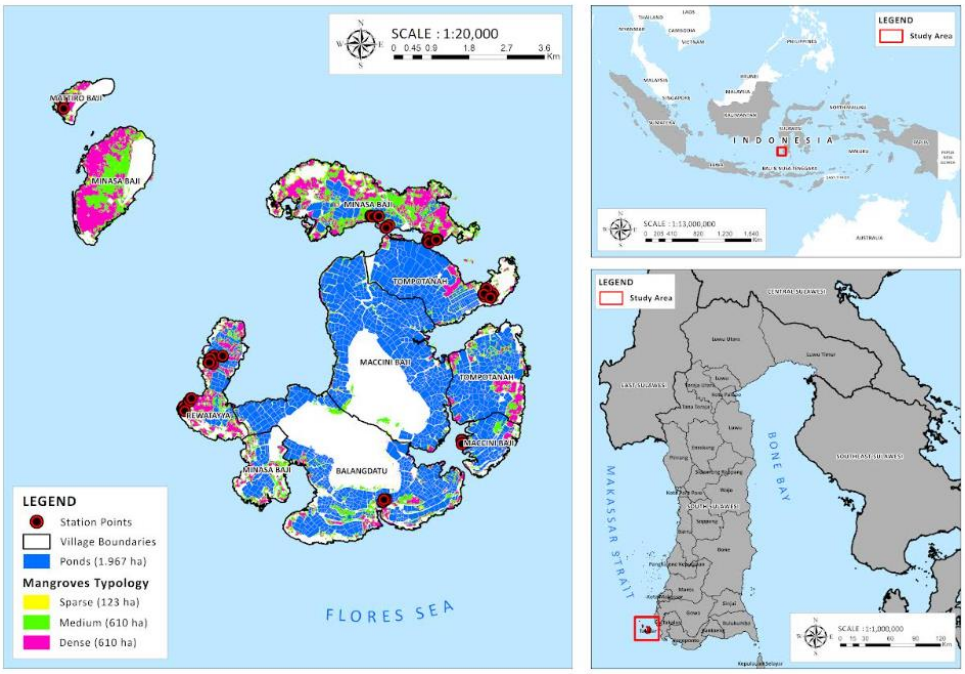

Fig. 1: Geographical location of the study area in Tanakeke Island, South Sulawesi, Indonesia

water depth were conducted using portable field instruments. To maintain sample integrity, water samples were secured in clean polyethylene bottles, held in a chilled cooler, and transferred to the laboratory for subsequent analysis. Laboratory parameters included total suspended solids (TSS), chemical oxygen demand (COD), total organic matter (TOM), nitrate (NO_3^-), nitrite (NO_2^-), and ammonia (NH_3). All analyses followed standard procedures for water and wastewater examination, with parameters selected because they are commonly used to assess water quality, nutrient dynamics, and ecological suitability in aquaculture and coastal ecosystems.

Fish sampling design and analysis

To analyze community structure and fisheries productivity relative to environmental gradients, fish sampling was carried out across varying mangrove zones. Sampling sites were selected using a stratified approach based on mangrove density classes (dense, moderate, sparse, and pond) to capture habitat heterogeneity. Within each stratum, 3 stations were established across key ecological zones (foreshore, interior, and transition). Sampling was performed under comparable tidal conditions to minimise temporal variability. Fish were collected using cast nets—a gear type commonly employed by local fishers—to minimize selectivity bias and ensure the capture of a diverse range of species and size classes. At each station, sampling was conducted at three points (100, 200, and 300 meters (m) from the mangrove edge) with three replicates per point. All captured individuals were identified to species level, and total length (cm) and weight in gram (g) were recorded. Fish community data were analysed to determine species composition, abundance, and biomass. Ecological indices, including Shannon-Wiener diversity (H'), evenness (E), and dominance (D), were calculated to describe community structure. Catch per unit effort (CPUE) was used as a proxy for fisheries productivity, and relationships between fish communities and mangrove attributes were examined using PCA (Kendall *et al*., 2021).

Household survey and food security assessment

A total of 336 household respondents were selected from 2,008 households across the study area using the Slovin formula to ensure representative sampling. To capture varying livelihood and food security conditions within the small island socio-ecological system, respondents were distributed equally across six study villages. Household food security was assessed using the household dietary diversity score (HDDS) and the household food insecurity access scale (HFIAS). HDDS was calculated based on a 24-hour recall across 12 food groups, while HFIAS measured food insecurity experiences over the past 30 days using nine standardised questions. These indicators offer complementary dimensions of analysis, capturing both the immediacy of food access and broader patterns of household vulnerability (Swindale and Bilinsky, 2026). To capture experience-based food insecurity, the HFIAS evaluates household conditions over the preceding 30 days through nine standardized questions addressing psychological anxiety, food quality, and volumetric quantity. Responses are scored on a frequency scale (0-3), with higher scores indicating greater food insecurity. Households are subsequently classified into four categories: food-secure, mildly food-insecure, moderately food-insecure, and severely food-insecure. Together, these indicators provide a complementary assessment of food access and vulnerability in mangrove-dependent coastal systems (Coates *et al*., 2007).

Data analysis

Descriptive statistics were used to summarize vegetation characteristics, environmental parameters, fisheries indicators, and household food security conditions across mangrove ecosystem gradients in Tanakeke Island. Mangrove vegetation structure was analyzed using the Shannon-Wiener diversity index (H'), evenness (E), species richness, and important value index (IVI). RAC were applied to assess trophic community structure and species dominance patterns. PCA was utilized to analyze the interactions among soil, water, nutrient, and trophic parameters across diverse ecosystem conditions. Prior to PCA, environmental variables were standardized to reduce scale differences and multicollinearity effects. Correlation analyses were further conducted to evaluate relationships among fisheries productivity household income, HDDS, and HFIAS indicators.

Socio-ecological system and governance analysis

To analyze governance dynamics and key drivers of mangrove-based food security, focus group discussions (FGDs) were conducted across six villages involving key stakeholders, including fishers, aquaculture farmers, women, community leaders, and local authorities. FGDs were used to identify relevant actors, system objectives, and influencing variables. To evaluate institutional dynamics, the Matrix of Alliance and Conflict: Tactic, Objectives and Recommendation (MACTOR) method were applied**.** By processing influence and actor-objective matrices, this framework maps stakeholder alignment with system objectives and categorizes actors into four distinct typologies: dominant, key, dependent, and autonomous (Noaman *et al*., 2024). System variables were analyzed using matrix of cross impact analysis (MICMAC), based on a cross-impact matrix to assess direct and indirect relationships among ecological, socio-economic, and institutional factors. The variables were mapped as driver, linkage, dependent, or autonomous components, a classification that successfully isolates key leverage points for targeted system interventions.

Multivariate analysis using PCA

PCA was applied to explore relationships among ecological and socio-economic variables and to reduce data dimensionality. By identifying the dominant components underlying village-level variability, the analysis facilitated a integrated interpretation of coupled mangrove conditions, environmental quality, and food security

indicators. The PCA results revealed clear clustering patterns, where villages with higher mangrove density were associated with more stable environmental conditions, better soil and water quality, higher HDDS, and lower HFIAS scores. Conversely, villages characterized by degraded mangrove ecosystems were tied to compromised environmental quality, diminished dietary diversity, and elevated food insecurity—findings that illustrate the clear covariance between ecosystem health and household.

Integrated analytical framework

An integrated socio-ecological analytical framework was developed by synthesizing ecological assessments, fisheries productivity analysis, household livelihood surveys, food security indicators, and multidimensional sustainability analysis (Quoc *et al.,* 2026). The framework applies a *systems-thinking approach* to identify the cascading pathways linking mangrove ecosystem integrity, environmental regulation, trophic productivity, fisheries performance, livelihood resilience, and household food security in small island systems.

RESULTS AND DISCUSSION

Evaluating food security in small island contexts demands a shift away from isolated production-oriented perspectives toward a holistic understanding of interconnected social-ecological processes. On Tanakeke Island, the results demonstrate that mangrove ecosystem integrity is a fundamental driver linking environmental stability, fisheries productivity, and household food security outcomes.

Mangrove ecosystem integrity gradient

The mangrove vegetation metrics presented in Table 1 capture a pronounced socio-ecological gradient across Tanakeke Island, profiling a transition from structurally intact forest stands to heavily degraded, aquaculture-dominated landscapes characterized by depressed diversity (H') and altered species dominance (Table 1). The Shannon–Wiener diversity index ranged from 0 to 0.8490 (0.4533 ± 0.4032), indicating that several mangrove areas were ecologically simplified and dominated by a limited number of species. Elevated community diversity (H’ = 0.849) and the presence of up to five species within the moderate mangrove zone point to a well-balanced vegetation architecture and pronounced habitat heterogeneity. In contrast, sparse mangrove zones exhibited lower diversity (H’ = 0.233), reduced evenness, and fewer species, indicating a more simplified vegetation structure. Species richness also varied considerably across sampling locations (0–5 species; 3.2500 ± 2.3629), reflecting heterogeneous ecological conditions among ecosystem zones. Because this study relies on observational data, direct causal relationships cannot be definitively established; however, these distinct patterns suggest underlying environmental variations, legacy land conversion, and hydrological changes induced by pond expansion and coastal development. All vegetated zones were primarily dominated by *Rhizophora stylosa*, although dominance patterns differed among ecosystem conditions. In dense and moderate zones, dominance remained accompanied by several associated species, suggesting relatively higher structural complexity, whereas sparse zones tended to show stronger dominance by fewer tolerant species, potentially indicating reduced functional diversity and ecological redundancy. These patterns of structural simplification align with findings from other disturbed tropical mangrove systems, where chronic habitat degradation drives decline in both ecological complexity and resilience (Alongi, 2021). The observed structural simplification across degraded mangrove zones was also associated with broader ecological patterns related to trophic stability, fisheries productivity, and household vulnerability. Although direct causality cannot be inferred, the consistency of these patterns across environmental gradients

Table 1: Ecological characteristics of mangrove vegetation across ecosystem gradients

Variable	Zone	Village	Replicates	Min-Max (Mean ± SD)
Shannon-Wiener Index (H')	4	6	3	0 - 0.8490 (0.4533 ± 0.4032)
Number of mangroves species	4	6	3	0 – 5 (3.2500 ± 2.3629)
Diversity index phytoplankton	4	6	3	1.89 – 2.05 (1.9940 ± 0.0698)
Plankton abundance	4	6	3	144920 - 168718 (158030 ± 9853)

indicates that structural vegetation simplification covaries with altered habitat quality, compromised ecological regulation, and a diminished capacity to support fisheries-based livelihoods. These findings are consistent with previous studies highlighting the important ecological role of mangrove integrity in sustaining coastal social–ecological systems (Sasmito *et al*., 2020).

The RAC of mangrove communities

Changes in mangrove ecosystem condition were reflected in differences in community structure patterns, as illustrated by the RAC in Fig. 2. The RAC profiles suggest a gradual shift from relatively complex and more evenly distributed vegetation assemblages toward increasingly simplified community structures along the observed mangrove degradation gradient (Fajriyati et al., 2026). Compared to dense forest areas, the moderate mangrove zones displayed steeper cumulative dominance curves. This pattern reflects the pronounced dominance of *Rhizophora stylosa* alongside a diminished evenness among associated species. This pattern may suggest reduced vegetation heterogeneity and lower ecological complementarity within the community structure. In sparse mangrove zones, the steeper RAC and lower species representation were associated with stronger dominance patterns and reduced diversity, which may reflect simplified habitat conditions and lower structural complexity. The pond system represented the most simplified ecological condition, where vegetation absence coincided with the loss of natural community structure and reduced biological heterogeneity. Although direct causality cannot be inferred from this correlational design, the uniformity of these RAC configurations across environmental gradients indicates that structural vegetation simplification covaries with broader shifts in habitat quality, trophic dynamics, and overall ecosystem functioning (Carrasquilla-Henao *et al*., 2022). Similar trends have been reported in disturbed mangrove ecosystems, where lower vegetation diversity and increased species dominance are often linked with reduced habitat heterogeneity, altered nutrient dynamics, and lower ecological resilience (Derviche *et al*., 2024). Conversely, dense mangrove areas tended to exhibit flatter RAC patterns and relatively higher evenness, indicating more balanced and functionally diverse assemblages. Prior studies underscore the role of structural complexity in mangrove ecosystems, demonstrating its direct links to heightened nursery functions, greater organic matter availability, and the reinforcement of ecological connectivity supporting coastal food webs (Gillis *et al.,* 2026). Within the context of this study, the observed RAC patterns provide inferential ecological evidence that variations in mangrove vegetation structure may be closely associated with differences in ecosystem stability, fisheries-supporting functions, and the resilience of coastal socio-ecological systems in small island environments, although direct causal relationships cannot be conclusively established from the present study design.

Mangrove vegetation structure and ecosystem integrity gradients across zonation

The ecological variation across the mangrove ecosystem gradients was clearly delineated by PCA, where the first two axes explained most of the total variance of 96.37 percent (%) (Table 2). The first axis (F1) accounted for 68.05% of the variation, suggesting that differences in mangrove

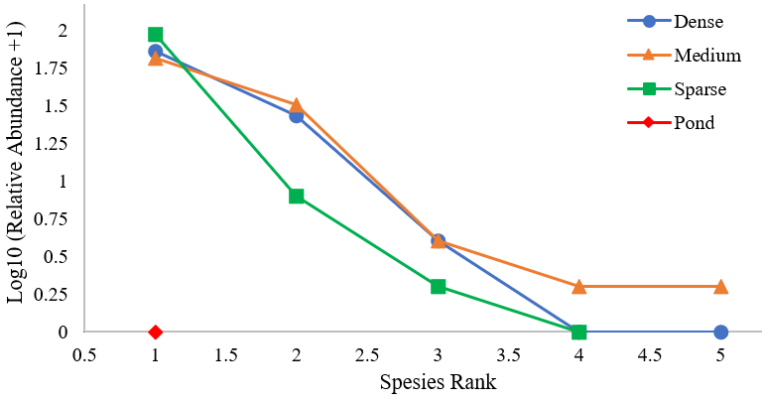

Fig. 2: RAC of mangrove communities across density gradients in Tanakeke Island

Table 2: Eigenvalue for Mangrove vegetation structure and ecosystem integrity gradients across zonation revealed by PCA biplot

Principal analysis (PA)	F1	F2	F3
Eigenvalue	2.7222	1.1327	0.1451
Variability (%)	68.0539	28.3175	3.6286
Cumulative %	68.0539	96.3714	100.0000

vegetation structure, species richness, and ecosystem condition represented the dominant ecological gradient across the study area. Consistent with expected ecological characteristics, a clear divergence emerged between the dense to moderate mangrove zones—characterized by elevated diversity and vegetation heterogeneity—and the sparse or pond-dominated landscapes, which suffered from structural simplification and heightened species dominance. Although this study was observational and correlational in nature, the consistency between PCA ordination and vegetation indicators suggests that changes in mangrove ecosystem condition may be associated with broader ecological variation related to habitat complexity and ecosystem functioning. These trends align with findings from other degraded tropical mangrove systems, where a loss of community diversity compromises ecological resilience and fundamentally alters ecosystem processes (Alongi, 2021).

The PCA biplot shown in Fig. 3 revealed clear ecological variation across mangrove ecosystem gradients, with the first two axes explaining 96.37% of the total variance, indicating that the ordination effectively captured the dominant ecological patterns within the study area. Dense and moderate mangrove zones tended to cluster together on the positive side of F1 and were closely associated with higher species richness, Shannon-Wiener diversity (H'), and phytoplankton diversity. These configurations indicate that heightened structural complexity within mangrove forests fosters elevated ecological heterogeneity and well-balanced community assemblages. In contrast, sparse mangrove zones were positioned separately and appeared more closely associated with phytoplankton abundance, potentially reflecting shifts in environmental conditions and trophic responses within simplified habitats. The pond zone showed the greatest separation from vegetated systems, indicating markedly different ecological characteristics following vegetation loss and landscape conversion. Despite the study's observational and correlational limits, consistent ordination patterns suggest that shifting mangrove vegetation structures reflect broader variations in ecosystem functioning, habitat complexity, and aquatic ecological conditions. Similar multivariate

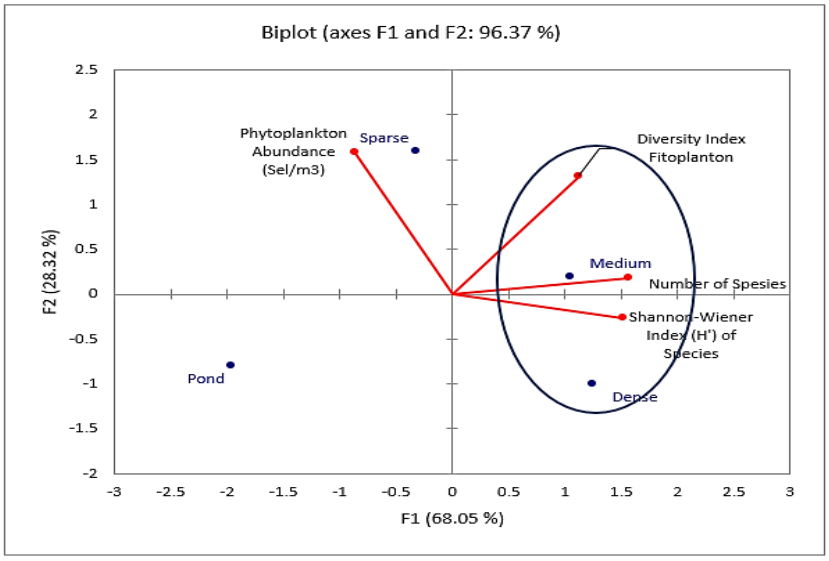

Fig. 3: Mangrove vegetation structure and ecosystem integrity gradients across zonation revealed by PCA biplot

patterns have been reported in disturbed mangrove ecosystems, where reduced vegetation diversity and structural simplification are often linked with altered nutrient dynamics, habitat heterogeneity, and ecological resilience (Mandal *et al.,* 2012; Alongi, 2021). Previous studies have also highlighted that structurally complex mangrove habitats are commonly associated with stronger ecosystem service functions (Zhang *et al*., 2023), including support for trophic productivity and coastal food webs. While these data reveal robust inferential patterns, they reflect ecological associations rather than direct causal pathway (Stakiw *et al*., 2026).

Environmental regulation changes

These gradients in mangrove ecosystem integrity are not only reflected in vegetation structure but also translate into shifts in environmental regulation, particularly in soil properties, water quality, and nutrient dynamics. Environmental regulation serves as a key pathway through which the structural integrity of mangrove ecosystems dictates coastal productivity. In mangrove-dominated systems, the interactions among soil structure, water quality, and nutrient dynamics form an integrated regulatory network that controls biogeochemical processes and energy flow. Rather than operating independently, these environmental variables function as an interconnected, coupled system that dictates the capacity of coastal ecosystems to maintain primary productivity and trophic stability.

Integrated soil-water-nutrient regulation across mangrove ecosystem gradients

Integrated soil-water-nutrient regulation across mangrove ecosystem gradients reflects how variations in ecosystem integrity reshape environmental processes that govern nutrient retention, water stability, and overall ecosystem functionality (Fig. 4). Soil properties across the mangrove gradient reveal a fundamental shift in retention capacity and ecological stability. As illustrated in Fig. 4, the elevated clay fractions and organic carbon content characteristic of dense and moderate mangrove zones serve to enhance nutrient retention, water-holding capacity, and soil microbial activity. These conditions create a stable substrate that supports efficient biogeochemical cycling. In contrast, the transition toward sparse mangrove, marked by increasing sand and pond system, marked by increasing silt

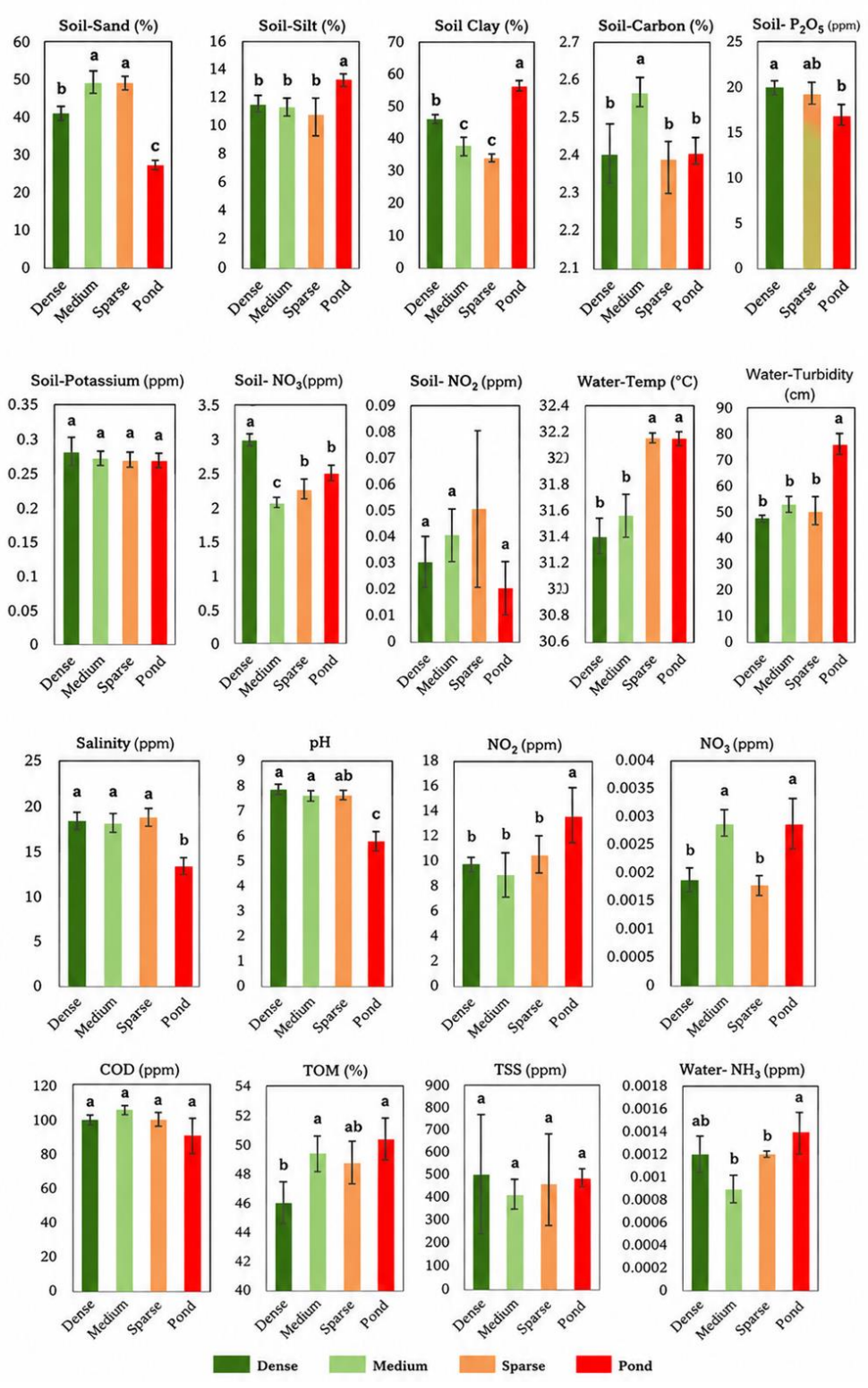

Fig. 4: Environmental regulation changes: soil, water, and nutrient system

and clay dominance and declining organic matter, indicating reduced retention capacity and a breakdown of soil structure. This shift increases the system's susceptibility to nutrient loss and environmental variability, weakening its ability to regulate ecological processes. Physicochemical water parameters further delineate this ecological transition. Structurally intact mangrove systems maintain elevated dissolved oxygen concentrations and buffered pH dynamics, signifying homeostatic ecological processes and efficient gas exchange. Lower turbidity and moderate temperature conditions also suggest a stable environment that supports biological activity. Conversely, degraded and pond systems exhibit reduced dissolved oxygen, higher turbidity, and elevated temperatures, signalling environmental stress and reduced ecological buffering capacity. These changes indicate that the system is shifting from a regulated state toward a more unstable and externally influenced condition. Nutrient dynamics further validate this environmental gradient. Elevated and stoichiometric balances of nitrogen and phosphorus within dense and moderate mangrove zones point to accelerated nutrient cycling driven by organic matter inputs from litterfall and subsurface root systems. This process ensures continuous nutrient regeneration and supports primary productivity. In contrast, nutrient dynamics in sparse and pond systems become increasingly imbalanced, with fluctuating concentrations of nitrogen forms (NO_3, NO_2, NH_3) and phosphorus. These disrupted biogeochemical pathways and the concurrent decline in microbial efficiency culminate in poorer nutrient utilization, imposing a strict ceiling on the system's primary productivity. When considered as an integrated system, these changes illustrate a clear transition from a regulated ecosystem to a degraded one. In intact mangrove areas, soil, water, and nutrient components function synergistically to retain, recycle, and distribute resources efficiently. In contrast, degraded systems exhibit decoupling of these components, resulting in nutrient leakage, unstable water conditions, and reduced ecological efficiency (Analuddin *et al*., 2025). Collectively, these concurrent physicochemical and nutrient trajectories demonstrate that structural complexity in mangrove forests secures enhanced environmental stability and bolsters key ecological regulation functions relative to degraded or aquaculture-converted systems (Song *et al.,* 2026). These environmental differences were also accompanied by variation in phytoplankton abundance and fisheries-related indicators, suggesting potential ecological linkages between habitat condition, nutrient dynamics, trophic productivity, and coastal ecosystem functioning (Goldberg *et al*., 2020). A broad body of literature corroborates these patterns, demonstrating that mangrove ecosystem integrity and localized nutrient regulation are fundamentally coupled with the fisheries-supporting capacities of tropical coastal ecosystems (Sun *et al*., 2020).

Linking mangrove vegetation structure to environmental regulation across ecosystem gradients: Evidence from PCA biplot

PCA revealed substantial environmental variation across mangrove ecosystem gradients, with the first two principal components explaining 92.48% of the total variance (Table 3). The first axis (F1) accounted for 64.17% of the variation, suggesting that differences in mangrove vegetation structure and nutrient-related parameters represented the dominant ecological gradient across the study area. The second axis (F2) accounted for an additional 28.32% of the total variance, capturing secondary variations linked to localized environmental conditions and sub-zone nutrient dynamics. The relatively small contribution of F3 (7.52%) indicates that most ecological variation was effectively represented within the first two axes. The PCA patterns suggest that nutrient availability and mangrove vegetation structure were closely associated across the ecosystem gradient.

Table 3: Eigenvalue for mangrove vegetation structure and nutrient availability by PCA biplot

Principal components	F1	F2	F3
Eigenvalue	8.3419	3.6811	0.9770
Variability (%)	64.1684	28.3163	7.5153
Cumulative %	64.1684	92.4847	100.0000

Areas with relatively intact mangrove vegetation tended to exhibit more stable nutrient-related conditions, potentially supported by greater organic matter accumulation, sediment retention, and root-mediated biogeochemical processes. Conversely, systems characterized by sparse vegetation and dominated by ponds seemed to show increased environmental variability, potentially indicating modified sediment conditions and more unstable nutrient dynamics. Although this study was observational and correlational in nature, these patterns are consistent with previous studies indicating that mangrove vegetation complexity is often associated with nutrient retention, sediment stability, and ecological regulation in tropical coastal ecosystems. The high cumulative variance explained by the PCA further suggests that vegetation structure and nutrient-related variables were strongly interconnected within the studied mangrove landscape (Fig. 5). Nonetheless, these results ought to be understood as ecological correlations and multivariate trends instead of conclusive causal mechanisms. Similar PCA-based ecological gradients have been widely reported in mangrove studies examining relationships among vegetation condition, nutrient cycling, and ecosystem functioning across disturbance gradients (Alongi, 2021). Ultimately, the ordination results indicate that the health of mangrove ecosystems is likely influenced by larger environmental regulatory frameworks and the availability of nutrients within small island coastal systems.

The PCA analysis revealed clear environmental variation across mangrove ecosystem gradients, with relatively intact mangrove zones tending to associate with more stable soil, water, and nutrient conditions, while degraded and pond systems clustered with parameters such as higher COD, temperature, and turbidity. These patterns imply that the configuration of mangrove vegetation might be intimately connected to variations in the capacity for environmental regulation capacity, nutrient dynamics, and trophic conditions. Dense and moderate mangrove systems also tended to exhibit more balanced phytoplankton and fisheries-related indicators compared to degraded systems, indicating potential ecological linkages between habitat condition, primary productivity, and fisheries-supporting functions. Even though the current study was observational and correlational, the reliability of the PCA ordination indicates that alterations in the condition of the mangrove ecosystem could be linked to wider ecological and socio-ecological variations within small island coastal systems like Tanakeke Island. This aligns with extensive coastal studies documenting bottom-up ecological links between nutrient regulation, primary productivity, and fisheries-supporting functions (Castrej *et al*., 2024; Castrejon and Defeo, 2025). Within the context of small island systems such as Tanakeke Island, these patterns further suggest that variation in environmental regulation capacity may be associated with broader socio-ecological consequences related to fisheries productivity (Kolapo and Sieber, 2025) and food security vulnerability (Cure *et al*., 2026). These findings should be interpreted as ecological associations and inferential patterns rather than definitive causal relationships, and further longitudinal or experimental studies would be needed to clarify direct causal pathways linking mangrove ecosystem condition, trophic productivity, and household food security outcomes.

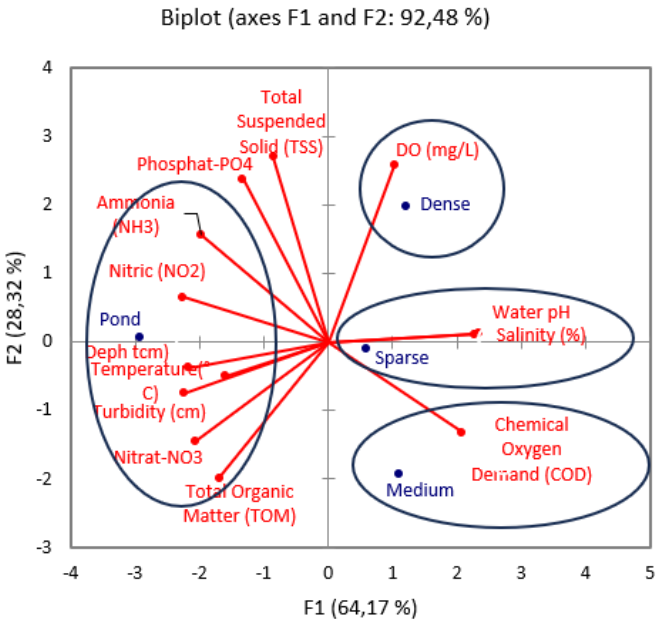

Fig. 5: Mangrove vegetation structure and nutrient availability by PCA biplot

Primary productivity and trophic foundation: phytoplankton, zooplankton, and benthic

Primary productivity provides the energetic foundation of coastal ecosystems, driving energy transfer through trophic levels and sustaining fisheries that underpin coastal livelihoods as illustrated in Fig. 6. Within mangrove-associated systems, primary productivity is strictly governed by ecosystem integrity; specifically, the structural composition of the vegetation dictates nutrient availability, organic matter inputs, and overall environmental stability. These processes shape the composition and dynamics of phytoplankton, zooplankton, and macrobenthic communities, which collectively form the trophic foundation linking ecosystem processes to fisheries productivity and food security. The RACs of phytoplankton, zooplankton, and macrobenthic communities revealed observable variation in trophic structure across mangrove ecosystem gradients. Dense mangrove systems tended to exhibit relatively flatter RAC patterns, indicating higher evenness and more balanced community composition across species ranks. These observed trends suggest a more resilient trophic organization, implying that ecological functions are more widely distributed throughout the system. In contrast, sparse mangrove and pond systems showed steeper RAC patterns, particularly within zooplankton and macro-benthic communities, suggesting stronger dominance by fewer taxa and lower community evenness. Although the present study was observational and correlational in nature, these patterns are consistent with ecological studies suggesting that simplified habitat conditions are often associated with reduced trophic complexity and lower ecological resilience. The observed trophic variation also appeared to correspond with differences in soil, water, and nutrient conditions across ecosystem zones. Dense and moderate mangrove forests tended to exhibit superior environmental stability, which in turn supported relatively balanced assemblages of both planktonic and benthic communities. The dominance of pond systems relative to mangrove cover suggests a potential shift from a relatively regulated ecosystem toward a more simplified

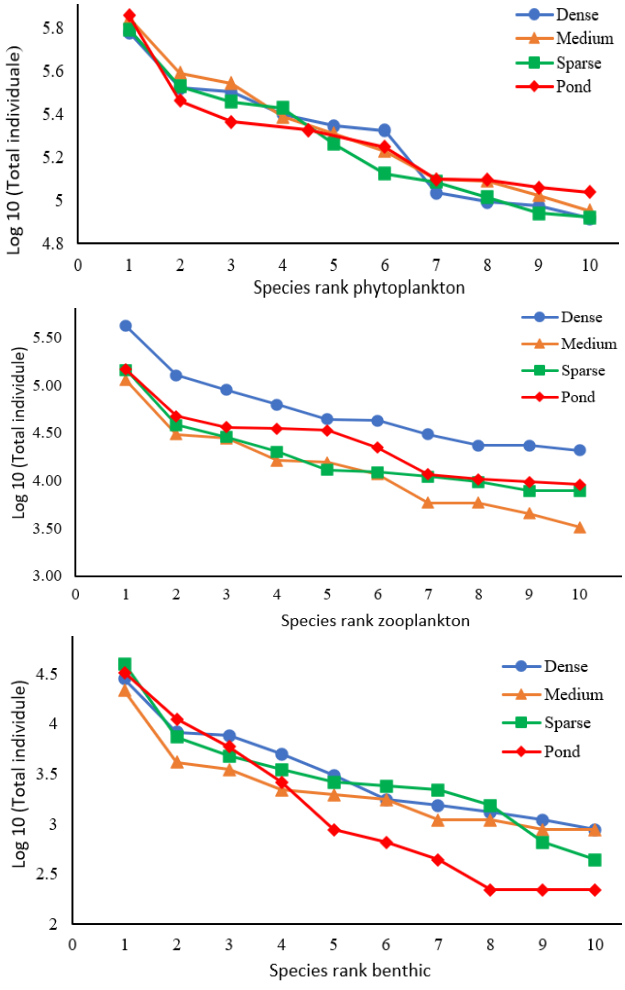

Fig. 6: Changes in trophic community structure across mangrove ecosystem integrity gradients based on RAC of planktonic and benthic communities

and externally dependent ecological state. Such patterns are consistent with ecological threshold theory (Groffman *et al*., 2006), where gradual habitat alteration may eventually reduce ecosystem resilience, nutrient regulation capacity, and trophic stability beyond recoverable limits. Conversely, systems dominated by ponds or showing signs of degradation demonstrated increased environmental fluctuation alongside less complex trophic architectures. Similar bottom-up ecological relationships linking nutrient dynamics, primary productivity (Omokaro 2025), and trophic organization have been widely discussed in coastal ecosystem studies (Aljahdali and Bala, 2025). Within the context of small island socio-ecological systems such as Tanakeke Island, these findings suggest that variation in mangrove ecosystem condition may be associated with broader differences in trophic stability, fisheries-supporting functions, and coastal food system resilience (Ruslan *et al.,* 2022).

Fisheries productivity and ecological dependency

The RAC of fish communities revealed observable differences in community structure across mangrove ecosystem gradients (Fig. 7). In dense mangrove systems, the presence of flatter curves and more extended species distributions reflects increased community evenness, signaling a more balanced distribution of fish assemblages

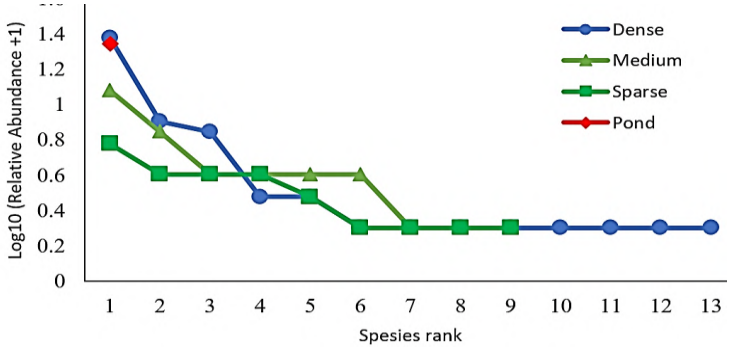

Fig. 7: Rank abundance curves illustrating changes in fish community diversity across mangrove gradient

across species ranks. Moderate mangrove zones showed similar patterns, although with slightly stronger dominance by a few taxa. In contrast, sparse mangrove systems displayed steeper curves and reduced species representation, suggesting lower community complexity and greater dominance by fewer species. In contrast, pond systems demonstrated a streamlined community structure, signaling the limited species richness inherent to habitats heavily altered by aquaculture. The finding indicate that the consistency of RAC patterns across ecosystem gradients suggests that variations in mangrove vegetation structure may be associated with differences in habitat complexity and fisheries-supporting ecological functions (Fig. 7). Dense and moderate mangrove systems, which also tended to exhibit more stable environmental and trophic conditions, were associated with relatively more balanced fish communities compared to degraded and pond-dominated systems. Similar ecological patterns have been reported in mangrove-associated fisheries where structurally complex habitats are often linked with higher community stability, trophic diversity, and nursery functions supporting coastal fish assemblages. Fluctuations in mangrove habitat integrity were reflected in the structural reorganization of trophic networks across planktonic, benthic, and fish assemblages. Dense and moderate mangrove systems tended to exhibit more balanced trophic composition, higher community evenness, and relatively stable RAC patterns, while sparse and pond-dominated systems showed increasing dominance by fewer taxa and simplified trophic structure. Such patterns underscore how variations in habitat complexity and environmental regulation shape trophic connectivity, ultimately dictating energy transfer dynamics within coastal food webs. The observed trophic simplification was also accompanied by lower fisheries indicators and broader household food security vulnerability, indicating potential socio-ecological linkages between ecosystem condition, fisheries sustainability, nutrient availability, and livelihood resilience in small island systems. Ultimately, these multi-taxa patterns highlight that fisheries productivity is intimately tethered to mangrove ecosystem integrity, which operates simultaneously through structural habitat support and top-down or bottom-up trophic regulation (Priya *et al.,* 2023). The transition from diverse and balanced fish communities to simplified and constrained systems represents a key mechanism through which ecosystem degradation undermines food security in small island environments (Galveia and Macusi, 2026).

Livelihood vulnerability and system dependency

These restrictions on fisheries productivity resonate past purely ecological boundaries, fundamentally affecting human livelihoods and illuminating the vulnerability of communities tethered to mangrove ecosystem services (Morris

et al., 2025). The socio-economic profile of households in Tanakeke Island reflects a system characterized by high dependence on natural resources and structural vulnerability (Table 4). The dominance of women respondents (69.35%) highlights their central role in household food management, while the age distribution, concentrated in the productive age range of 31-50 years, indicates active engagement in livelihood activitiesThis vulnerability is compounded by low educational attainment; over 80% of respondents lack formal schooling beyond the elementary level, indicating limited adaptive capacity and highly restricted alternative livelihood pathways. Socio-economic activities in the study area are heavily dictated by marine resources, with fishing and seaweed farming accounting for 53.57% and 23.21% of primary livelihoods, respectively. This structural dependence signifies a heightened vulnerability to environmental fluctuations. This dependency is reinforced by income patterns, where more than half of households earn between United States Dollar (USD) 3 - 6 per day, closely matched by expenditure levels, suggesting minimal financial buffering capacity. Such conditions reflect a narrow margin between income and expenditure, increasing household sensitivity to fluctuations in resource availability. Globally, coastal populations that exhibit high dependence on small-scale fisheries alongside limited economic diversification face severe vulnerabilities to environmental degradation and climatic shifts (Kapapa *et al*., 2024). In this study, these socio-economic conditions interact with ecological changes, creating a cascading vulnerability effect (Cohn *et al*., 2024). Declines in ecosystem integrity reduce fisheries productivity, directly constraining income and limiting access to food, ultimately reinforcing food insecurity (Montano *et al.,* 2025). This feedback mechanism highlights that livelihood vulnerability extends beyond purely economic dimensions, maintaining a direct structural link to overall ecosystem integrity (Vikraman *et al*., 2026).

Food security outcomes

Household survey results revealed that food security conditions in Tanakeke Island remain highly vulnerable across multiple dimensions of the coastal food system (Fig. 8). Only 7.15% of households were classified as food secure, while most experienced moderate (64.58%) or mild (25.59%) food insecurity, and 2.68% faced severe food insecurity. These data demonstrate that food insecurity in Tanakeke extends beyond a short-term disruption, signaling broader structural fragility inherent to the island socio-ecological system. Household food availability appeared to depend strongly on external markets and fisheries-based resources. Market purchases represented the largest food source (45.24%), followed by fisheries and mangrove-related sources (38.39%), while only a relatively small proportion originated from household food production activities (8.33%). This pattern underscores a deficit in local food self-sufficiency, suggesting that household security remains highly contingent upon both fluctuating natural resource productivity and market access. Food access indicators further illustrate economic vulnerability among coastal households. Most respondents were categorized within vulnerable (37.21%) and limited access (33.93%) groups, while only 7.14% were considered food secure in terms of access. Such trends suggest that volatile economic returns and restricted purchasing power act as structural barriers, compromising household food security and dietary diversity. Dietary composition data showed a strong reliance on cereals, fish, and staple carbohydrate sources, while consumption of vegetables, fruits, dairy products, and other nutrient-rich food groups remained relatively low. Despite fish serving as the predominant protein source, the observed low dietary diversity suggests underlying nutritional deficits. Additionally, food security remained highly volatile across the study area, with over half of the households (50.59%) exhibiting high vulnerability, while a distinct minority (13.09%) achieved

Table 4: Socio-economic characteristics and livelihood vulnerability

Variable	Frequency (n)	Percentage (%)
Gender		
Men	103	30.65
Women	233	69.35
Age		
<21	4	1.19
21 - 30	48	14.29
31 - 40	73	21.73
41 - 50	118	35.12
51 - 60	54	16.07
61 - 70	34	10.12
>70	5	1.49
Education status		
Bachelor	1	0.29
Senior high school	22	6.55
Junior high school	37	11.01
Elementary school	137	40.77
Not attend school	139	41.38
Marital status		
Single	10	2.98
Merried	303	90.18
Widower	13	3.87
Widow	10	2.98
Divorced	0	0
Livelihood		
Seaweed farmers	78	23.21
Fisherman	180	53.57
Sheelfish fisherman	23	6.85
Seaweed binders	6	1.79
Fish buyer	3	0.89
Charcoal maker	28	8.33
Fish farmer	18	5.36
Household income		
≤ 50.000	31	9.23
50.001 – 100.000	170	50.6
100.001 – 150.000	91	27.08
150.001 – 200.000	24	7.14
> 200.000	20	5.95
Household expenditure		
≤ 50.000	47	13.99
50.001 – 100.000	218	64.88
100.001 – 150.000	66	19.65
150.001 – 200.000	3	0.89
> 200.000	2	0.59

relatively stable food security statuses. Household perceptions further supported this pattern, with 61.01% reporting declining food availability from mangrove and fisheries resources. Although the present study was observational in nature, the consistency between ecological and household-level patterns suggests that changes in mangrove ecosystem conditions may be associated with broader food security vulnerability in small island coastal systems. Household decision-making patterns reveal that women play a dominant role in food purchasing and management, highlighting their critical contribution to maintaining household food security under constrained conditions. However, these metrics also reveal an inequitable distribution of labor, wherein the responsibility for mitigating food insecurity is disproportionately borne by women—a reflection of entrenched social hierarchies within the socio-ecological system. Taken together, these findings

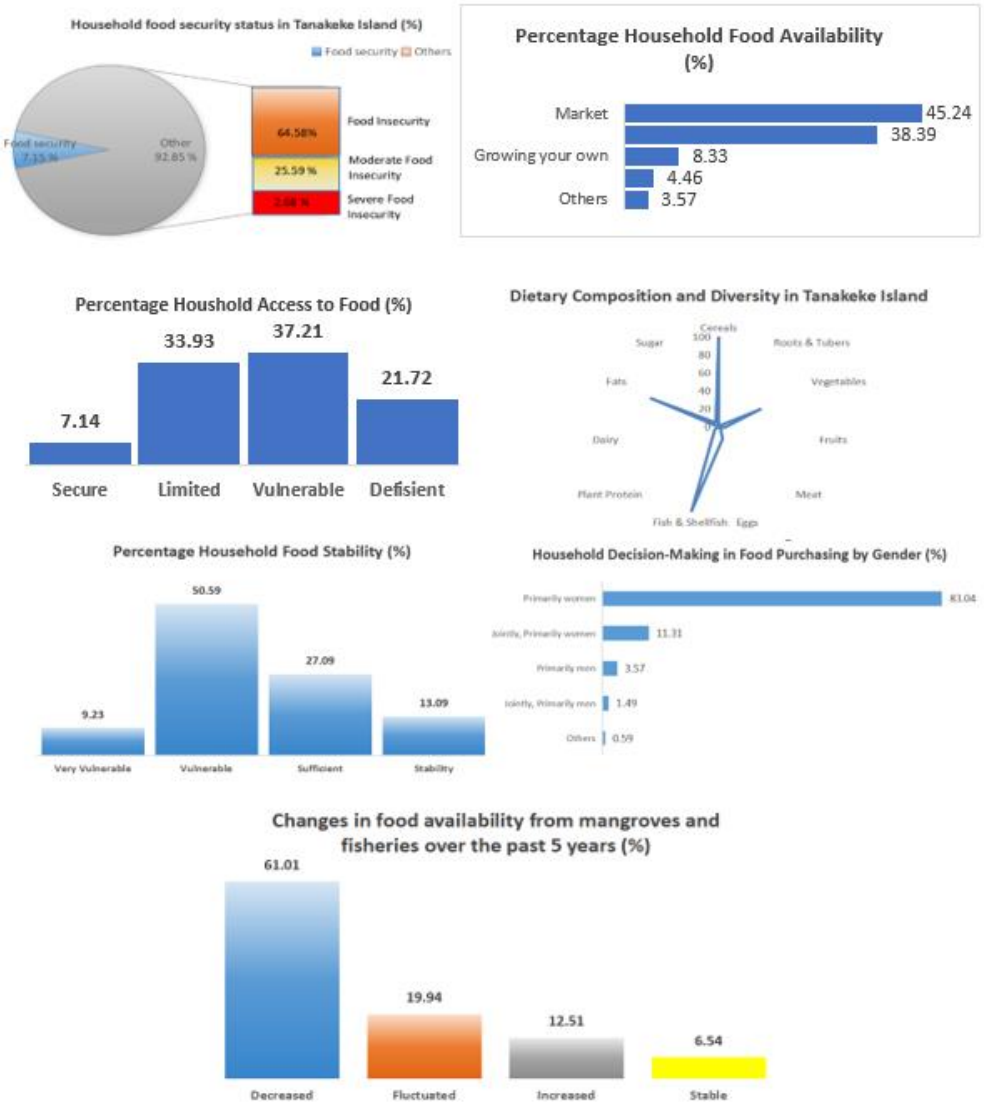

Fig. 8: Multidimensional household food security outcomes and ecosystem dependency in Tanakeke Island

illustrate a tightly coupled socio-ecological system in which food security outcomes are directly shaped by ecosystem conditions (Yan *et al.*, 2026). Declines in mangrove integrity reduce fisheries productivity which in turn limits income and food availability, ultimately constraining access, utilisation, and stability. These cascading dynamics demonstrate that the long-term viability of coastal food systems is fundamentally contingent upon maintaining overarching ecosystem integrity (Varyvoda and Uglas, 2022). Overall, food security in Tanakeke Island is not merely a function of food supply, but an emergent property of ecosystem-dependent livelihoods. The strong reliance on mangrove-associated fisheries, combined with limited diversification and declining ecosystem productivity, creates a structurally vulnerable system. Ultimately, these results underscore that preserving mangrove ecosystem integrity is a dual necessity, functioning

both as a cornerstone for ecological sustainability and a prerequisite for fostering resilient, equitable food systems within small island settings (Akram *et al*., 2023). Table 5 shows significant relationships among fisheries productivity, household economic conditions, and food security indicators on Tanakeke Island. CPUE among fishers exhibited a strong positive correlation with household income ($r = 0.687$; $p < 0.01$), suggesting that higher fisheries productivity tended to be associated with increased household earnings. CPUE exhibited a positive correlation with household expenditure ($r = 0.320$; $p < 0.01$), indicating that households with higher fish typically possessed higher purchasing power and economic engagement. Food insecurity, measured using the HFIAS, showed significant negative correlations with CPUE ($r = –0.517$; $p < 0.01$) and household income ($r = –0.530$; $p < 0.01$). These configurations demonstrate that lower fisheries yields and constrained incomes collectively exacerbate household vulnerability to food insecurity. Meanwhile, HDDS exhibited weak but significant positive correlations with CPUE ($r = 0.110$; $p < 0.05$) and income ($r = 0.114$; $p < 0.05$), indicating that improved fisheries productivity and economic conditions may be associated with slightly better dietary diversity. The negative correlation between HFIAS and HDDS ($r = –0.202$; $p < 0.01$) further suggests that households experiencing higher food insecurity tended to have lower dietary diversity. Overall, the observed correlation patterns imply vital socio-ecological relationships between fisheries productivity, the economic capacity of households, and the outcomes related to food security. In small island systems where livelihoods remain highly dependent on fisheries resources, fluctuations in fisheries productivity may influence not only household income but also food access and dietary quality. These results reinforce the consensus in coastal food system literature that a community's vulnerability to food insecurity is heavily mediated by local ecological conditions and corresponding fisheries performance (Ruslan *et al*., 2022). These trade-offs indicate that increasing dominance of aquaculture ponds beyond ecological carrying capacity may weaken the long-term resilience of small island coastal food systems. The findings suggest important long-term ecological and socio-economic trade-offs between mangrove conservation and aquaculture intensification in Tanakeke Island. These dynamics highlight a distinct socio-ecological trade-off: localized pond expansion generates short-term economic gains but correlates significantly with diminished mangrove integrity, simplified trophic webs, and degraded environmental regulatory capacity.

Governance

Beyond biophysical processes, the sustainability of mangrove-dependent fisheries and food systems is strongly shaped by socio-ecological drivers and governance dynamics. Within fragile small island systems like Tanakeke, the complex interplay between ecological conditions, institutional capacity, and stakeholder dynamics dictates whether ecosystem integrity is successfully maintained or progressively degraded. Several variables, as observed in Fig. 9, including local community participation, mangrove rehabilitation efforts, and market access, exhibit both high influence and high dependence, positioning them as critical linkage factors within the system. These elements act as connectors between ecological processes and socio-economic outcomes, mediating the translation of ecosystem services into livelihood benefits. Owing to this dual role, these actors exhibit heightened sensitivity to environmental shifts and occupy a highly strategic position for targeted intervention. The influence-dependence dynamics reveal that Tanakeke Island's mangrove management is embedded within a tightly coupled socio-ecological framework, where local food security directly hinges on the alignment of ecological health, fisheries yield, and institutional governance. Variables related to food availability, access, and stability were positioned within

Table 5: The Relationship between CPUE, revenue, expenditures, HFIAS, and HDDS

Variables	CPUE Nelayan	Pendapatan	Pengeluaran	HFIAS	HDDS
CPUE	1	0.687**	0.320**	-0.517**	0.110*
Income		1	0.289**	-0.530**	0.114*
Expenditure			1	-0.251**	0.078
HFIAS				1	-0.202**
HDDS					1

Note: ** p-value < 0.01; * p-value < 0.05

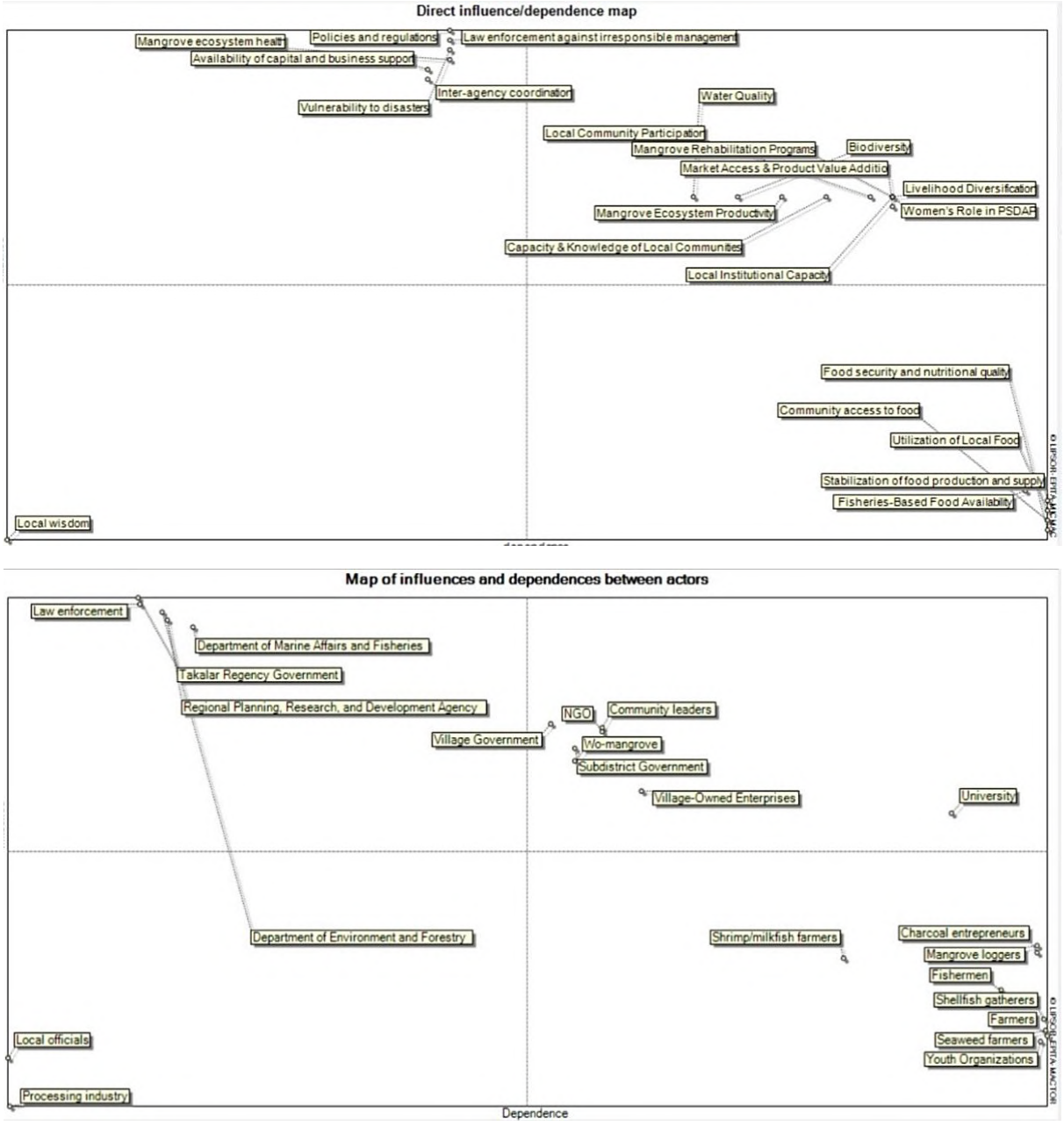

Fig. 9: Influence-dependence structure of key variables and actors in mangrove-based food systems

high-dependence zones, indicating that household food security may be strongly shaped by upstream environmental and institutional processes. Actor analysis further revealed notable asymmetries among stakeholders. The influence-dependence structure highlights that state environmental and fisheries agencies function as highly influential actors, driving both policy formulation and resource governance frameworks. In contrast, local actors such as fishers, seaweed farmers, and small-scale producers appeared highly dependent on ecosystem conditions while having relatively limited influence over decision-making processes. Community leaders and village level institutions occupied intermediate positions, suggesting their potential role as bridging actors capable of connecting governance frameworks with local practices. Although this study was observational and systems-oriented in nature, the overall influence-dependence structure suggests that weak coordination, limited institutional capacity, and ineffective governance may be associated with declining ecosystem integrity and increased livelihood vulnerability within small island coastal systems. Overall, these findings underscore that mangrove ecosystem integrity is a function of a deeply integrated socio-ecological system, shaped by the continuous feedback between ecological variables and institutional arrangements (Chaves and Christine, 2025). The imbalance between highly influential governance actors and highly dependent local communities highlights a critical gap that must be addressed to achieve sustainable fisheries and resilient food systems (Hayashida-Carillo, 2025). Enhancing the integration of governance and community involvement is crucial for preserving ecosystem functionality and ensuring long-term food security in small island environment (Subroto *et al.*, 2026).

Conceptual framework: Linking mangrove ecosystem integrity to multidimensional food security

This study presents a conceptual system dynamics model that elucidates how mangrove ecosystem integrity structurally drives fisheries productivity, livelihood capacity, and ultimately shapes multidimensional food security outcomes in small island socio-ecological systems. The established model reveals that the integrity of the mangrove ecosystem is not solely an ecological aspect, but functions as the foundational structure of the coastal food system, as depicted in Fig. 10. On Tanakeke Island, significant differences in vegetation structure, Shannon-Wiener Index, important value index, density, soil quality, water quality, phytoplankton, and fish abundance indicate that ecosystem integrity determines the system's capacity to support key ecological functions. Environmental degradation within the aquaculture zone serves as an indicator of disrupted nutrient cycling and biogeochemical processes, ultimately destabilizing ecosystem productivity. Importantly, this study also reveals that the current landscape composition of Tanakeke Island has exceeded its ecological carrying capacity threshold. The island currently consists of approximately 1,343 hectares (ha) of mangroves and 1,967 ha of aquaculture ponds, representing a ratio of roughly 40% mangrove to 60% pond area. Rather than being defined as a rigid numerical boundary, the ecological threshold on Tanakeke Island was deduced from persistent socio-ecological patterns linked to the current landscape configuration of approximately 40% mangrove cover and 60% aquaculture ponds. This interpretation was supported by integrated indicators, including reduced vegetation diversity, altered nutrient and water quality parameters, trophic simplification reflected in RAC patterns, declining fisheries indicators, and widespread household food insecurity. Collectively, these trends demonstrate an ongoing shift away from a stable, locally regulated ecosystem toward an ecologically simplified state characterized by heightened external socio-ecological state. These findings suggest that environmental degradation may contribute to broader socio-ecological vulnerability and livelihood instability. The relationship between mangrove ecosystems and

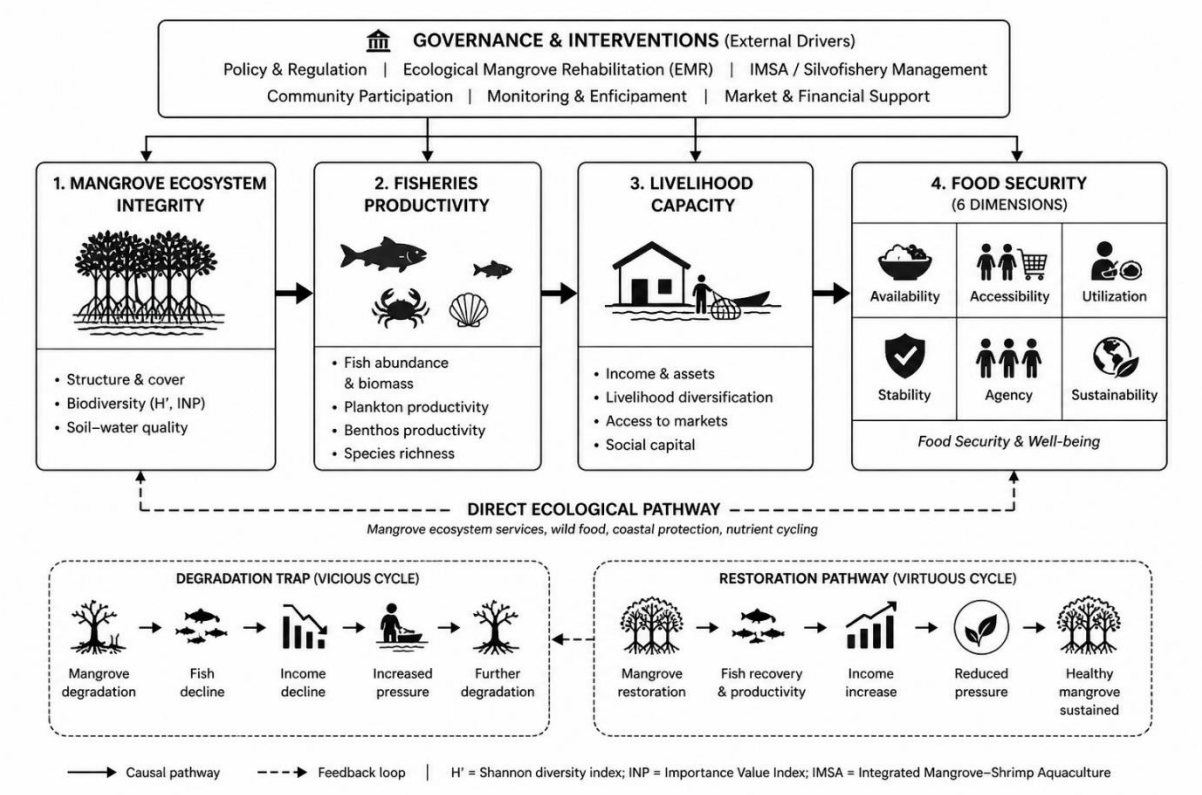

Fig. 10: Mangrove ecosystem integrity as a foundation of food security in small island socio-ecological systems

fishery productivity in this study is not linear but rather operates through cascading trophic processes that link habitat structure to food-web dynamics. The analysis reveals that the presence of phytoplankton, zooplankton, and macrobenthos is typically elevated in mangrove zones characterized by robust ecosystem conditions, alongside a more consistent community structure as demonstrated by the RAC. This pattern is consistent with global studies showing that mangroves support fisheries productivity through trophic support, nursery habitat provision, and environmental stabilization (Cure *et al.,* 2026; Carrasquilla-Henao *et al.*, 2022). Recent studies also demonstrated that mangrove ecosystem characteristics strongly regulate coastal ecological stability and aquatic habitat quality (Suyadi *et al.,* 2025). One of the key contributions of this model is identifying livelihood capacity as a transmission channel linking ecological productivity to household food security. Regions characterized by superior environmental quality typically exhibited more resilient fisheries productivity and livelihood outcomes. Studies integrating morphological and molecular approaches further confirmed that healthy mangrove ecosystems support higher fish diversity and ecological connectivity within coastal waters (Basyuni *et al.,* 2025b). This aligns with findings from various studies, which emphasise that the fisheries sector in coastal areas functions not only as a food source but also as a key pillar of household economies, determining access to food (Swan *et al.*, 2026). Unlike conventional approaches that assess food security solely in terms of availability, this study adopts a six-dimensional framework, namely availability, accessibility, utilization, stability, agency, and

sustainability. The assessment underscores a distinct food security imbalance: while the availability dimension is relatively secure, localized accessibility and long-term stability present significant institutional hurdles. Low HDDS values (4–4.7) and the small proportion of food-secure households (±7%) suggest that food insecurity is shaped not only by production limitations, but also by weak access and system resilience. These findings strengthen the perspective that food security arises from intricate interactions among ecological, economic, and social factors, instead of just a result of the production system (Wallner-Hahn *et al.,* 2022). The dynamic system model developed in this study identifies two main pathways: the degradation trap and the restoration pathway, which explain the long-term dynamics of the socio-ecological system in Tanakeke. The degradation pathway highlights a distinct socio-ecological cascade: contracting mangrove cover impairs fisheries productivity, which directly translates into reduced community income. This situation increases pressure on resources, such as aquaculture expansion and overexploitation, ultimately accelerating ecosystem degradation. Comparable findings showed that mangrove degradation and illegal logging significantly reduce ecosystem carbon stocks and ecological resilience in tropical coastal systems (Basyuni *et al.,* 2025a). This phenomenon aligns with the concept of the "poverty environment trap" commonly observed in tropical coastal regions (Sanga *et al*., 2026). Conversely, the restoration pathway demonstrates that nature-based interventions such as ecological mangrove rehabilitation (EMR) and integrated mangrove sustainable aquaculture (IMSA) can trigger a positive cycle. Enhanced ecological conditions can bolster fisheries productivity, augment local incomes, and alleviate pressure on natural resources, thereby fostering a more resilient socio-ecological system.

CONCLUSION

This study demonstrates that mangrove ecosystem integrity is closely associated with fisheries productivity, livelihood resilience, and food security within small island socio–ecological systems. Across the observed ecological gradient in Tanakeke Island, the transition from relatively intact mangrove ecosystems to pond-dominated landscapes was consistently accompanied by reduced environmental regulation capacity, trophic simplification, declining fisheries indicators, and widespread household food insecurity. These findings suggest that changes in mangrove ecosystem condition may influence coastal food systems through interconnected ecological and socio-economic pathways linking nutrient dynamics, trophic productivity, fisheries performance, and household livelihoods. The study further demonstrates that small island food insecurity is not merely a function of food availability or fisheries production but is shaped by multi-dimensional vulnerabilities. Despite the continued contribution of marine resources to household diets, low dietary diversity, unstable livelihoods, and limited adaptive capacity suggest that food security outcomes are strongly associated with broader ecological and socio-economic vulnerability. Beyond their roles in carbon sequestration and shoreline stabilization, mangrove ecosystems function as critical ecological infrastructure that directly safeguards fisheries sustainability, household livelihood stability, and broader food system resilience. Conceptually, this research contributes by integrating ecosystem integrity, trophic dynamics, fisheries productivity, livelihood resilience, ecological carrying capacity, and multidimensional food security within a unified socio-ecological framework. While the observational and correlational nature of this study precludes definitive causal assertions, the persistent alignment of ecological, fisheries, and household-

level data offers compelling inferential evidence of the tight coupling between mangrove ecosystems and small island food systems. From a management perspective, strengthening food security and climate resilience in coastal areas requires integrated ecosystem-based approaches that simultaneously restore mangrove ecological functions, improve fisheries sustainability, support livelihood diversification, and strengthen inclusive community-based governance systems. To enhance long-term socio-ecological resilience within small island coastal systems, strategic interventions must prioritize EMR, hydrological restoration, IMSA models, livelihood diversification, and robust, collaborative community governance.

AUTHORS' CONTRIBUTIONS

R. Fadilah contributed to this study by formulating the research concept, designing the experiment, applying for funding, analyzing the data, writing the initial draft of the manuscript, and refining the manuscript. C. Kusmana contributed to formulating the research concept, supporting the writing, reviewing, and revising the manuscript. S.H. Sutjahjo contributed to formulating the research concept, supporting the writing, reviewing, and revising the manuscript. Sulistiono contributed to formulating the research concept, supporting the writing, reviewing, and revising the manuscript. Machfud contributed to formulating the research concept, supporting the writing, reviewing, revising, editing, and validating the 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, 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
cm	Centimeter
COD	Chemical oxygen demand
CPUE	Catch per unit effort
DO	Dissolved oxygen
E	East
E	Evenness
EMR	Ecological mangrove rehabilitation
ES	ecosystem services
FGD	Focus group discussion
H'	Shannon-Wiener Diversity
ha	Hectare
HDDS	Household dietary diversity score
HFIAS	Household food insecurity access scale
IMSA	Integrated mangrove sustainable aquaculture
IVI	Importance value index
g	Gram
km²	Square kilometers
MAKTOR	Matrix of alliance and conflict: tactic, objectives and recommendation
MAO	Matrix of actor objectives
MDI	Matrix of direct influence
m	Meter
MICMAC	Matrix of cross impact analysis
NH_3	Ammonia
NO_3^-	Nitrate
NO_2^-	Nitrite
PA	Principal analysis
PCA	Principal component analysis
PO_4^{3-}	Phosphate
RAC	Rank abundance curve
SES	Social-ecological systems
SD	Standard deviation
S	South
TOM	Total organic matter
TSS	Total suspended solids
USD	United States Dollar

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ORIGINAL RESEARCH ARTICLE

Isolation and application of indigenous microorganisms for hydrogen sulfide removal from biogas via biofiltration

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ABSTRACT

BACKGROUND AND OBJECTIVES: Hydrogen sulfide is a major contaminant in biogas that leads to corrosion of equipment, unpleasant odors, and reduced energy efficiency. Alternative approaches for the elimination of hydrogen sulfide, including chemical scrubbing and adsorption, frequently incur high costs and pose environmental challenges. In contrast, biological removal using microorganisms has emerged as a sustainable and cost-effective alternative. Therefore, the study objectives were to isolate and evaluate efficient microorganisms for hydrogen sulfide removal from biogas and to assess their performance in a biofiltration system.

METHODS: Soil samples were collected from a swine farm and enriched in sulfur-based selective media to isolate hydrogen sulfide -degrading microorganisms. Two strains, *Sphingomonas paucimobilis* and *Enterobacter cloacae*, were selected based on their growth and hydrogen sulfide removal capability. The strains were fixed onto coconut husk and implemented in a laboratory-scale biofilter. Biogas composition was analyzed before treatment, and hydrogen sulfide removal efficiency was evaluated at gas flow rates of 0.3–0.5 liters per minute, corresponding to empty bed residence times of 4.0–6.6 minutes.

FINDINGS: The initial hydrogen sulfide concentration in untreated biogas was 4,281 (±26) part per million. Both strains exhibited the capability to mitigate hydrogen sulfide, with removal efficiencies progressively enhancing throughout the operational phase, thereby suggesting microbial adaptation and subsequent biofilm establishment on the coconut husk matrix. The biofilter inoculated with *Sphingomonas paucimobilis* showed a rapid increase in performance, achieving 36.5 percent removal on day 1, increasing to over 80 percent within the first week, and reaching a maximum efficiency of 84.8 percent on day 13. During the stable phase of operation, the system maintained relatively high removal efficiencies before showing a slight decline toward the end of the experiment, possibly due to substrate limitation or accumulation of metabolic by-products. Under similar operating conditions, the biofilter utilizing *Enterobacter cloacae* demonstrated inferior performance, reaching a maximum removal efficiency of only 76.7 percent alongside reduced long-term stability.

CONCLUSION: Overall, *Sphingomonas paucimobilis* exhibited superior performance in hydrogen sulfide removal compared to *Enterobacter cloacae*. The results indicate that this strain possesses significant potential for use in biofiltration systems aimed at biogas purification, providing an eco-friendly and sustainable method for the reduction to mitigate sulfide.

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INTRODUCTION

Biogas is a renewable energy source generated through the anaerobic digestion of organic materials. Its composition primarily consists of methane (CH_4) with 50–70 percent (%) and carbon dioxide (CO_2), with 20–50%, with lesser amounts of nitrogen (N_2), with 0–5% oxygen (O_2), with 0–2% ammonia (NH_3), with 0–1% and hydrogen sulfide (H_2S) with 0.005–2%, equivalent to 50–10,000 part per million (ppm) (Sun *et al.,* 2015). H_2S is a colorless, flammable, and water-soluble gas that is denser than ambient air. Well-known for its characteristic rotten-egg odor, the compound poses severe respiratory hazards and acts as a potent irritant to the eyes and upper respiratory tract. Additionally, H_2S exhibits strong corrosive properties, particularly toward metals, accelerating oxidation and corrosion. This gas is commonly encountered in various industries, such as petroleum refining, food processing, livestock farming, wastewater treatment, and biogas production. The rapid reaction of H_2S with moisture within biogas systems yields sulfuric acid, resulting in a highly corrosive environment. The resulting acid can significantly degrade equipment, machinery, and internal combustion engines utilized in biogas-fueled power generation, leading to higher maintenance costs and reduced system lifespan. Therefore, the removal of H_2S from biogas before its utilization is essential to ensure environmental protection (Lee *et al*., 2007; Takuwa *et al*., 2009). Efficient H_2S removal is imperative prior to biogas formatting to maximize energy output and ensure system longevity. Existing desulfurization technologies typically fall into two main categories: chemical and biological treatments. Chemical treatments involve liquid-phase reactions, precipitation of sulfur into insoluble solids, and absorption via membrane-based technologies (Horikawa *et al*., 2004). Chemical treatment remains a dominant approach for H_2S removal from natural gas, largely due to its high efficiency and compatibility with industrial-scale systems. However, numerous drawbacks are increasingly drawing attention to its long-term practicality and environmental sustainability. Technologies such as amine scrubbing, iron oxide-based absorption, and chemical oxidation have been widely implemented, yet they present challenges related to cost, safety, environmental impact, and system complexity. Among the most widely utilized techniques is amine-based scrubbing, which employs alkanolamine solvents such as monoethanolamine (MEA) and diethanolamine (DEA). While effective, this method is characterized by significant energy requirements, particularly during the solvent regeneration phase which involves high-temperature steam stripping. Solvent degradation via oxidation and thermal pathways progressively generates heat-stable salts over time. Consequently, the accumulation of these byproducts drives up operational costs and maintenance overhead due to the necessity of periodic waste disposal and solvent replenishment (Ma *et al*., 2025; Wang *et al*., 2011). Iron-based adsorbents, such as iron sponge systems, are also employed for H_2S capture, particularly in small- to medium-scale gas streams. In these systems, H_2S reacts with iron oxide to form iron sulfide. Although initially effective, the adsorbent material becomes saturated quickly and must be regenerated or replaced (Phothilangka*,* 2026). The regeneration process, typically involving air oxidation, poses a fire risk due to the formation of pyrophoric iron sulfide—a major safety concern in continuous operations (Choudhury and Lansing, 2021). Chemical oxidants, including hydrogen peroxide, sodium hypochlorite, and potassium permanganate, directly convert H_2S into sulfate or elemental sulfur. Despite its operational simplicity, this method often produces secondary waste streams, such as sulfate-rich brines and chemical residues. Managing these byproducts necessitates downstream treatment, escalating operational complexity and environmental overhead (Pu *et al*., 2018). Another key limitation of chemical processes lies in their non-specificity.

Chemical oxidants may react not only with H_2S but also with other reduced compounds or interfering gases, thereby reducing treatment efficiency and increasing chemical consumption. For instance, in gas streams containing substantial amounts of carbon dioxide, amine-based scrubbers exhibit reduced selectivity due to CO_2 co-absorption, further lowering the system's capacity for H_2S removal (Mandal and Bandyopadhyay, 2006). Operational limitations arise when chemical treatments are deployed in dynamic environments; specifically, fluctuations in gas flow or shifting H_2S levels disrupt the precise stoichiometry necessary to maintain optimal reaction efficiency. Unlike biological systems that self-adjust via microbial activity, chemical systems are less adaptable and can experience rapid performance drops under non-ideal conditions (Syed *et al*., 2006; Abatzoglou and Boivin, 2009). Biological processes, particularly biofiltration, offer a sustainable alternative. Biofiltration systems utilize microorganisms to degrade gaseous pollutants, providing key advantages such as lower investment and operational costs, simplified maintenance, and minimal secondary waste generation (Kolekar *et al*., 2019). Biofiltration utilizing indigenous microorganisms presents significant environmental, operational, and economic advantages over conventional physicochemical desulfurization technologies. Biological systems operate under mild conditions with lower energy requirements and minimal chemical consumption, thereby reducing secondary pollution and hazardous waste generation. The use of locally adapted microbial communities may further decrease startup time, improve process resilience, and lower operational costs associated with inoculum preparation and reactor maintenance. Such benefits make biological desulfurization an ideal candidate for decentralized agricultural biogas applications. Within this domain, biological desulfurization leveraging sulfur-oxidizing bacteria (SOB) is rapidly emerging as a sustainable and economically advantageous alternative to traditional physical or chemical methods. SOB represent a metabolically diverse group capable of transforming reduced sulfur species like H_2S into elemental sulfur (S) or sulfate (SO_4^{2-}) through enzymatic oxidation. These pathways typically involve key catalytic systems such as the Sox enzyme complex, sulfur dioxygenases, and flavocytochrome c sulfide dehydrogenases (Tang *et al*., 2009). Depending on the microbial strain and operating conditions, H_2S can be oxidized fully into sulfate or partially into elemental sulfur, the latter being desirable for recovery as a valuable byproduct (Friedrich *et al*., 2005). Microbial desulfurization via SOB converts aggressive sulfur compounds into stable, non-corrosive derivatives. This biological mitigation is essential for preventing the degradation of biogas-powered engines and generation equipment. SOB are capable of converting H_2S into elemental sulfur (S) through partial oxidation, or into SO_4^{2-} via complete oxidation. Additionally, other reduced sulfur compounds such as thiosulfate ($S_2O_3^{2-}$) and tetrathionate ($S_4O_6^{2-}$) can also be oxidized to sulfate by these microorganisms (Rujisangvittaya and Phoolphundh, 2015). These microorganisms are categorized into two primary groups: 1) Autotrophic bacteria, which synthesize their own organic compounds using carbon dioxide as their carbon source. Within this group, some species harness light energy (Phototrophic Bacteria), while others derive energy from inorganic substances (Chemoautotrophs). 2) Heterotrophic Bacteria, which rely on external organic matter as their carbon source. Certain species utilize light for energy (Photoheterotrophs), whereas others depend on organic compounds (Chemoheterotrophs) to sustain their metabolic activities (Kolekar *et al*., 2019). The biological removal process of H_2S increases the sulfate concentration within the recirculation medium. Concurrently, this accumulation of sulfate correlates with a progressive improvement in hydrogen sulfide removal efficiency (Ramírez *et al.,* 2009). Various SOB strains, including *Fastidiosipila*, *Enterobacter*, *Sphingomonas*, *Hydrogenophaga*, *Pseudomonas*

alcaligenes, *Rhodopseudomonas*, *Sphingobium yanoikuyae*, *Pseudomonas anguilliseptica*, *Enhydrobacter aerosaccus*, and *Acidithiobacillus thiooxidans*, have shown significant potential for improving biological hydrogen sulfide removal processes (Cheng *et al*., 2018; Namgung *et al*., 2012; Nisola *et al*., 2010). Numerous microbial strains including *Acidithiobacillus*, *Paracoccus*, and *Thiobacillus* have demonstrated efficient H_2S removal under varying environmental conditions. Previous studies have shown that sulfur-oxidizing microorganisms such as *Acidithiobacillus*, *Thiobacillus*, and *Paracoccus* can achieve H_2S removal efficiencies exceeding 90–99% under optimized operating conditions (Syed *et al.*, 2006; Janssen *et al.*, 2009). Syed *et al.* (2006) reported that a mixed SOB culture in a biofiltration system achieved more than 95% efficiency in converting H_2S into sulfur. Janssen *et al.* (2009) further described a large-scale biological desulfurization system treating gas streams containing more than 2,000 ppm H_2S with removal efficiencies exceeding 99%. Despite exhibiting high efficiency, numerous engineered or commercially cultivated microbial strains necessitate strict environmental control to sustain stable metabolic activity. Indigenous microbial consortia may offer advantages in long-term stability and resistance to fluctuating field conditions due to their prior acclimation to the local biogas environment. Indigenous microorganisms isolated from swine farm environments are considered promising candidates for biological desulfurization because they are naturally adapted to elevated concentrations of hydrogen sulfide, ammonia, moisture, and organic contaminants commonly found in livestock biogas systems (Biró *et al.*, 2025). Compared with externally introduced or commercially cultivated strains, native microbial consortia generally exhibit superior environmental adaptability, enhanced biofilm formation capability, and greater tolerance to fluctuating operational conditions (Handayani *et al.*, 2024). Furthermore, the use of indigenous microorganisms may reduce reactor acclimation time and improve long-term biofilter stability under field conditions, particularly in tropical agricultural environments. Systems designed for biological desulfurization include packed-bed biofilters, biotrickling filters, and suspended growth reactors (Kulkarni and Ghanegaonkar, 2019). Compared with externally introduced or commercially cultivated strains, native microbial consortia generally exhibit superior environmental adaptability, enhanced biofilm formation capability, and greater tolerance to fluctuating operational conditions (Fortuny *et al*., 2008). Although SOB-based systems have not been widely deployed at large scale for natural gas, pilot trials show significant promise. For instance, Janssen *et al*. (2009) described a large-scale installation treating gas streams with H_2S levels exceeding 2,000 ppm, which consistently achieved removal rates greater than 99%. These findings underscore the potential of SOB in commercial gas treatment when operated under optimized conditions. Performance of SOB-driven systems is sensitive to a range of operational variables such as potential of hydrogen (pH), oxygen concentration, temperature, and nutrient availability. To favor the partial oxidation of H_2S to elemental sulfur over complete oxidation to sulfate, the maintenance of strictly regulated microaerobic conditions is imperative (Kleinjan *et al*., 2005). Studies involving microbial community profiling have revealed dominance of strains like *Sulfurimonas* and *Halothiobacillus* in systems tailored for gas-phase desulfurization (Tang *et al*., 2009). Current biotechnological research focuses on genetic modification to bolster microbial resilience against toxic intermediates, thereby maximizing metabolic oxidation efficiency. Concurrently, hybrid treatment strategies combining SOB with physicochemical processes are gaining interest, aiming to improve system resilience and throughput (Rasi *et al*., 2011). Notwithstanding these benefits, widespread adoption remains constrained by critical engineering and biological limitations. Operational challenges such as biomass

overgrowth, biofilm instability, and sulfur scaling must be addressed to maintain consistent performance. To address these limitations, recent studies have shifted toward optimizing bioreactor architecture, implementing process automation, and identifying robust microbial strains capable of delivering high removal efficiency and long-term stability. In this context**,** the present study aims to isolate and evaluate effective microorganisms for H_2S removal from biogas and to assess their performance in a biofiltration system. The study was conducted in Lampang, Thailand, during 2024–2025.

MATERIALS AND METHODS

Isolation of microorganisms from a swine farm

Soil samples were collected from multiple sites along the perimeter of a wastewater treatment pond within the swine farm. These samples provided the inoculum source for isolating indigenous microorganisms capable of H_2S biodegradation under laboratory conditions. The gathered soil was subjected to a tenfold serial dilution series, followed by microbial isolation using the spread plate method. An aliquot of 0.1 milliliters (mL) from each dilution level was plated onto a selective medium formulated for the cultivation of SOB. The medium composition per liter of distilled water was as follows: 1.2 grams (g) Ammonium sulfate (Na_2HPO_4), 1.8 g Potassium dihydrogen phosphate (KH_2PO_4), 0.1 g Magnesium sulfate heptahydrate ($MgSO_4$).$7H_2O$, 0.1 g Ammonium sulfate [$(NH_4)_2SO_4$], 0.03 g Calcium chloride ($CaCl_2$), 0.01 g Ferric chloride hexahydrate ($FeCl_3$).$6H_2O$, 0.02 g Manganese sulfate tetrahydrate ($MnSO_4$).$4H_2O$, 10 g Sodium thiosulfate pentahydrate ($Na_2S_2O_3$).$5H_2O$, 0.5 g Sodium bicarbonate ($NaHCO_3$), 2.0 g Potassium nitrate (KNO_3) and 15 g Agar. The inoculated plates were incubated at 37°C for five days. Candidate indigenous microorganisms were selected according to their ability to utilize sulfur compounds for growth and their underlying sulfur-oxidizing potential. Furthermore, these specific isolates exhibited remarkably rapid growth kinetics and enhanced resilience to environmental fluctuations compared to the remaining pool of isolates. Subsequently, distinct single colonies that successfully proliferated on the selective medium were carefully isolated and maintained on sulfur-supplemented slant agar for further study (Duangporn *et al*., 2008). Microbial identification was performed using the VITEK®2 COMPACT automated microbial identification system for microbial classification and species identification, which is based on biochemical profiling and phenotypic characteristics.

Preparation of microbial inoculum and biofilter packing material

Pure microbial cultures were transferred into 100 mL sulfur liquid medium in 250 mL Erlenmeyer flasks and incubated at 37 degrees Celsius (°C) with agitation at 120 revolutions per minute (rpm) for 3 days. The cultures were subsequently scaled up in 3.5 liters (L) sulfur liquid medium using a 6 L culture vessel to obtain sufficient biomass for biofilter inoculation. Owing to its local availability and low cost, coconut husk serves as an ideal biofiltration packing matrix. This material possesses a highly porous architecture and high moisture retention capacity, both of which actively promote microbial attachment and robust biofilm development. Its fragments (1–3 centimeters (cm)) were sieved to remove fine particles, washed with distilled water, and sterilized by autoclaving at 121°C and 15 pounds per square inch (psi) for 20 minutes (min). The prepared microbial inoculum was immobilized onto the coconut husk at a ratio of 7 L inoculum per 2 kilograms (kg) (10^7 colony forming units per milliliter (cfu/mL)) packing material and incubated for 3 days prior to application in the biofiltration system. Subsequently, the inoculated packing material was conditioned to maintain a moisture content of approximately 50–60% before being packed into the biofilter column. The column was sequentially charged with the coconut husk

substrate to achieve a target packing density of approximately 200 kilogram per cubic meter (kg/m³).

Biofilter setup and operation

The biofiltration system consisted of a transparent acrylic column with a diameter of 2 inches and a height of 1 meter (m) operated in an upflow mode. Biogas was introduced through the bottom inlet of the column and discharged via the top outlet. The reactor was packed with coconut husk supporting the immobilized microbial consortia. Three experimental conditions were established:

i. biofilter inoculated with *Enterobacter cloacae* FLB11,
ii. biofilter inoculated with *Sphingomonas paucimobilis* A21, and
iii. uninoculated control containing only coconut husk.

Each experimental condition was performed in 3 replicates.Biogas was continuously supplied at a flow rate of 0.3–0.5 liters per minute (L/min), corresponding to an empty bed residence time (EBRT) of approximately 4.0–6.6 min. The gas flow rates were regulated by control valves and monitored via flow meters, with the comprehensive layout of the biofiltration system schematically illustrated in Fig. 1. Moisture content within the biofilter bed was maintained at approximately 50–60% throughout the operation by periodic spraying of sterile nutrient medium onto the packing material. This hydroseeding-like moisture control strategy was applied to prevent drying of the biofilm and to ensure uniform moisture and nutrient distribution within the reactor. The system operated without an external oxygen supply, relying solely on the ambient oxygen within the biogas stream (approximately 2–3%) to sustain a microaerobic environment conducive to microbial sulfur oxidation. The pH of the biofilter moisture phase was monitored periodically using a calibrated pH meter and remained approximately neutral (pH 6.5–7.5) throughout the experiment. Biofilter operation was conducted under ambient laboratory temperature conditions (approximately 32–37°C). Pressure drop across the biofilter system was visually monitored during operation to observe potential clogging or airflow obstruction caused by biomass accumulation or sulfur deposition. No severe blockage or operational failure was observed, and the biofilter maintained stable performance under varying inlet conditions throughout the experiment with consistent operational efficiency.

Biogas analysis and hydrogen sulfide removal efficiency

To monitor system performance, the concentrations of H_2S, NH_3, and O_2 were measured at the biofilter inlets and outlets. A portable biogas analyzer (Bio Genius Model IRCD4 210406) served as the primary analytical tool, with its accuracy verified through parallel gas detection tube measurements. Biofilter performance was evaluated over a minimum operational period of 30 days, with measurements conducted at 7-day intervals. The experiments were performed in triplicate (n = 3). Hydrogen sulfide removal efficiency was calculated according to Eq. (1) (Chen *et al.*, 2008):

$$H_2S \text{ removal efficiency } (\%) = \frac{Cin - Cout}{Cin} \times 100 \quad (1)$$

Where:
C_{in} = Inlet H_2S concentration (ppm)
C_{out} = Outlet H_2S concentration (ppm)

Statistical analysis

The collected data were analyzed for significant differences using analysis of variance (ANOVA), and differences between means were compared using Duncan's new multiple range test in statistical package for the social sciences (SPSS) statistical software (version 26). Significance testing was performed with an alpha value set over at 0.05.

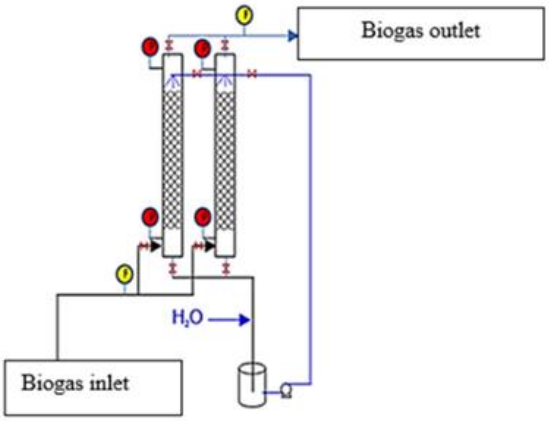

Fig. 1: The schematic diagram of the Biofiltration system

RESULTS AND DISCUSSION

Isolation of microorganisms capable of hydrogen sulfide decomposition

To isolate hydrogen sulfide-degrading microorganisms under controlled laboratory conditions, soil samples were collected from multiple locations surrounding a swine farm wastewater treatment pond. A selective medium specifically designed for SOB was used to facilitate the enrichment and isolation process. As a result, 11 microbial isolates exhibiting growth on the selective medium were successfully obtained. The isolated were taxonomically classified into four distinct species, as summarized in Table 1, were identified as *Sphingomonas paucimobilis*, *Burkholderia cepacia*, *Enterobacter cloacae*, and *Bacillus* spp. These species were consistently isolated from the swine farm's surrounding soil, confirming they are native to this habitat. Consequently, this observation underscores the critical role of environmental parameters—most notably oxygen availability—in dictating microbial succession and functional activity within biofilter systems. In another study, Rattanapan *et al.* (2010) demonstrated the use of *Alcaligenes faecalis* T307 in a laboratory-scale 5-liter biofiltration reactor for H_2S removal. The strain originally isolated from concentrated latex wastewater, was immobilized on granular activated carbon and achieved complete (100%) H_2S removal efficiency at inlet concentrations of 2,000–4,000 ppm. Sustaining this performance at gas flow rates of 35 and 5.86 liters per hour (L/h), highlights the robust potential of specialized bacterial strains to operate efficiently across a spectrum of operational conditions. Further research on H_2S elimination through SOB-based treatment systems identified several bacterial species critical to biogas purification. Notable isolates included *Acinetobacter towneri* (MF765755), *Enterobacter asburiae* (MF765756), *Aeromonas veronii* (MK659586), *Sulfurovum*, and *Sulfuricurvum* (Haosagul *et al.*, 2020). Furthermore, investigators evaluating SOB applications in ethanol biogas generation utilized high-throughput nucleic acid sequencing to characterize the microbial strains inhabiting these bioscrubber systems. The predominant bacterial species contributing to H_2S degradation in those systems were *Fastidiosipila*, *Hydrogenophaga*, *Pseudomonas anguilliseptica*, *Pseudomonas alcaligenes*, *Sphingobium yanoikuyae*, and *Enhydrobacter aerosaccus* (Haosagul *et al.*, 2020). Among the isolated strains, *Sphingomonas paucimobilis* and *Enterobacter cloacae* are Gram-negative bacteria categorized under to the Heterotrophic Bacteria group. As chemoorganoheterotrophs, they derive energy through chemical reactions involving organic substrates. Notably, these strains exhibited robust

Table 1: Classification results of bacteria isolated in the laboratory

Sample code	Identified bacterial strains
A21	*Sphingomonas paucimobilis*
A22	*Burkholderia cepacia*
B210	*Burkholderia cepacia*
B27	*Sphingomonas paucimobilis*
B213	*Enterobacter cloacae*
B32	*Burkholderia cepacia*
FLB11	*Enterobacter cloacae*
FLB22	*Bacillus spp.*
F32	*Burkholderia cepacia*
F24	*Burkholderia cepacia*
D21	*Enterobacter cloacae*

H_2S, oxidation activity, yielding less hazardous compounds including elemental sulfur and sulfate. This finding aligns with previous studies, including Kim *et al*. (2026) reported that a microalgae-bacteria consortium achieved over 65% ammonium removal and efficient biogas upgrading, even at 5,000 ppm H_2S and pH < 4. The system's resilience was driven by the synergy between microalgae and stress-tolerant bacteria, such as *Sphingomonas* and *Fuscovulum*, offering a sustainable, chemical-free solution for digestate and biogas treatment. In this study, two bacterial strains, *Sphingomonas paucimobilis* A21 and *Enterobacter cloacae* FLB11, the selected strains exhibited rapid growth, stable colony formation, and strong adaptability to sulfur-rich conditions, suggesting their potential involvement in sulfur oxidation processes. Therefore, *Sphingomonas paucimobilis* A21 and *Enterobacter cloacae* FLB11 were identified as the most promising candidates for subsequent application within the biofiltration system evaluated in this study. In microbiological and bioremediation contexts, *Sphingomonas* and *Enterobacter* are recognized as heterotrophic sulfur-oxidizing bacteria (HSOB), in contrast to obligate autotrophic SOB such as *Thiobacillus*, which rely primarily on the Sox multienzyme system (SoxAXYZBCD pathway) for energy conservation through direct oxidation of reduced sulfur compounds to sulfate. (Friedrich *et al*., 2001; Ghosh and Dam, 2009). Sulfide:quinone oxidoreductase (SQR) drives predominant heterotrophic sulfur oxidation, catalyzing the initial conversion of (H_2S) to elemental sulfur (S). Notably, this pathway serves a detoxification-oriented role rather than functioning as a conventional energy-conserving mechanism (Marcia *et al*., 2009). This metabolic flexibility enables HSOB to maintain activity under organic-rich and dynamically fluctuating conditions where autotrophic SOB are often inhibited. Additionally, both *Sphingomonas* and *Enterobacter* are strong biofilm-forming bacteria capable of producing extracellular polymeric substances (EPS), which enhance cell adhesion, improve mass transfer, and create protective microenvironments that buffer against sudden changes in H_2S concentration and operational stress (Flemming and Wingender, 2010). Furthermore, the EPS matrix facilitates the formation of redox microgradients within the biofilm, thereby promoting spatially organized sulfur oxidation and enhancing overall process stability. Collectively, the integration of SQR-mediated sulfide detoxification and EPS-supported biofilm architecture explains the superior resilience of heterotrophic systems under shock loading conditions (Oyarzún *et al*., 2003) rendering them more suitable for real-world biogas desulfurization applications than conventional, *Thiobacillus*-dominated autotrophic systems. Building on the findings of previous research and the bacterial strains isolated in the current study, *Sphingomonas paucimobilis* and *Enterobacter cloacae* were selected for further investigation regarding their roles in biogas desulfurization.

Biogas composition

The sampling and subsequent analysis of the raw biogas prior to any treatment revealed the concentrations of major components, namely methane, carbon dioxide, and hydrogen sulfide. The detailed composition is summarized in Table 2. Compositional analysis of the biogas indicated a high CH_4 content; this is highly favorable for energy generation, as methane constitutes the primary combustible fraction. The presence of carbon dioxide in significant amounts reduces the calorific value of the biogas and typically requires removal to enhance energy efficiency. Furthermore, even trace concentrations of H_2S, present severe operational risks regarding infrastructure corrosion and pose substantial environmental hazards. Effective desulfurization is thus a critical step in biogas upgrading. These findings underscore the importance of pre-treatment and purification steps tailored to the specific composition of the biogas, particularly in systems aimed at producing biomethane or using biogas in combined heat and power (CHP) units. As shown in Table 2, the raw biogas feed was characterized by a high H_2S concentration. Generally, H_2S concentrations in biogas range from 0.005% to 2% (50–20,000 ppm) (Pinate *et al*., 2017; Elshiekh *et al*., 2016). This elevated H_2S content observed in this study can primarily be attributed to the use of swine manure as the feedstock. The high-protein diets formulated to optimize growth kinetics in finishing pigs directly contribute to the high concentration of crude protein and nitrogen excreted in swine manure. Consequently, residual nitrogen compounds and partially degraded protein persist in the manure, leading to increased H_2S formation during anaerobic digestion. Interestingly, ammonia gas was found to be nearly undetectable in the biogas samples. This trend suggests low initial ammonia yield during the anaerobic digestion phase, paired with high gas volatility that accelerates its subsequent stripped release or dissipation. Furthermore, it is likely that most ammonia was removed during the initial stages of manure handling—specifically during the animal waste washing and wastewater transport from the barns to the biogas system—thereby explaining its negligible presence in the final biogas product.

Hydrogen sulfide removal efficiency of isolated microorganisms

To evaluate the H_2S removal efficiency of the isolated microorganisms, they were immobilized onto a biofiltration medium and tested under controlled conditions. The biofiltration system containing the immobilized microorganisms was operated at a biogas flow rate ranging from 0.3–0.5 L/min, corresponding to an empty bed residence time (EBRT) of 4.0-6.6 min. To evaluate the long-term stability and H_2S removal efficiency of the microbial consortium, the system (Fig. 2) was continuously supplied with biogas for at least 30 days, with monitoring conducted at seven-day intervals.

Hydrogen sulfide removal by Enterobacter cloacae FLB11

Enterobacter cloacae has demonstrated strong potential for the biological removal of H_2S from biogas, a critical process due to the corrosive nature of H_2S and its negative impact on biogas utilization. Extensive studies have demonstrated that various microbial inoculants, most notably *Enterobacter cloacae*, serve as highly effective agents in biofiltration systems designed for hydrogen sulfide H_2S desulfurization. In this study, experimental results revealed that the isolated strain *Enterobacter cloacae* FLB11, immobilized on coconut husk, exhibited effective removal performance. Furthermore, *Enterobacter cloacae,* in tandem with other SOB, actively biotransforms H_2S into benign end-products like elemental sulfur through microbial metabolic processes pathways (Singh and Mandal, 2011; Borgne and Baquerizo, 2019). The immobilized biofilter system also demonstrated stable microbial activity and sustained hydrogen sulfide degradation efficiency under continuous operating conditions over extended experimental durations.

Table 2: Biogas composition used in the study

Biogas Component	Percentage (%)
Methane (CH_4)	53.67 (± 0.47)
Carbon dioxide (CO_2)	45.67 (± 0.82)
Ammonia (NH_3)	Not Detected
Hydrogen sulfide (H_2S)	4,281 (± 26) ppm



Fig. 2: Biofiltration system utilized for hydrogen sulfide removal

When biogas containing H_2S concentration of approximately 4,269–4,292±26 ppm was introduced at a flow rate of 0.3–0.5 L/min, with an EBRT of 4.0–6.6 min, the system achieved notable high H_2S removal efficiencies. The biofiltration system immobilized with *Enterobacter cloacae* FLB11 exhibited variable H_2S removal efficiency throughout the experimental period. On day 1, the system achieved an initial removal efficiency of 33.4%, which gradually increased to 60.4% by day 6, followed by 76.7% on Day 13, and 75.9% on day 20. During the final stages of operation, the system exhibited a progressive decline in performance, ultimately dropping to an efficiency of 63.3%. The gradual decline in H_2S removal efficiency observed during prolonged operation may have resulted from several interacting factors, including sulfur accumulation within the packing material, excessive biofilm growth, reduced gas permeability, and limitations in mass transfer. Moreover, dynamic microenvironments, characterized by localized fluctuations in moisture, nutrient availability, and oxygen profiles likely regulated temporal microbial activity. Saturation of adsorption sites within the coconut husk packing material may also have contributed to reduced abiotic H_2S retention during extended operation. These factors are commonly associated with long-term performance deterioration in biofiltration systems. The highest H_2S removal

efficiency occurred between Days 13 and 20, with an average of 76.3% during this peak operational phase. The system achieved an average H_2S removal efficiency of 62.2% over the course of the 33-day study. The detailed removal performance across the monitoring period is presented in Table 3 and illustrated in Fig. 3.

Hydrogen sulfide removal by Sphingomonas paucimobilis A21

According to the experimental results, the biofiltration system immobilized with *Sphingomonas paucimobilis* A21 exhibited an initial a H_2S removal efficiency of 36.5% on Day 1. The efficiency increased progressively, reaching 83.2% on Day 6, 84.3% on Day 13, and 82.1% on Day 20, before showing a slight declining in the later stages of the experiment. Early-stage H_2S removal was partly driven by physical adsorption onto the coconut husk packing material, as evidenced by an initial reduction in concentration within the uninoculated control. However, the lower and less stable removal efficiency observed in the control system compared with the inoculated biofilters indicates that sustained H_2S removal was primarily associated with microbial oxidation activity. *Sphingomonas paucimobilis,* a known SOB, has demonstrated promising potential for H_2S removal, particularly in biological treatment systems such as biotrickling filters. Combining immobilized media with optimized operational parameters significantly enhances H_2S removal efficiency in these systems. Studies have indicated that biotrickling filters can achieve high H_2S removal efficiencies, with one study reporting an average removal efficiency of 91.8% and a maximum elimination capacity of 78.37 grams per cubic meter per hour ($g/m^3 \cdot h$) under optimal conditions (Sun *et al*., 2019). The use of SOB immobilized in carrier media has been shown to enhance H_2S removal, with Kang *et al.* (2020) reporting a maximum removal rate up to three times higher than systems lacking SOB. In the present study, the isolated microorganism demonstrated a measurable capability for H_2S removal from biogas under laboratory-scale conditions. The most effective H_2S removal performance was observed between Days 6 and 20, with an overall average H_2S removal efficiency of 69.7% during the 33-day operational period. The stable H_2S removal performance observed after microbial acclimation suggests that the indigenous microorganisms successfully maintained biological activity throughout the continuous biogas exposure period. A detailed summary of removal performance is provided in Table 4 and visually illustrated in Fig. 4. Although the biofilters demonstrated relatively stable H_2S removal during the 33-day operational period, further long-term and pilot-scale studies are required to evaluate operational stability and scalability under practical operating conditions. The system demonstrated satisfactory short-term operational stability, with no severe clogging, packing material deterioration, or operational failure observed during the experimental period. This study identifies *Sphingomonas paucimobilis* A21 and *Enterobacter cloacae* FLB11 as the most efficient microbial strains for biogas H_2S desulfurization. Both strains were isolated from soil samples collected around the swine farm, specifically near and behind the wastewater treatment pond. The robust growth of these microorganisms in selective sulfur media is consistent with their known metabolic capabilities as SOB and aligns with previous H_2S biofiltration studies. For example, Phanphong (2016) reported an H_2S removal efficiency of up to 98% in biofilters used in crude palm oil extraction facilities. In that study, *Azospirillum* sp. and *Paracoccus* sp. were dominant during the initial phase, whereas *Enterobacter* sp., *Rhodopseudomonas* sp., and *Sphingomonas* sp. became predominant following aeration. The observed temporal succession implies that environmental fluctuations within the biofilter directly modulate microbial community dynamics, ultimately dictating removal efficiency and long-term process stability.

Table 3: Hydrogen sulfide removal efficiency of *Enterobacter cloacae* FLB11

Date	Initial H_2S Concentration (ppm)	H_2S concentration after treatment in ± Standatd deviation (SD)		Removal efficiency using *E. cloacae* FLB11 (%)
		without *E.cloacae* FLB11 (ppm)	with *E. cloacae* FLB11 (ppm)	
1	4292±30	3204±60^{a}	2860±41^{A}	33.40%
6	4271±23	3033±50^{c}	1693±27^{B}	60.40%
13	4287±8	2940±33^{b}	997±7^{D}	76.70%
20	4269±28	2902±66^{d}	1027±46^{D}	75.90%
27	4276±34	2983±57^{c}	1568±27^{C}	63.30%
33	4291±34	3032±56^{c}	1574±36^{C}	63.30%
average	4281±26	3016±54	1620±31	62.20%

Remark: Similar superscript letters indicate no statically significant difference ($p > 0.05$). Different superscript letters indicate significant difference within column ($p < 0.05$).

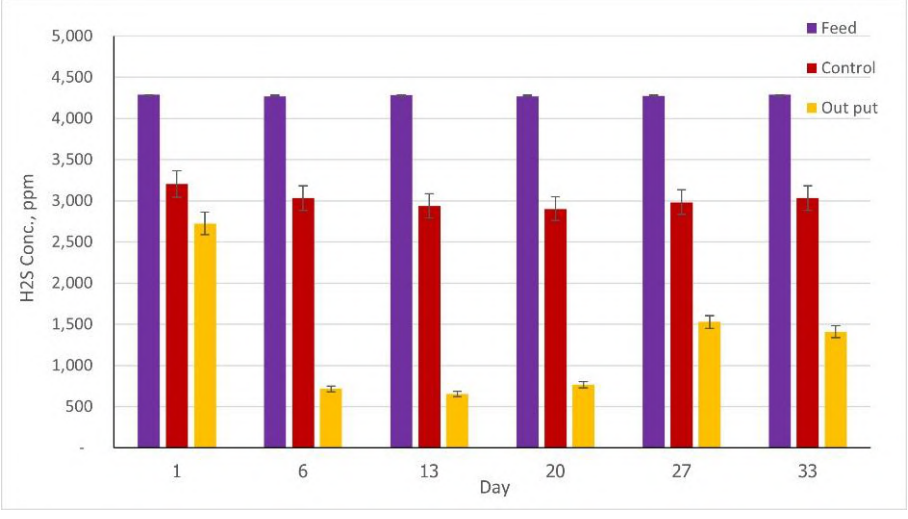

Fig. 3: Hydrogen sulfide removal efficiency of *Enterobacter cloacae* FLB11

Table 4: Hydrogen sulfide removal efficiency of *Sphingomonas paucimobilis* A21

Date	Initial H_2S Concentration (ppm)	H_2S Concentration after Treatment (±S.D.)		Removal Efficiency using *S. paucimobilis A21* (%)
		without *S. paucimobilis A21* (ppm)	with *S. paucimobilis A21* (ppm)	
1	4292±30	3204±60^{a}	2725±49^{A}	36.50%
6	4271±23	3033±50^{c}	716±18^{D,E}	83.20%
13	4287±8	2940±33^{b}	653±29^{E}	84.80%
20	4269±28	2902±66^{d}	765±28^{D}	82.10%
27	4276±34	2983±57^{c}	1529±28^{B}	64.30%
33	4291±34	3032±56^{c}	1410±11^{C}	67.10%
average	4281±26	3016±54	1299±17	69.70%

Remark: Similar superscript letters indicate no statically significant difference ($p > 0.05$). Different superscript letters indicate significant difference within column ($p < 0.05$).

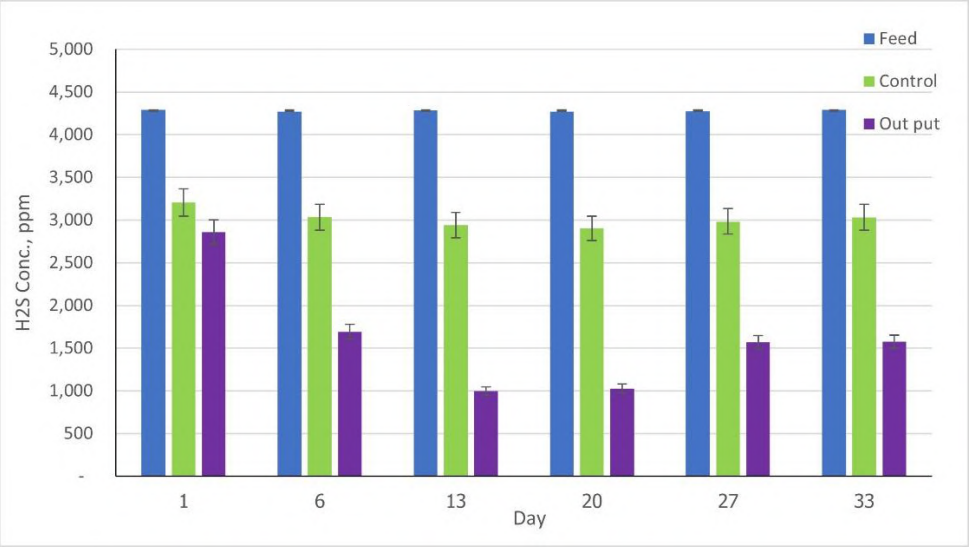

Fig. 4: Hydrogen sulfide removal efficiency of *Sphingomonas paucimobilis* A21

The present findings are also consistent with those of Haosagul *et al.* (2020), who isolated several SOB species from swine farm biogas treatment systems. These included *Acinetobacter towneri* (MF765755), *Enterobacter asburiae* (MF765756), *Aeromonas veronii* (MK659586), *Sulfurovum*, and *Sulfuricurvum*. Such species have been previously documented to contribute to the oxidation of H_2S under aerobic or microaerophilic conditions. Among the two strains evaluated in this study, *Sphingomonas paucimobilis* A21 exhibited superior performance when immobilized on coconut husk and exposed to biogas containing H_2S concentrations ranging from 4,269 to 4,292 (±26) ppm. The biogas was introduced at a flow rate of 0.3–0.5 L/min, corresponding to an empty bed residence time (EBRT) of 4.0–6.6 min. Gradual microbial adaptation and biofilm maturation led to a steady increase in removal efficiency, progressing from 36.5% (Day 1) to 83.2% (Day 6), and peaking at 84.8% on Day 13. This peak performance phase, which occurred between Days 13 and 20, recorded an average removal efficiency of 76.3%. Although efficiency dropped slightly to 67.1% late in the 33-day experiment because of potential biofilm overgrowth or substrate limitations, the system maintained a cumulative average removal efficiency of 69.7%. In comparison, *Enterobacter cloacae* FLB11 also showed potential but with lower peak performance and less stability over time. Nonetheless, its demonstrated robustness within selective sulfur media implies a strategic utility in co-culture or sequential configurations, particularly in scenarios where environmental fluctuations threaten the efficacy of a single-strain system. The present study demonstrated that biofilters inoculated with *Sphingomonas paucimobilis* A21 and *Enterobacter cloacae* FLB11 were capable of biologically removing H_2S from biogas, achieving maximum removal efficiencies of 84.8% and 76.7%, respectively, under identical operating conditions. Although both strains exhibited measurable H_2S biodegradation activity, *S. paucimobilis* A21 consistently outperformed *E. cloacae* FLB11, indicating a greater adaptability and metabolic capacity for sulfur-containing compounds. When compared with existing literature, the removal efficiencies observed in the investigated biological system can be considered moderate; nonetheless, they remain within the established range for conventional aerobic biofiltration. Table 5 summarizes the performance comparison between this work and prior studies.

Table 5: Comparison of biological systems for H_2S removal

Study/ system	Reactor type	Dominant microorganism(s)	H_2S removal efficiency (RE)	Sources
Biotrickling filter with *Acidithiobacillus caldus*	Biotrickling filter	*A. caldus*	>99%	Semi-pilot scale; high inlet H_2S concentration (~2000 ppm) (Reddy *et al*., 2019)
Thiobacillus denitrificans / biofilter	Biofilter	*T. denitrificans*	~99%	Lab-scale community study (Tombuloglu *et al*., 2025)
Paracoccus versutus CM1	biofilter	*Paracoccus versutus*	~99.5–99.7%	pilot-scale (Kumdhitiahutsawakul *et al*., 2022)
Biotrickling filter / (effect of O_2 supply)	Biotrickling filter	Sulfur-oxidizing bacterial community	94–100%	Influence of oxygen dosage (Zhang *et al*., 2022)
Biofilter with peat packing	Biofilter	Indigenous microorganisms	~99%	Emphasis on peat as packing / support material (Omri *et al*., 2013)
Biofilter with compost	Biofilter	Indigenous microorganisms	~94%	Compost used as packing material (Lien *et al*., 2021; Das *et al*., 2019)
Anoxic biotrickling filter	Biotrickling filter	*Thiobacillus* spp.	>99%	Autotrophic anoxic conditions (Borges *et al*., 2025)
Sphingomonas paucimobilis A21 / biofilter	Biofilter	*S. paucimobilis*	84.8% (Day 13)	This study
Enterobacter cloacae FLB11 / biofilter	Biofilter	*E. cloacae*	76.7%	This study

Several studies have documented substantially higher H_2S removal efficiencies, often exceeding 95–99%, particularly in systems employing SOB such as *Thiobacillus, Acidithiobacillus, or Paracoccus species* (Tombuloglu *et al*., 2025; Aita *et al*., 2016; Juntranapaporn *et al*., 2019). These microorganisms are well recognized for their autotrophic metabolism and strong capacity to oxidize H_2S into elemental sulfur or sulfate, which explains their consistently high performance in both biofilter and biotrickling filter configurations. In contrast, *S. paucimobilis* and *E. cloacae* are heterotrophic bacteria and are not typically classified as specialized sulfur oxidizers. Thus, their capacity for H_2S mitigation is presumably mediated by indirect oxidation pathways, co-metabolic mechanisms, or synergistic interactions with the indigenous microbiota, as opposed to direct chemolithoautotrophic pathways. Differences in metabolic pathways between these heterotrophic strains and classical SOB may partly account for the comparatively lower removal efficiencies observed in this study. However, sulfur oxidation products such as elemental sulfur and sulfate were not analyzed in the present study; therefore, the specific biodegradation pathways of H_2S could not be directly confirmed. Further studies utilizing sulfur speciation analysis is warranted to comprehensively elucidate the detailed mechanisms of sulfur transformation within the biofilter system. Operational configuration is another critical factor influencing overall system performance. The superior efficiency of biotrickling filters relative to conventional biofilters is primarily driven by key operational parameters, including continuous liquid recirculation, enhanced gas–liquid mass transfer, and regulated pH and nutrient availability. Many high-efficiency systems reported in the literature operated as biotrickling filters and maintained optimal conditions for sulfur oxidation, including adequate oxygen supply and effective removal of acidic by-products. In contrast, the biofilter configuration employed in the present study may have imposed limitations related to mass transfer and metabolite accumulation, thereby restricting the maximum achievable H_2S removal efficiency under prolonged continuous operational and fluctuating environmental conditions. Periodic biofilm saturation may have reduced system stability and performance over time.

The physicochemical characteristics of the packing material play a critical role in determining overall biofilter performance. Prior studies have demonstrated that substrates including peat, compost, wood chips, and porous synthetic media can significantly improve microbial colonization and biological activity by virtue of their elevated porosity and moisture retention capacities (Omri *et al*., 2013; Das *et al*., 2019; Zhu *et al*., 2020). The moderate removal efficiencies observed in this study suggest that further optimization of packing material properties could improve microbial attachment and gas–biofilm contact, ultimately enhancing H_2S degradation. Evaluating the operational longevity of the coconut husk packing matrix was beyond the immediate scope of the present study. However, during the 33-day continuous operation, the coconut husk exhibited minimal physical deterioration or compaction, indicating good structural stability under the tested conditions. No significant clogging or severe pressure drop was observed throughout the experimental period. These observations suggest that coconut husk may be suitable for extended biofilter operation under practical conditions. While this study could not conclusively establish the timeline for media regeneration, cleaning, or replacement, these frequencies will ultimately dictate long-term performance based on biomass growth, sulfur accumulation, and moisture management. Further long-term field-scale investigations are therefore recommended to evaluate packing material durability and maintenance requirements under continuous operation. Nevertheless, the frequency of regeneration, cleaning, or replacement could not be conclusively determined from the current study, as these factors likely depend on long-term sulfur accumulation, biomass growth, moisture management, and operational loading conditions. Accordingly, further long-term, pilot-scale or field-scale investigations are essential to comprehensively characterize the operational longevity and maintenance schedules of the packing substrate under continuous load.The performance difference between *S. paucimobilis A21* and *E. cloacae FLB11* further underscores the importance of microbial selection. *S. paucimobilis* is known for its environmental resilience, biofilm-forming capability, and tolerance to toxic compounds, which may explain its faster acclimation and higher removal efficiency throughout the operational period. From a physiological standpoint, the survival and continued metabolic activity of these indigenous microorganisms under elevated sulfur conditions can be attributed to adaptive mechanisms that enhanced their resilience against H_2S toxicity. Such mechanisms may include modifications in cell membrane structure, improved regulation of intracellular pH homeostasis, enhancement of stress-protective enzymatic systems, and the production of extracellular polymeric substances (EPS) within the biofilm matrix. Furthermore, the establishment of a biofilm on the coconut husk packing substrate served to protect the immobilized microorganisms against adverse environmental fluctuations, thereby fostering enhanced long-term microbial stability within the biofilter system. From a metabolic perspective, sulfur-oxidizing microorganisms are capable of converting H_2S into intermediate sulfur compounds and ultimately into sulfate under aerobic conditions. The sustained H_2S removal efficiency observed throughout the operational period indicates that the indigenous isolates were able to maintain active sulfur-oxidation metabolic pathways and continuously adjust their biological activity in response to increasing sulfur loading. Moreover, the extended presence of H_2S may induce the expression of key sulfur-oxidizing metabolic pathways, thereby driving the observed

increase in long-term removal efficiency (Rattanapan *et al*., 2011; Le and Baquerizo, 2019). The enhanced performance may also be associated with sulfur oxidation-related enzymes such as sulfide:quinone oxidoreductase (SQR), which facilitates rapid sulfide detoxification and oxidation. In addition, the unique glycosphingolipid-containing cell envelope of *S. paucimobilis* may contribute to improved tolerance against toxic sulfur compounds and greater operational stability during long-term biofiltration processes (Hou *et al*., 2018; Yabuuchi *et al*., 1990; Tangaromsuk *et al*., 2002). In contrast, *E. cloacae* may exhibit lower tolerance to H_2S toxicity or to acidic intermediates generated during oxidation, resulting in reduced and less stable long-term activity. Albeit exhibiting lower removal efficiencies than select systems documented in the literature, the results obtained in the present work remain highly significant. The successful application of non-classical sulfur-oxidizing bacteria highlights the potential of alternative microbial resources for H_2S biofiltration, particularly in low-cost or decentralized biogas treatment systems. Concurrently, the incremental enhancement in removal efficiency observed over the operational period implies that prolonged acclimation phases or the establishment of robust microbial consortia may yield superior system performance. Mixed microbial consortia employed in biotrickling filter systems have also been reported to improve process stability and resistance to fluctuating H_2S loading conditions, suggesting a potential direction for future development of the present biofiltration system. Despite the promising H_2S removal efficiencies achieved by the coconut husk-supported biofilter, long-term performance may be compromised by sulfur deposition, biomass accumulation, media degradation, and concomitant pressure drops. Therefore, periodic maintenance, including moisture regulation, nutrient supplementation, and partial replacement of packing material, may be necessary to sustain stable reactor performance during prolonged operation. Compared with previously reported industrial biofiltration systems, the present system exhibited comparable H_2S removal capability while utilizing low-cost indigenous microorganisms and locally available agricultural waste materials. These attributes indicate that the proposed approach may be viable for decentralized biogas purification configurations; nonetheless, further pilot-scale investigations and long-term operations remain necessary to comprehensively evaluate its practical implementation. However, further long-term investigations and pilot-scale studies are still required to evaluate operational stability, scalability, and economic feasibility under practical operating conditions. Overall, this study contributes to the growing body of knowledge on biological H_2S removal by demonstrating that heterotrophic bacteria such as *S. paucimobilis A21* can achieve stable and reproducible H_2S removal under controlled biofilter conditions. Albeit advantageous, biofiltration systems remain susceptible to operational complications during extended operation, namely packing material clogging, excessive biofilm accumulation, gas channeling, and increased pressure drop. Furthermore, this study demonstrates the effectiveness of applying indigenous microbial consortia isolated from swine farm soil for H_2S removal in a biofiltration system operated under conditions closely resembling real biogas treatment scenarios, with microbial identification resolved to the species level. This approach differs from previous studies that predominantly employed pure cultures or well-characterized sulfur-oxidizing bacteria such as *Sphingomonas*, *Enterobacter*, *Thiobacillus*, and *Paracoccus*, which

were mainly evaluated under controlled laboratory conditions. By contrast, the current investigation underscores the functional performance of indigenous microbial communities subjected to long-term adaptation within authentic environmental matrices. These indigenous microbial consortia were exposed to complex environmental pressures, including fluctuating H_2S concentrations, variable organic loading rates, and non-sterile conditions. Over time, this environmental adaptation likely cultivated greater ecological fitness and metabolic flexibility within the community, allowing for sustained sulfur oxidation under fluctuating operational conditions. The absence of bioaugmentation requirements and the elimination of prolonged acclimation periods highlight the practical advantages of the proposed system, particularly for applications requiring operational simplicity and cost-effectiveness, such as small-scale agricultural or farm-based biogas facilities. Overall, this study bridges the gap between laboratory-scale microbiological investigations and real-world biogas purification applications, supporting the notion that indigenous microbial consortia represent a more robust and sustainable alternative to conventional pure-culture-based biofiltration systems.

However, microbial population dynamics, biofilm thickness, and biomass accumulation were not quantitatively monitored in the present study; therefore, microbial adaptation and biofilm development were inferred primarily from the observed trends in H_2S removal performance. Accordingly, subsequent studies directions should encompass the cultivation of specialized microbial consortia, the optimization of critical operational parameters (including empty bed residence time, oxygen availability, and moisture retention), and systematic comparative evaluations between conventional biofilters and biotrickling filter systems to maximize biochemical performance and operational resilience.

CONCLUSION

This study demonstrated the successful isolation and application of indigenous microorganisms for the biological removal of H_2S from swine farm biogas using a laboratory-scale biofiltration system. A total of 11 microbial isolates were obtained from soil surrounding a swine wastewater treatment pond and taxonomically identified as belonging to four major bacterial groups, including *Sphingomonas paucimobilis*, *Enterobacter cloacae*, *Burkholderia cepacia*, and *Bacillus* spp. Among these isolates, *Sphingomonas paucimobilis* A21 and *Enterobacter cloacae* FLB11 exhibited the highest potential for H_2S biodegradation and were therefore selected for further evaluation. Both microbial strains were successfully immobilized onto the coconut husk matrix and subsequently utilized within a continuous biofiltration configuration operated under identical environmental parameters. Significant reductions in H_2S concentrations within raw biogas derived from swine manure validate the potential of utilizing indigenous heterotrophic bacterial strains for engineered biogas desulfurization systems. Among the tested strains, *S. paucimobilis* A21 achieved superior performance, reaching a maximum H_2S removal efficiency of 84.8% and maintaining a higher average removal efficiency throughout the 33-day operational period compared with *E. cloacae* FLB11, which achieved a maximum efficiency of 76.7%. The incremental enhancement in removal efficiency observed over the operational period signifies effective microbial acclimation and the concomitant development of a biofilm structure within the biofiltration media. The findings further suggest that environmental heterotrophic bacteria, although not traditionally classified as specialized SOB, possess significant potential for

H_2S removal under aerobic biofiltration conditions. The ability of these microorganisms to tolerate elevated H_2S concentrations and sustain biological activity within low-cost carrier materials highlights their applicability for decentralized and environmentally sustainable biogas purification systems. Particularly, the application of coconut husk as an abundant and inexpensive support matrix presents significant operational advantages, facilitating effective microbial immobilization and robust biofiltration performance. Although the removal efficiencies obtained in this study were lower than those reported for certain specialized biotrickling filter systems employing autotrophic SOB, the present work contributes important insight into the utilization of alternative microbial resources for biological desulfurization. Moreover, the present study underscores the profound influence exerted by microbial selection, operational configurations, and support matrix properties on the macroscopic performance of the biofiltration system. In summary, this research provides a scientific basis for the development of low-cost biological H_2S removal technologies applicable to livestock biogas systems, particularly in agricultural regions where swine waste is abundantly available. Future studies should encompassthe development of mixed microbial consortia, optimization of oxygen transfer and empty bed residence time, long-term operational stability, and scale-up evaluation under authentic field conditions to further maximize process resilience and commercial applicability.

AUTHOR CONTRIBUTIONS

S. Srithong designed the study experiments on microbial isolation and identification and performed the analysis, interpretation of the experimental results concerning the isolated microorganisms and prepare the manuscript for publication. O. Janngam drafted the experimental results section related to the laboratory isolation of microorganisms. Yanee Keereeta conducted the literature review on microorganisms associated with the study. P. Wangngiw carried out the laboratory experiments on the isolation of microorganisms from the samples. P. Phothilangka conceived and devised the overall research process, conducted soil microbial sampling, designed and performed the experiments on biogas quality improvement using a biofiltration system, analyzed and presented the results, and prepared the manuscript for publication.

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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
ANOVA	Analysis of variance
C_{in}	Inlet H_2S Concentration
C_{out}	Outlet H_2S Concentration
$CaCl_2$	Calcium chloride
CFU/mL	Colony forming Units per milliliter
CH_4	Methane
cm	Centimeters
CO_2	Carbon dioxide
DEA	Diethanolamine
EBRT	Empty bed residence times
EPS	Extracellular polymeric substances
$FeCl_3 \cdot 6H_2O$	Ferric chloride hexahydrate
g	Grams
$g/(m^3 \cdot h)$	Grams per cubic meter per hour
H_2S	Hydrogen sulfide
HSOB	heterotrophic sulfur-oxidizing bacteria
kg	Kilograms
kg/m^3	*Kilogram per cubic meter*
KH_2PO_4	Potassium dihydrogen phosphate
KNO_3	Potassium nitrate
L	Liters
L/h	Liters per hour
L/min	Liters per minute
m	Meters
MEA	Monoethanolamine
min	Minutes
mL	Milliliters
$MgSO_4 \cdot 7H_2O$	Magnesium sulfate heptahydrate
min	Minutes
$MnSO_4 \cdot 4H_2O$	Manganese sulfate tetrahydrate
N_2	Nitrogen
Na_2HPO_4	Sodium hydrogen phosphate
$Na_2S_2O_3 \cdot 5H_2O$	Sodium thiosulfate pentahydrate
$NaHCO_3$	Sodium bicarbonate
NH_3	Ammonia
$(NH_4)_2SO_4$	Ammonium sulfate
O_2	Oxygen
pH	Potential of hydrogen
ppm	Part per million
psi	Pounds per square inch
RE	Removal efficiency
rpm	Revolutions per minute
S	Sulfur
SPSS	Statistical package for the social sciences

S.D.	Standard deviation
$S_4O_6^{2-}$	Tetrathionate
SO_4^{2-}	Sulfate
SOB	Sulfur-oxidizing bacteria
SoxAXYZBCD pathway	Sox multienzyme system

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Health and environmental awareness as a catalyst for sustainable travel toward low-carbon intention among tourists' wellness

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ABSTRACT

BACKGROUND AND OBJECTIVES: Health consciousness has become an important factor in promoting sustainable travel behavior and encouraging low-carbon tourism among wellness tourists in Thailand. Growing consumer consciousness regarding personal well-being and ecological sustainability actively drives tourists to adopt eco-friendly behaviors and mitigate their carbon footprints. The study objectives were to investigate the structural relationships between health consciousness, environmental concern, attitude, subjective norms, and perceived behavioral control, as well as their direct and indirect effects on ecologically responsible travel decisions.

METHODS: Data were collected from 465 respondents using a structured questionnaire measuring health consciousness, environmental concern, attitudes toward sustainable travel, subjective norms, perceived behavioral control, and low-carbon travel intention. Using version 26 of a statistical package for the social sciences, a statistical analysis was carried out that encompassed confirmatory factor analysis, structural equation modeling, discriminant validity testing, and multiple regression analysis. The applied analytical framework ensured robust evaluation of the proposed relationships and the overall model fitness.

FINDINGS: The results indicated that health consciousness significantly influenced environmental concern, attitudes toward sustainable travel, and low-carbon travel intention. Empirical evidence indicates that environmental concern significantly strengthens tourists' sustainable travel attitudes and their intention to choose low-carbon travel. Among the theory of planned behavior constructs, attitude toward sustainable travel had the strongest influence on low-carbon travel intention, followed by perceived behavioral control and subjective norms. Mediation analysis confirmed that the relationship between health consciousness and low-carbon travel intention is significantly mediated by both environmental concern and sustainable travel attitudes. The regression analysis explained 68 percent of the variance in low-carbon travel intention. These findings suggest that tourists with greater awareness of personal health and environmental sustainability are more likely to engage in environmentally responsible travel behaviors. The study further highlights the importance of integrating health-oriented and sustainability-focused strategies within tourism planning to encourage low-carbon travel practices and support long-term sustainable tourism development in Thailand.

CONCLUSION: The outcomes of this study demonstrate that enhancing health consciousness, environmental sensitivity, and positive behavioral attitudes can substantially elevate low-carbon travel intention and support sustainable tourism development. The findings also confirm the relevance of the Theory of Planned Behavior in explaining sustainable travel decisions among wellness tourists in Thailand. Furthermore, environmental concern and sustainable travel attitudes significantly mediate the relationship between health consciousness and low-carbon travel intention, offering practical insights for developing effective sustainable tourism strategies.

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INTRODUCTION

The changing climate pushes the tourism sector to decrease greenhouse gas (GHG) emissions, as tourism represents one major source of greenhouse gas. In Thailand, the advancement of low-carbon tourism initiatives is imperative to foster long-term sustainability and ensure robust environmental protection (Sakcharoen *et al.,* 2024). The post-Coronavirus-2019 (COVID-19) health and wellness tourism industry has grown exponentially owing to heightened health awareness, accelerated economic recovery, and increasing demand for whole experiences, combining medical and nonmedical services to achieve physical, mental, and spiritual health (Gan *et al.,* 2023). While wellness tourism is experiencing rapid growth and driving business development in China, Thailand stands out as a globally competitive wellness destination. Benefiting from an advanced healthcare system, deep cultural roots, and diverse wellness offerings, Thailand effectively provides tourists with comprehensive mental, physical, and spiritual health improvement (Theerathitichaipa *et al.,* 2025). Thailand's cultural values, social beliefs and traditional wellness practices can have a significant impact on tourists' health consciousness (HC) and their responsible behavior in travelling environment. Holistic health and wellness, mindfulness and harmony with nature in cultural values can help raise awareness of personal health and environmental sustainability, thereby having a positive impact on low-carbon travel intention. To bolster sustainable tourism, various frameworks have been increasingly promoted in Thailand, characterized by the adoption of green tourism programs, eco-certification schemes, environmentally conscious hotel operations, and capital investments in sustainable transit infrastructure. These activities can contribute to improving tourists' environmental awareness and promoting the use of low-carbon tourism. In addition, there may be differences between domestic and international wellness tourists as the latter might be affected by global sustainability campaigns and environmental awareness programmes, while the former may be influenced by the local cultural values, familiarity with the destinations and accessibility to sustainable tourism services. Consequently, understanding the connection between cultural context, sustainable tourism policies, and behavioral factors is crucial for elucidating the intention to embrace low carbon travel among wellness tourists in Thailand, as well as for formulating effective sustainable tourism strategies. Climate change has increased awareness of environmentally responsible tourism practices and encouraged the development of low-carbon tourism strategies. The research makes another contribution to the field of environmental science and management literature, as it explores the potential relationship between HC and sustainable travel behaviors on the one hand, and low-carbon tourism development and climate-based destination management on the other. Knowledge about the determinants of low-carbon travel intentions can help policymakers and tourism planners develop tourism management policies that are oriented toward carbon reduction and environmental protection. Grounded in the theory of planned behavior (TPB), this study examines tourists' behavioral intentions toward low-carbon travel practices, specifically focusing on sustainable transportation and eco-friendly hotels (Ma *et al.,* 2024). Rising climate change and global greenhouse gas emissions present challenges for sustainable tourism, especially in island destinations. Investigating low-carbon tourism approaches and visitor behaviors in island destinations can harmonize sustainable economic viability with environmental sustainability (Fakfare and Wattanacharoensil, 2024). Post-COVID-19 health awareness and life stress promote wellness tourism; China and South Korea are major markets that affect tourist behavior and well-being (Zhou *et al.,* 2023). The accelerating

threat of climate change to glacial ecosystems and ski tourism underscores the critical imperative for fostering pro-environmental behaviors among tourists. Thus, research on tourists' experiences and place attachment may inspire more pro-environmental behaviors in tourism and life (Boadu *et al.,* 2025). Environmental strains on fragile plateaus, driven by climate change, have been severely exacerbated by the rapid expansion of rural tourism. Thus, it is critical to understand rural residents' pro-environmental behavior and strike a balance between economic development and environmental conservation and sustainability (Fang *et al.,* 2025). Tourism emissions from growth have prompted research on low-carbon tourism, where sustainability and experience can be balanced by studying the main factors influencing tourist choice in the decision to select a low-carbon tourist destination. Environmentally friendly short videos have been shown to be powerful tools for promoting tourist behavior (Chen and Cheng, 2023). As an emerging phenomenon, the integration of wind power generation and tourism is actively developed in China, where wind farms serve as sustainable attractions. These sites generate local economic and educational benefits, elevate environmental awareness, and promote eco-friendly travel practices (Liu *et al.,* 2025). Rapid tourism growth offers economic benefits but raises sustainability challenges. Environmental knowledge, Tourists' social interaction and pro-environmental conduct are greatly influenced by an eco-destination's image and biospheric values, which promote the growth of sustainable tourism. (Alashiq and Aljuhmani, 2025). Spurred by the environmental impact of greenhouse gas emissions from a growing tourism sector, the framework of low-carbon tourism seeks a sustainable equilibrium between leisure entertainment and resource conservation. Thus, the key determinants of the factors leading tourists to choose low-carbon travel destinations need further research (Liu *et al.,* 2023). Low-carbon tourism addresses greenhouse gas emissions from tourism expansion, with the goal of balancing sustainability with enjoyment while critical elements affecting visitors' preferences to choose eco-friendly, low-carbon places are investigated (Janchai and Suvittawat, 2025). Building on the low-carbon destination attributes identified by Fakfare and Wattanacharoensil (2023), this study applies the stimulus–organism–response (SOR) framework combined with importance–gap satisfaction and competitive analysis (IGSCA) and multigroup analysis. While it successfully identifies risk-influenced attitudes and behavior gaps but is limited by sample scope and pandemic-specific context. To investigate the environmental determinants of low-carbon tourism (Wang and Phakdeephairot, 2024) using the SOR model, questionnaires and SEM were used. The study's scope is bounded by a distinct regional emphasis and the inherent biases of self-reported data. Nevertheless, the empirical results indicate that nearly all examined factors positively influence behavior, leaving values as the sole exception. This study investigated the causes and geographical disparities of low-carbon tourism in Fujian (Zhan *et al.,* 2025), analysed the effects of policy awareness using questionnaires and regression, and identified attitudes as significant determinants, while awareness had mixed effects; limitations included regional scope and self-reported data. By exploring low-carbon transition pathways and identifying drivers and barriers present in characteristic towns (Wan *et al*., 2025), stakeholders were assessed through the application of game theory and system dynamics, yielding scores of 63.3 overall, 66.9 for Zhou Zhuang, and 57.6 for Tongli; limitations included the specificity of cases and the assumptions of the model. Tourists' understanding of degrowth and its link to sustainability should be explored (Pinto *et al.,* 2025). An online survey of 261 respondents revealed low awareness but alignment with sustainable behavior; younger tourists resisted such behavior, and the limitations included the use of a small convenience sample and self-reported responses. The relationship between

slow-paced tourism and personal transformation, as well as well-being, has been studied (Vo-Thanh *et al.,* 2025). Applying a hypothetico-deductive approach via covariance-based structural equation modeling (CB-SEM) to a sample of 319 tourists, this study reveals that co-creation and self-transformation significantly enhance visitor well-being. Although these findings are bounded by a cross-sectional design, a localized sample size, and the inherent biases of self-reported measures, they provide a foundation to examine how shifting conclusions regarding environmental sustainability might intersect with or disrupt tourist well-being (Alizadeh *et al.,* 2024). Drawing on 30 semi-structured interviews, this study reveals that responsible travel behavior enhances visitor well-being, whereas irresponsible behavior induces guilt. While the generalizability of these findings is constrained by a small qualitative sample, the study successfully identifies key indicators for low-carbon tourism itinerary planning are (Lin and Heeren, 2025). Expert consultations revealed that "sustainable management" and "environmental education" were most impactful, followed by green energy and monitoring; limitations included a qualitative approach, a small sample size, and a lack of quantitative validation. To examine the factors influencing tourists' low-carbon behavior at glacier destinations (Lv *et al.,* 2024), on-site data collection and virtual reality (VR) experiments revealed that engagement increased behaviorvia place attachment and responsibility; boundaries included the experimental context and limited generalizability. Effects of low-carbon tourist awareness, place attachment, and behaviors on sustainable village expansion (Lin *et al.,* 2022). Utilizing a mixed-methods approach, this study analyzed existing questionnaire data (n=828) alongside expert interviews using multiple regression analysis. The empirical results indicate that while environmental awareness significantly increased eco-behavior, financial cost exerted no significant effect on adoption; however, the generalizability of these findings is constrained by a reliance on self-reported data and a narrow regional focus. Seeking to develop a model linking low-carbon travel with visitor well-being, Yu *et al.* (2023) conducted SEM analysis (n = 523). Their findings revealed positive effects (β =0.189–0.327), though the study was limited by a cross-sectional design, regional bias, and a reliance on self-reported measures; nonetheless, their framework helps identify critical factors influencing tourists' sustainable travel choices (Naik *et al.,* 2025). The study's results demonstrated that environmental concern (EC) had a beneficial impact on intentions, with age acting as a mediator and moderator in this context. Notably, the use of self-reported measures and the cross-sectional approach are two critical limitations that also raise questions about generalizability. The focus was on carbon-neutral travel behavior among younger travelers (Hatamifar *et al.*, 2025). A questionnaire using data to verify TPB and a norm activation model (NAM) revealed that social norms are relevant and that positive effects are 4.2 times greater. Limitations included the use of regional-level data and self-reported data on a cross-sectional basis. To explore Indian tourists' intention to adopt energy-saving behaviors for carbon neutrality (Siddiqui and Sujood, 2025). The use of existing data (n=456) and SEM revealed that aggregated NAM-TPB factors were meaningful; limitations such as self-reports, cross-sectional nature and lack of generalizability apply. To identify the market segments of medical tourists on the basis of push–pull motivations (Cha *et al.,* 2024). The multilingual survey (31 items) revealed 3 segments: quality, necessity of services and remaining seekers; constraints: self-reported data; sampling bias; and limited generalizability of the results. Seeking to explore the integration of artificial intelligence (AI) with circular economy principles in tourism, Bang-Ning *et al.* (2025) deployed a mixed-methods approach combining stakeholder insights with PLS-SEM. Their findings indicate that while AI implementation significantly improves resource management, systemic

resistance continues to hinder widespread adoption. Furthermore, the study's generalizability is bounded by context specificity, a limited sample, and evolving technology constraints. The effect of healthy tourism motivation on participation and pleasure of Himalayan spa resorts was investigated (Manhas *et al.*, 2025). The use of questionnaires (n=260) with SEM revealed positive effects and mediation; limitations included a limited sample size, regional focus, and self-reported responses. The key contributions are as follows: 1) Confirms health consciousness (HC) as the key psychological incentive impacting the intention toward low-carbon travel and ties health advantages to low-carbon tourist behaviors. 2) When EC and health awareness are integrated, the TPB framework extends its structural utility, thereby enhancing the model's predictive power regarding sustainable travel choices. 3) Demonstrates important direct and mediating relationships using SEM and regression analyses and provides robust support for behavioral pathways. 4) Emphasizing attitudes, social influence, and perceived behavioral control as key motivators offers critical strategic pathways for accelerating the adoption of sustainable mobility among wellness travelers in Thailand. Although artificial intelligence (AI)-powered tourism management studies were reviewed to provide broader sustainability context, the present study primarily focuses on behavioral and environmental determinants of low-carbon travel intention rather than AI-based tourism systems. Thailand was selected because it is an internationally recognized wellness tourism destination with strong growth in sustainable and health-oriented tourism services, providing an appropriate context for examining relationships between HC and low-carbon travel intention. However, contextual characteristics may limit direct generalization to other countries or tourism environments. This study aimed to investigate the structural relationships among HC, perceived behavioral control, personal attitudes, subjective norms (SN) ecological concern, and their direct and indirect effects on ecologically responsible travel decisions. This study was conducted among wellness and medical tourists in major tourism destinations in Thailand during 2025.

The study gap

Previous studies on low-carbon tourism primarily focused on environmental concern, social norms, or behavioral intention using conventional TPB or sustainability frameworks (Hatamifar *et al.,* 2025; Siddiqui and Sujood, 2025). Although sustainable tourism and low-carbon travel behavior have been widely investigated, limited studies have examined how HC functions as a psychological driver influencing environmentally responsible travel behavior among wellness tourists. Furthermore, few studies have integrated HC, environmental concern, and the constructs of the TPB into a cohesive framework to elucidate low-carbon travel intention in wellness tourism contexts (Naik *et al.,* 2025). Existing research has also largely focused on specific regional populations, with limited evidence from Thailand despite its global importance as a wellness tourism destination (Theerathitichaipa *et al.,* 2025). Consequently, comprehending the direct and indirect connections among HC, environmental concern, attitude, subjective norms, perceived behavioral control, and low-carbon travel intention remains insufficient. Addressing these gaps may provide broader insights into sustainable tourism behavior and supports the development of environmentally responsible tourism management strategies. The current study distinguishes itself from previous studies in the field of TPB-based sustainable tourism analysis, which mainly emphasized either HC or solely one of the other two components of TPB separately, by incorporating all three components of the TPB, and especially by adding environmental concern in addition to HC, into its analysis. The study makes a contribution by investigating the psychological antecedents of the environmental sustainability behavior in relation

to the concept of HC, and the direct and mediating pathways of the environmental concern and attitude toward sustainable travel. This comprehensive framework provides deeper insights into the behavioral mechanisms that facilitate low-carbon tourism and promote environmentally sustainable destination management.

Hypothesis development

The study approach adopted for this study is the examination of the relationship between HC, EC, AT, SN and PBC and the effects of the combination of these on low-carbon travel intention (LCTI). All psychological, environmental and social factors are shown to affect sustainable travel behavior. Fig. 1 illustrates the hypothesized correlations among these structural dimensions for wellness travelers in Thailand.

HC relationships

HC serves as a crucial catalyst for sustainable travel practices, positively influencing EC, AT and LCTI. A high level of health awareness can promote the low-carbon consciousness of health tourists, which can inspire positive attitudes and reinforced health tourists' intentions for low-carbon travel.

H1: HC is positively related to EC. HC → EC
H2: HC is positively related to AT. HC → AT
H3: HC is positively related to LCTI. HC → LCTI

Environmental concern effects

The EC has a substantial effect on sustainable travel behavior by increasing AT and LCTI. Increased awareness of environmental concerns motivates wellness tourists to embrace eco-friendly and low-carbon travel activities with more positive attitudes and intents.

H4: EC is positively related to AT. EC → AT
H5: EC is positively related to LCTI. EC → LCTI

Theory of planned behavior constructs

AT, SN, and PBC significantly influence LCTI. Positive attitudes, social influence, and greater perceived control strengthen wellness tourists' willingness to adopt eco-friendly and intention toward low-carbon travel behavior.

H6: AT is positively related to LCTI. AT → LCTI
H7: SN is positively related to LCTI. SN → LCTI
H8: PBC is positively related to LCTI. PBC → LCTI

Mediating effects

EC and AT act as key mediators between HC and LCTI. Greater health awareness indirectly strengthens low-carbon travel intention by enhancing environmental concern and fostering more positive attitudes toward sustainable travel behavior.

H9: EC mediates the relationship between HC and LCTI. EC → HC → LCTI
H10: AT mediates the relationship between HC and LCTI. AT → HC → LCTI

All the hypotheses were supported, confirming that HC directly or indirectly influences low-carbon travel intention, with strong contributions from attitude, environmental concern, and behavioral factors.

MATERIALS AND METHODS

HC and behavioral elements that affect the intention toward low-carbon travel were explored through the collection of information from wellness tourists in Thailand. The survey includes six constructs, namely, HC, EC, AT, SN, PBC, and LCTI. Additional demographic variables, including age, gender, educational background, and travel purpose, were collected to help differentiate sustainable travel behavior. These respondents were requested to report their opinion, attitude and intention towards travelling low carbon on a 5-point Likert scale. The data analysis method is carried out by SPSS (version 26) and quantitative analysis method including multiple regression analysis, confirmatory factor analysis (CFA), SEM and test of discriminant validity to establish the validity of measurement instruments. Multiple regression analysis was adopted to analyze the

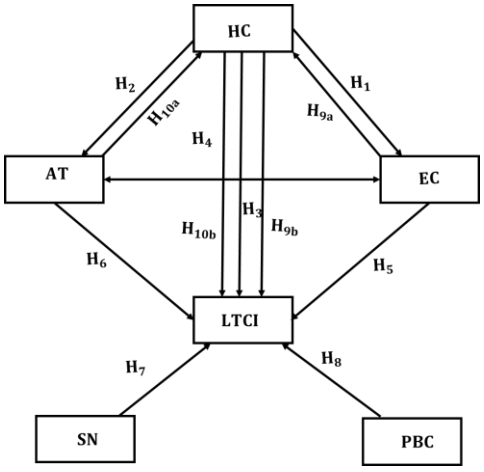

Fig. 1: Conceptual framework of the hypothesized structural model

direct effects of HC, eco-consciousness, attitude, norms in society and sense of behavior control on sustainable travel. Furthermore, SEM was used to explore the relational effects, including both direction and indirect influences of the independent variables on the dependent variable. The entire flow is displayed in Fig. 2.

Data collection

Data were collected from a sample of 465 respondents who had participated in wellness and medical tourism in Thailand. To ensure participants were representative of prominent wellness and medical tourism hubs in Thailand, a convenience sampling technique was implemented across key destinations during 2025. The respondents were the adults (≥18 years) who had already experienced either wellness tourism, medical tourism or sustainable travel related activity and were willing to participate in the survey voluntarily. Incomplete surveys and responses from individuals lacking relevant travel experience were excluded from the final analysis. Participants were selected from a pool of travelers with prior experience in sustainable tourism practices and services, such as utilizing eco-friendly accommodations, engaging in wellness tourism, adopting green transportation methods, and participating in low carbon tourism. A total of 465 valid responses were retained for final analysis. Table 1 presents the demographic breakdown of the sampled population. Fig. 3 displays the subject information broken down into (a) level of education, (b) occupation, (c) monthly income and (d) frequency of travel. A sample size of 465 respondents comfortably exceeds the recommended minimum threshold for SEM. This robust sample ensures adequate statistical power and enhances model stability for the proposed empirical analysis. In addition to the primary constructs, demographic characteristics including age, gender, education level, occupation, monthly income, travel frequency, and tourism type were collected to describe respondent profiles and assess potential differences in health consciousness and low-carbon travel intention among wellness tourists. Previous studies indicate that demographic factors may influence environmental awareness, sustainable travel attitudes, and environmentally responsible behavior. Furthermore, prior experience with wellness tourism or sustainable travel practices can enhance environmental concern and strengthen positive attitudes toward low-carbon travel behavior. Exposure to environmental awareness campaigns, sustainability-related information, and digital wellness content can also contribute to shaping tourists' perceptions and

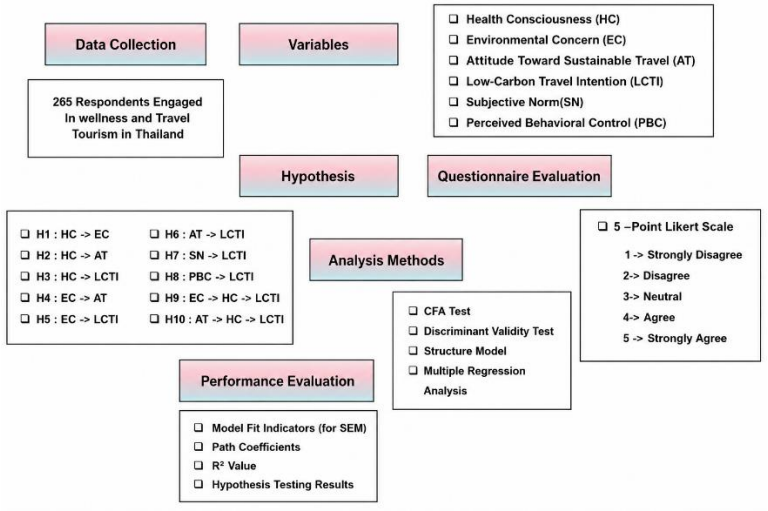

Fig. 2: Methodological workflow for evaluating health consciousness and its impact on low-carbon travel intention among wellness tourists

Table 1: Demographic characteristics

Demographic factor	Category	Count (n=465)	Percentage (%)
Gender	Male	232	49.8
	Female	233	50.2
Age group	18–25 years	102	21.9
	26–35 years	161	34.7
	36–45 years	107	23.0
	46–55 years	60	12.8
	Above 55 years	35	7.5
Education level	High School	56	12.1
	Bachelor's degree	213	45.7
	Master's degree	144	30.9
	Doctorate/others	52	11.3
Occupation	Student	86	18.5
	Employed (private/public)	240	51.7
	Self-employed	107	23.0
	Retired	32	6.8
Monthly income	Below $1000	113	24.2
	$1000–$2000	154	33.2
	$2001–$3000	104	22.3
	Above $3000	94	20.4
Travel frequency	Once a year	126	27.2
	2–3 times a year	207	44.5
	More than 3 times	132	28.3
Type of tourism	Wellness tourism	274	58.9
	Medical tourism	191	41.1

intentions regarding sustainable tourism. Although these contextual factors were considered conceptually in interpreting travel behavior, the present research primarily focused on examining the structural relationships among health consciousness, environmental concern, attitude, subjective norms, perceived behavioral control, and low-carbon travel intention. The composition of the wellness tourist segments indicates that they are comprised of diverse wellness tourists who possess varying levels of education levels, occupation types, travel frequencies, and monthly incomes brackets. The heterogeneity of the sample provides comprehensive insights into how different segments perceive health consciousness and adopt intention toward low-carbon travel behavior in sustainable tourism contexts.

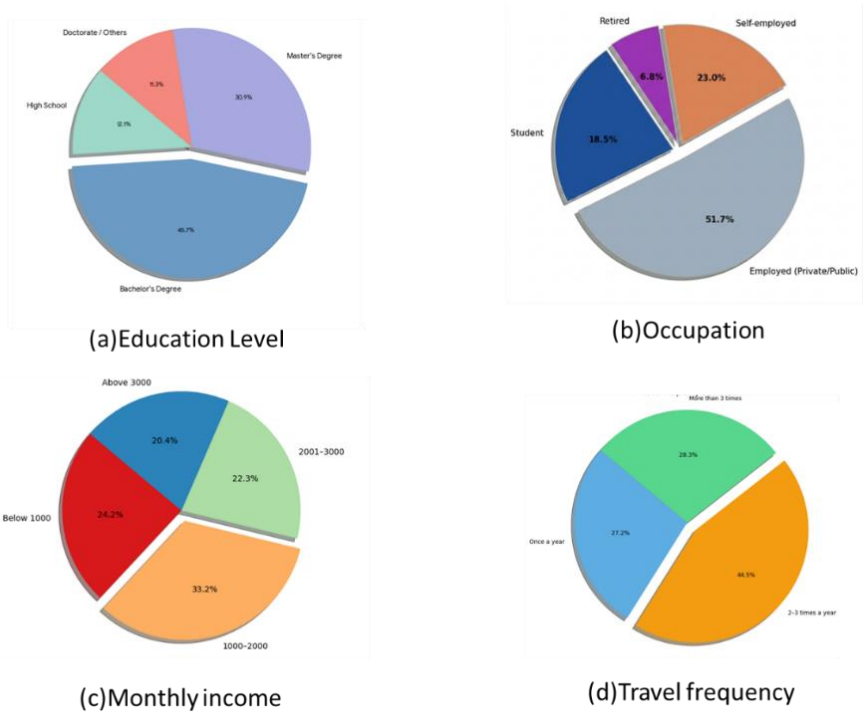

Fig. 3: Demographic and behavioral profile of wellness tourists based on
(a) education level (b) Occupation, (c) monthly income, (d) travel frequency

Variable explanation

The sample consists of 465 individuals who are informed about health and sustainable travel. A questionnaire was developed on the basis of the core research constructs (HC, EC, AT, SN, PBC, and LCTI), and it included age, gender, education level, occupational income, frequency and pattern of travel, and travel style. Demographics: Gathering to identify respondent characteristics and evaluate the extent to which background attributes, including age, gender, level of education, profession, income, frequency of travel, and tourist style, may influence awareness and the intention to travel sustainably.

HC: Evaluates an individual's knowledge, attentiveness, and concern regarding their physical and mental well-being, while capturing their intrinsic motivation to engage in a healthy lifestyle and wellness tourism.

EC: This measures the understanding of environmental issues and the influence of tourism on climate change to assess environmental concern and the willingness to conserve natural resources.

AT: Defines the degree to which an individual evaluates environmentally responsible travel with a favorable or unfavorable disposition.

SN: Is the perception of social pressure from family members, friends, transport companions and social reference groups that may affect ET. Positive social networking can raise awareness and boost intentions to use sustainable, low carbon travel. Normative beliefs and social approval are then considered to be important behavioral determinants in the TPB model.

PBC: PBC looks at the perceived ability of individuals to travel in ways that are sustainable (including ease/difficulty of choosing low-carbon travel options). Contextual factors like travel costs, cost of eco-tourism services, access to sustainable transportation, access to green tourism infrastructure and cost to adopt low carbon

tourism behavior also influence the perceived behavioral control. Furthermore, the use of new digital technologies, such as eco-travel applications, carbon footprint monitoring systems, and smart tourism systems, can enhance awareness, access to sustainability information and trust in choosing sustainable travel options. While not directly measured in the present study, these elements provide vital contextual background for interpreting the sustainable travel behaviors of wellness-focused tourists.

LCTI: This dimension assesses travelers' willingness and intrinsic motivation to adopt low-carbon practices, including the utilization of eco-friendly transport and accommodations, alongside a conscious effort to minimize their overall environmental impact during transit.

Questionnaire design

Six latent variables were employed to investigate the relationship between HC and LCTI for the wellness tourists in Thailand. Health awareness: HC; environmental concern: EC; attitudes toward sustainable travel: AT; social influence: SN; perceived control: PBC. LCTI represents the desire to travel in a low carbon way and is the total sum of behavioral and psychological influences on sustainable travel. The structural organization of the questionnaire, delineated by its respective latent variables, is outlined in Table 2. Each item was scored using a five-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree). Prior to full-scale administration, individual measurement items were slightly modified based on pilot test feedback to enhance clarity, readability, and overall instrument reliability and validity. To minimize potential common method bias and social desirability effects associated with self-reported data, respondent anonymity and confidentiality were guaranteed, participation was strictly voluntary, and the survey items were constructed using clear neutral wording and logically organized response structures for better participant comprehension.

RESULTS AND DISCUSSION

To evaluate the hypotheses, a rigorous two-stage SEM approach was employed, beginning with the measurement model to validate the proposed associations among the constructs. The reliability and validity of the measurement models for HC, EC, AT, SN, PBC, and LCTI were first tested using CFA. Discriminant validity was subsequently assessed to confirm that the latent constructs were empirically distinct from one another. Second, SEM was employed to simultaneously evaluate the direct and mediated effects of the independent constructs on the LCTI of wellness tourists in Thailand.

CFA test

The latent variables of health-conscious sustainable travel behavior (HC, EC, AT, SN, PBC, and LCTI) were measured by CFA to test the measurement model structure. CFA was performed to assess the relationships between observed indicators and their corresponding latent factors, verifying that the measurement items accurately captured the theoretical dimensions of each construct. The CFA model is estimated using Eqs. 1 and 2 (Siddiqui and Sujood, 2025):

$$X = \Lambda_x \xi + \delta \quad (1)$$

$$Y = \Lambda_y \eta + \epsilon \quad (2)$$

where X and Y represent the observed indicators for exogenous and endogenous constructs, Λ_x and Λ_y denote the factor loading metrics, ξ and η represent the latent constructs, and δ and ϵ represent the measurement errors. Table 3 demonstrates the CFA outcomes, while Fig. 4 depicts the path diagram showing the factor loadings. The evaluation of the research's reliability and validity was conducted using Cronbach alpha, CR, AVE, and confirmatory factor analysis. All constructs passed the set criteria for reliability and validity as their Cronbach alpha and CR were above 0.70 and AVE was above 0.50.

Table 2: Questionnaire structure and variables

Variables	Questionnaire Items
HC	How often do you consider your health when making travel decisions? How much do you like activities to improve your physical and mental health when travelling? What's your take on keeping a healthy lifestyle throughout your travels?
EC	How concerned are you about the environmental impact of tourism activities? To what extent do you believe tourism contributes to climate change? How important is environmental protection when choosing travel destinations?
AT	How positively do you view choosing eco-friendly or low-carbon travel options? To what extent do you believe sustainable travel is beneficial for the environment? How favourable is your overall attitude toward sustainable tourism practices?
SN	Do your friends and family encourage you to choose environmentally friendly travel options? To what extent do social expectations influence your travel decisions? How important is social approval when choosing sustainable travel behavior?
PBC	How easy is it for you to choose low-carbon or eco-friendly travel options? Do you feel you have enough resources (time, money, access) to travel sustainably? To what extent do you feel in control of making environmentally responsible travel choices?
LCTI	How likely are you to choose low-carbon transportation for future travel? To what extent do you intend to stay in eco-friendly accommodations? How willing are you to reduce your environmental impact during travel?

Table 3: Reliability and validity of constructs

Latent Construct	Items	Loading Values	Mean (M)	SD	Cronbach's α	CR	AVE	DG rho	VIF
HC	HC1, HC2, HC3	0.86, 0.83, 0.81	4.12	0.70	0.88	0.91	0.71	0.87	2.3
EC	EC1, EC2, EC3	0.85, 0.82, 0.80	4.18	0.72	0.87	0.90	0.69	0.85	2.4
AT	AT1, AT2, AT3	0.88, 0.84, 0.81	4.05	0.74	0.89	0.92	0.73	0.88	2.2
SN	SN1, SN2, SN3	0.84, 0.82, 0.79	3.98	0.76	0.86	0.89	0.68	0.84	2.3
PBC	PBC1, PBC2, PBC3	0.87, 0.85, 0.82	4.10	0.71	0.88	0.91	0.72	0.86	2.5
LCTI	LCTI1, LCTI2, LCTI3	0.90, 0.87, 0.85	4.22	0.69	0.90	0.93	0.75	0.88	2.6

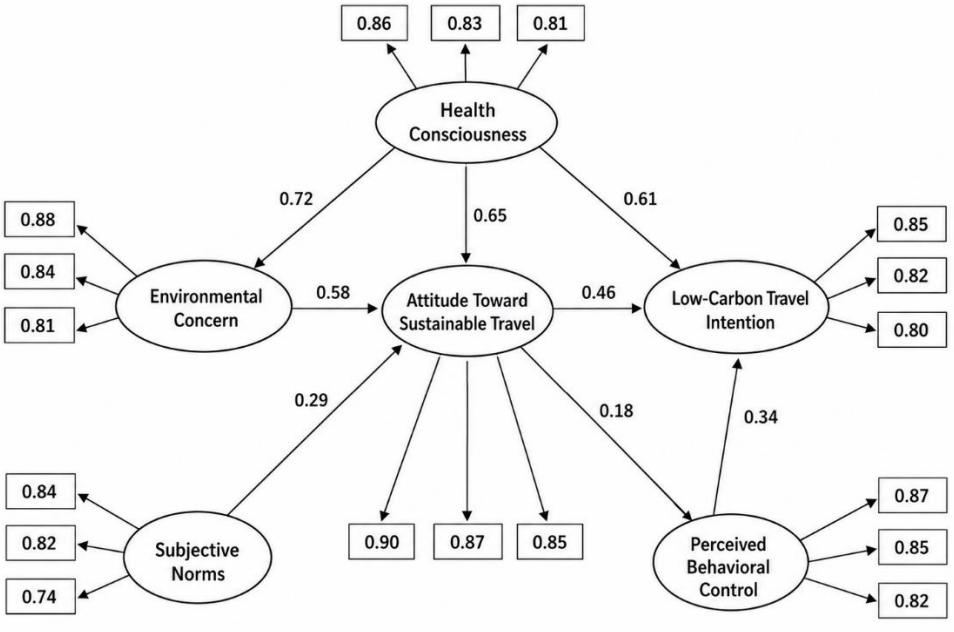

Fig. 4: Visual representation of construct relationships

The CFA results confirm the strong reliability and validity for HC, EC, AT, SN, PBC, and LCTI, with CR and loadings > 0.70, AVE (0.68–0.75), and no multicollinearity (VIF: 1.9–2.5). Discriminant validity is also confirmed, indicating that all hypotheses are distinct and effectively assess low-carbon travel intention among wellness tourists. As shown in Fig. 5, all the components have high reliability and convergent validity, validating the measurement model's resilience for wellness visitors. The findings indicate that all constructs (HC, EC, AT, SN, PBC, and LCTI) demonstrate satisfactory validity and reliability. Consequently, the established reliability and validity of the measurement scales provide a robust foundation for investigating the low-carbon travel intentions of wellness tourists in Thailand.

SEM

The hypothesized relationships were tested using SEM, with LCTI as the dependent variable and HC, EC, AT, SN, and PBC as the independent variables. SEM enables the simultaneous testing of multiple direct and indirect (mediated) relationships within a single model, while concurrently evaluating the framework's explanatory power via R2 values. The standardized path coefficient (β) and pvalue for each relationship are simultaneously considered to validate the impact of measurement error and complex relationships within the model structure. Hence, it is pertinent to examine the concurrent impact of psychological, environmental, and behavioral factors on LCTI. The outcomes surpass the realm of behavioral intention, indicating potential ramifications for environmental sustainability initiatives. These encompass the advocacy of low-carbon tourism practices, the decrease of carbon emissions linked to tourism, and the endorsement of sustainable destination management strategies. Increased health awareness combined with environmental concern can encourage environmentally responsible tourism behaviors aligned with long-term sustainability objectives.

Discriminant validity test

Discriminant validity ensures that the indicators assessing the impact of health-conscious sustainable travel behavior (HC, EC, AT, SN, PBC, and LCTI) are unique from one another. The Fornell–Larcker criterion states that discriminant validity is established when the square root of the AVE for each object exceeds its correlations with all other latent variables. This indicates that a given construct shares more variance with its assigned indicators than with alternative constructs by employing Eq. 3 (Siddiqui and Sujood, 2025):

$$\sqrt{AVE_i} > r_{i,j} \tag{3}$$

where, AVE_i indicates the AVE for construction i and r_{ij}relates to the correlation between constructs i and j. The discriminant validity test confirms that HC, EC, AT, SN, PBC, and LCTI represent independent and theoretically distinct constructs for explaining low-carbon travel intention among wellness tourists in Thailand. Table 4 presents the discriminant validity results among the constructs. The Fornell-Larcker criterion was employed to assess discriminant validity, indicating that the square root of the AVE for each construct exceeded the correlation coefficients between constructs. Furthermore, all HTMT ratios remained lower than 0.85, which is considered an ideal value to establish discriminant validity. The discriminant validity and convergent validity assessments reveal that all the construct measurements are unique (AVE=0.82–0.87; interconstruct correlations=0.49–0.72). This suggests a solid measurement model capable of understanding and measuring low-carbon travel intentions among Thailand wellness tourists with strong construct reliability, validity, and predictive analytical consistency.

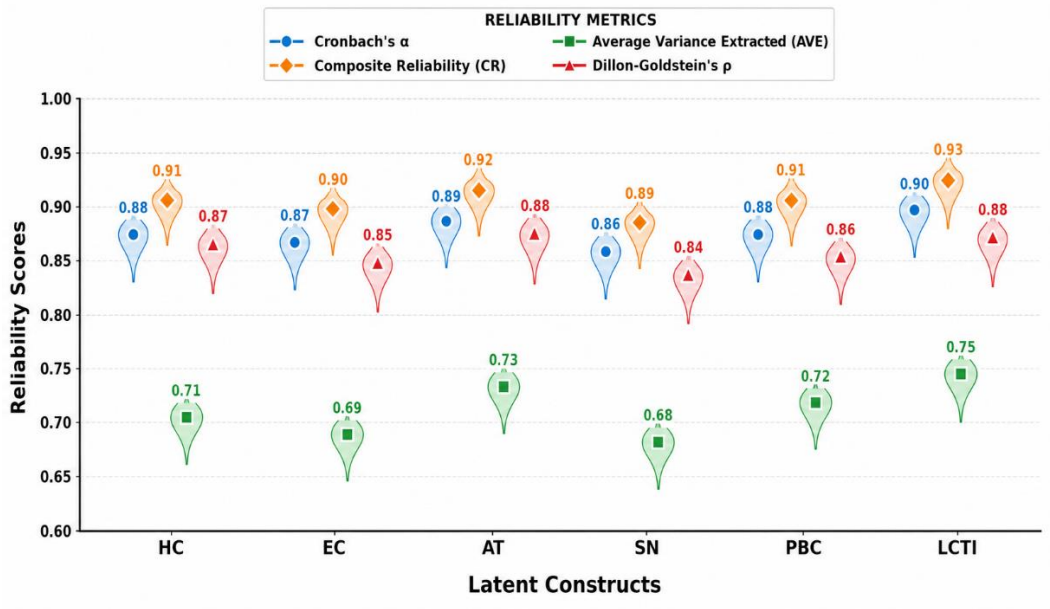

Fig. 5: Measurement model reliability and validity of health consciousness conclusions for Low-carbon travel intention

Table 4: Assessment of discriminant validity

Construct	HC	EC	AT	SN	PBC	LCTI
HC	0.84					
EC	0.62	0.83				
AT	0.58	0.65	0.86			
SN	0.49	0.52	0.60	0.82		
PBC	0.55	0.57	0.63	0.66	0.85	
LCTI	0.60	0.64	0.71	0.68	0.72	0.87

Structural model

The structural model demonstrates the function of health consciousness in mediating LCTI via EC, AT, SN, and PBC. The model illustrates the sequential influence of health consciousness on environmental awareness and favorable ecological attitudes, which collectively culminate in the sustainable travel behavior of wellness tourists in Thailand. The structural correlations can be proved using Eqs. 4, 5 and 6 (Wang and Phakdeephairot, 2024; Siddiqui and Sujood, 2025):

$$EC = \beta_1\ HC + \zeta_1 \quad (4)$$

$$AT = \beta_2\ HC + \beta_3\ EC + \zeta_2 \quad (5)$$

$$LCTI = \beta_4\ HC + \beta_5\ EC + \beta_6\ AT + \beta_7\ SN + \beta_8\ PBC + \zeta_3 \quad (6)$$

where, β coefficients (β_1-β_8) represent the standardized path effects between the constructs in the structural model and ζ terms (ζ_1, ζ_2, ζ_3) represent the residual error terms for each endogenous variable. All these models reveal the direct and indirect influence of HC on LCTI mediated through EC and AT as mediators and that SN and PBC act as complementary behavioral predictors. The structural pathways are also detailed in Table 5, depicting the hypothesized structural connections of sustainable travel behavior. The findings of the structural model confirmed all the hypotheses put forward, with statistically significant standardized path estimates (β) and p-values below 0.05. The statistical significance of both the direct and indirect effects was established, confirming that environmental concern and attitudes regarding

Table 5: Structural paths and hypotheses

Hypothesis	Path relationship	Beta(β)	p value	t value	Decision
H1	HC → EC	0.41	0.001	6.12	Supported
H2	HC → AT	0.36	0.002	5.44	
H3	HC → LCTI	0.29	0.004	4.91	
H4	EC → AT	0.33	0.001	5.67	
H5	EC → LCTI	0.27	0.006	4.38	
H6	AT → LCTI	0.45	0.004	7.20	
H7	SN → LCTI	0.31	0.003	5.02	
H8	PBC → LCTI	0.38	0.001	6.45	
H9	EC→ HC → LCTI	0.18	0.010	3.92	
H10	AT → HC → LCTI	0.22	0.003	4.75	

sustainable tourism acted as mediators in the intention to pursue low-carbon travel. The model's hypothesized associations have substantial support, since all the hypotheses are statistically significant ($p < 0.05$). Structural path studies support all hypothesized links in the case of Thailand wellness tourists, with substantial path coefficients among the variables. As shown in Fig. 6, HC directly affects EC (β=0.41), AT (β=0.36), and LCTI (β=0.29). AT has the greatest direct impact on LCTI (β=0.45), followed by PBC and SN. The analysis presents path coefficients (β) and t values for the hypothesized path impacts of health consciousness on low-carbon travel intention. An established correlation between environmental concern and sustainable travel attitudes indicates that greater environmental literacy and awareness of climate issues serve to strengthen favorable perceptions toward environmentally responsible tourism behavior. Increased understanding of climate-related impacts associated with tourism activities can encourage wellness tourists to support sustainable travel practices and adopt stronger low-carbon travel intentions. Furthermore, eco-labels, green certifications, and destination branding that emphasizes sustainability may increase tourists' confidence in eco-friendly tourism services, thus promoting environmental concern and positive perceptions of sustainable travel. However, the present study focused primarily on behavioral intention rather than actual travel behavior; therefore, whether stated low-carbon travel intention translates into real environmentally responsible behavior requires further investigation using longitudinal or behavioral data. These findings indicate that all the hypotheses (H1–H10) are positively and significantly related among wellness tourists in Thailand and that H6 is the most powerful in terms of its influence (β = 0.45, t = 7.20), whereas H9 is the least powerful (β = 0.18, t = 3.92). This important role of subjective norms on travelers' intention to travel in low-carbon mode indicates that social reference groups, such as family members, friends and travel companions, may help with low-carbon travelers' decisions. Social support and subjective norms regarding sustainable behavior can significantly reinforce an individual's intention to select eco-friendly travel alternatives. Moreover, infrastructure for sustainable tourism, such as environmentally friendly tourism accommodation, sustainable transportation and adoption of renewable energy, and sustainable tourism approaches in the hospitality sector can facilitate positive attitudes toward low carbon travel, by making it more accessible and removing barriers to sustainable tourism decisions. While these contextual factors fell outside the scope of the current empirical investigation, they may serve as critical facilitators of low-carbon travel intentions and warrant exploration in future studies to deepen the understanding of sustainable tourism behavior. The results show that psychological

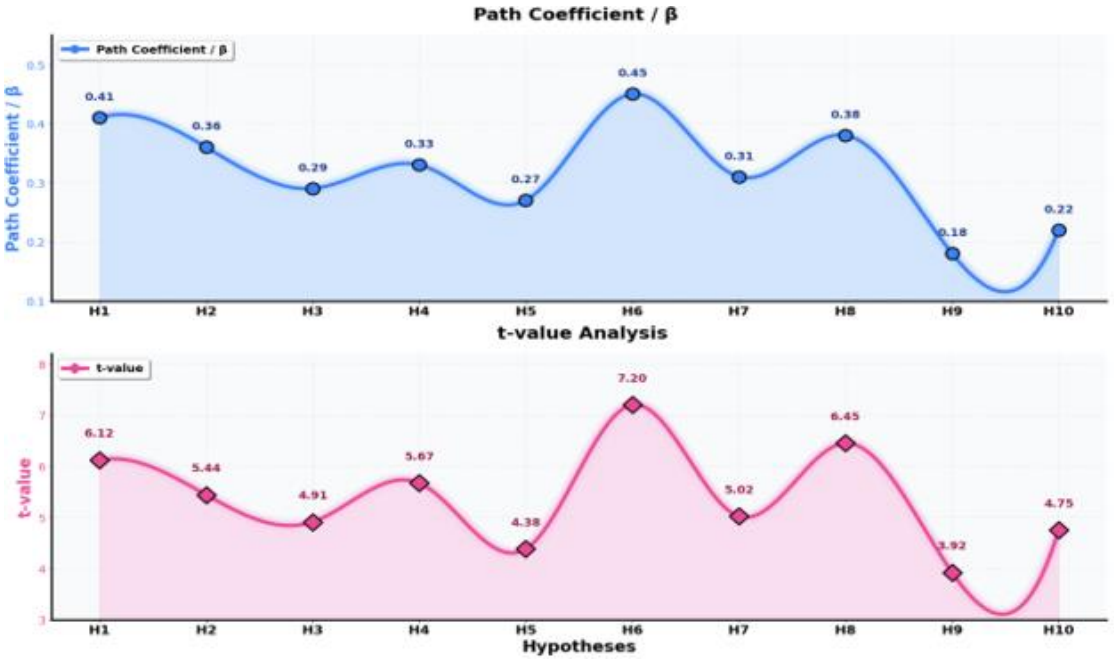

Fig. 6: β and t values for hypotheses on health consciousness and low-carbon travel intention

factors like environmental responsibility and moral obligation possess a downstream impact, thereby bolstering positive attitudes toward sustainable travel and strengthening low-carbon travel intention among environmentally conscious wellness tourists in Thailand. There was a slightly greater direct effect of health consciousness on low carbon travel intention (β = 0.29) than environmental concern (β = 0.27), suggesting that perceived personal health benefits may be more powerful in motivating sustainable travel decisions. Furthermore, the perception of an environmentally friendly image of a location, combined with the principles of ecotourism aimed at wellness, can positively influence sustainable travel perspectives, particularly regarding physical and mental wellness. Because these variables were not directly quantified in the current study, subsequent research should empirically investigate their influence on sustainable travel behavior. The environmental concern was found to significantly mediate the relationship between health consciousness and low-carbon travel intention (H9: β = 0.18, p = 0.010), suggesting that health awareness can help boost the sustainable travel intention through environmental concern. Furthermore, macro-level disruptions—such as global health crises and climate-induced environmental challenges—frequently elevate consumer consciousness regarding personal health and sustainability, subsequently driving a shift toward pro-environmental travel choices. The results indicate that health consciousness has a positive effect on the low-carbon travel intention, which is recognized as positive implications for personal health from the use of sustainable travel behavior. Other psychological factors, such as environmental identity, ecological commitment and moral responsibility, can further reinforce sustainable travel attitudes and low carbon travel intention. Also, sustainable lifestyle practices, such as the consumption of organic products and sustainable foods, are closely intertwined with pro-environmental tourism behaviors and environmentally responsible consumer decision-making.

Multiple regression analysis

Using multiple regression, the effects of HC, EC, AT, SN, and PBC on LCTI were determined for Thailand wellness tourists. LCTI was identified as the dependent variable, and HC, EC, AT, SN, and PBC were identified as independent variables for multiple regression, using Eq. 7 (Naik *et al.,* 2025; Siddiqui and Sujood, 2025):

$$LCTI = \beta_0 + \beta_1 HC + \beta_2 EC + \beta_3 AT + \beta_4 SN + \beta_5 PBC + \varepsilon \quad (7)$$

where, LCTI is the dependent variable representing low-carbon travel intention; β_0 is the intercept; $\beta_1 \ldots \beta_8$ are the regression coefficients for each predictor variable; HC, EC, AT, SN, and PBC are the independent variables; and $and\ \varepsilon$ is the error term. Table 6 shows the multiple regression results for the factors influencing the LCTI among wellness tourists. All the predictor factors are very significant ($p < 0.005$). HC, EC, AT, SN, and PBC substantially influenced the LCTI of Thailand wellness tourists and explained a large proportion of the LCTI ($R=0.82$, $R^2=0.68$). AT had the greatest influence ($\beta = 0.41$; $p=0.001$), followed by PBC and HC ($\beta = 0.36$; $\beta = 0.32$). The data in Fig. 7 confirm these significant associations when B and tvalues are used. Table 7 presents the goodness-of-fit indices used to evaluate the adequacy of the proposed CFA and SEM models. The obtained goodness-of-fit measures complied with established SEM evaluation criteria, confirming that the structural framework possessed acceptable adequacy and a robust overall model fit. These results confirmed the robustness and suitability of the proposed conceptual framework for structural analysis. AT is the most significant factor ($\beta = 0.26$, $t = 6.78$), whereas EC is the least influential predictor. All constructions had substantial effects on wellness tourists' intention to travel low-carbon in Thailand, with t values greater than 4.0. This study utilized cross-sectional survey data gathered from a sample of 465 wellness tourists in Thailand. Although the sample size was adequate for SEM analysis, the use of self-reported responses and convenience sampling may limit generalizability and introduce response bias, which restricted generalizability. These results are largely consistent with empirical evidence from previous sustainable tourism studies, confirming that environmental concern and favorable travel attitudes positively influence low-carbon travel intention (Ma *et al.,* 2024). However, prior studies have also documented weaker linkages among these behavioral constructs, noting that economic barriers, restricted environmental consciousness, and inadequate green tourism infrastructure often hinder compliance (Sakcharoen *et al.,* 2024). The stronger relationships observed in the present study may be associated with the increasing environmental consciousness and wellness-oriented travel preferences among tourists in Thailand. These findings indicate that sustainable travel intention could vary across tourism contexts, demographic characteristics, and environmental awareness levels. Reliance on self-reported interview data introduces potential response bias, while the inherent nature of the cross-sectional design precludes definitive causal inferences. Context-specific findings restrict broader application of triple helix model relationships (Alizadeh *et al.,* 2024). Constraints included a Finland-focused sample, limiting generalizability. The utilization of a cross-sectional design and self-reported measures may have introduced response bias, thereby limiting the capacity for definitive causal inference. The increased relevance for young people diminished the relevance for others; combining the TPB and NAM potentially overlooked other behaviors (Hatamifar *et al.,* 2025). To address these defects and provide a design, this study ensured an appropriate sample size and diversity of wellness tourists; measured a range of dimensions using a

Table 6: Multiple regression analysis results

Independent variable	B	β	t	Sig.	R	R^2
Health consciousness (HC)	0.21	0.32	5.21	0.001	0.82	0.68
Environmental concern (EC)	0.18	0.28	4.63	0.002		
Attitude toward sustainable travel (AT)	0.26	0.41	6.78	0.001		
Subjective norms (SN)	0.19	0.30	5.09	0.003		
Perceived behavioral control (PBC)	0.24	0.36	6.15	0.001		

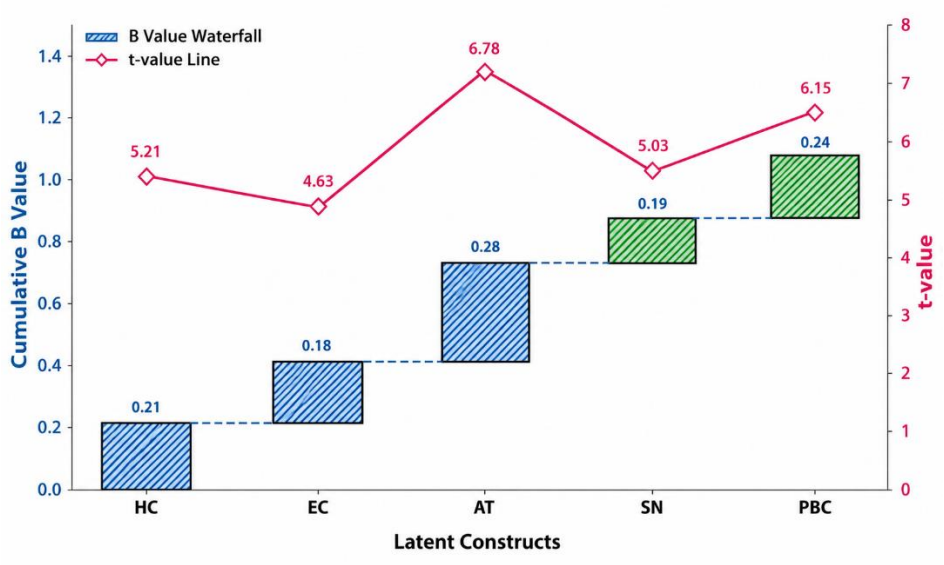

Fig. 7: Comparative analysis of B-values and t values for structural relationships among health consciousness constructs and low-carbon travel intention

Table 7: Goodness-of-fit indices for CFA and SEM model evaluation

Fit index	Recommended threshold	Model evaluation
χ^2/df	< 3.00	Acceptable fit
RMSEA	< 0.08	Good fit
CFI	> 0.90	Good fit
TLI	> 0.90	Acceptable fit
GFI	> 0.90	Satisfactory fit
SRMR	< 0.08	Good fit

well-established and reliable scale to avoid response bias; and used a variety of analytical methods, including multiple regression (the prediction ability of this model was significant), and demonstrated that HC, EC, AT, SN, and PBC significantly predicted LCTI. The SEM results revealed a direct and mediated relationship, as well as model routes connecting HC and LCTI via EC and AT. Furthermore, the thoughtful construction of surveys and the maintenance of respondent anonymity, along with a multifaceted viewpoint, could mitigate answer bias and yield a more complete analysis of low-carbon travel intention. This study focused on perceived effects to explain travel behavior. Furthermore, this analysis does not account for broader contextual factors, such as economic costs and infrastructure availability. Additional methodological limitations include the reliance on a single travel survey method and a geographically restricted sample size within Thailand. While AI-supported tourism management research was considered to help

establish a broad understanding of sustainability issues, this study concentrates on factors affecting low carbon traveling intentions in particular, not on AI-supported tourism management. Possible extensions of this study include the use of real behavioral data with larger sample sizes and the introduction of context-specific effects such as policy, technology and availability that may explain and predict intention toward low-carbon travel behavior. The empirical insights yielded by this study carry profound implications for both environmental management strategies and the formulation of sustainable tourism policy. Encouraging intention toward low-carbon travel behavior among wellness tourists is likely to be beneficial in achieving environmental sustainability and mitigating the environmental impacts of tourism in Thailand. Consequently, this study extends beyond behavioral psychology and sustainable tourism literature to offer valuable incremental contributions to the field of environmental management. Consequently, this study extends beyond behavioral psychology and sustainable tourism literature to offer valuable incremental contributions to the field of environmental management.

Future scope of the research

To advance this line of inquiry, future research should expand along four key dimensions. First, subsequent studies could incorporate objective environmental performance indicators, carbon footprint metrics, or longitudinal interventions to more accurately assess the long-term impacts of sustainable tourism. Second, adopting cross-cultural and longitudinal research designs would allow investigators to track the temporal evolution of sustainable travel behaviors. Third, future models should integrate these omitted contextual and technological variables to construct a more holistic framework of how PBC interacts with and drives pro-environmental travel choices. Fourth, researchers should investigate how specific reference groups—such as family, friends, and travel companions—interact with micro-contextual tourism factors, including eco-friendly accommodations, sustainable transportation systems, and the implementation of green services, to influence low-carbon travel intentions. Finally, subsequent studies should explore how macro-level factors—such as sustainable destination branding, green certifications, and eco-labeling—interact with climate change and environmental awareness to shape pro-environmental travel choices. Travel behavior observation should be integrated in longitudinal methods to gain deeper understanding of the relationship between the intention and the actual environmentally responsible tourism practices.

CONCLUSION

This study investigated the role of health consciousness in shaping low-carbon travel intention among wellness tourists in Thailand by integrating health-related psychological factors with environmental and behavioral dimensions. By demonstrating an empirical link between health consciousness and the health-directed behaviors of tourists, this study extends the scope of sustainable tourism frameworks and establishes these wellness habits as potent predictor of sustainable behavior. The study integrates environmental concern, attitude towards sustainable travel, subjective norms and perceived behavioral control in an integrated behavior model and offers a holistic explanation of the factors impacting low carbon travel intention in the context of wellness tourism.The empirical findings demonstrate that health consciousness significantly influences environmental concern, sustainable travel attitudes, and the intention to engage in low-carbon travel. The SEM analysis demonstrated that health consciousness positively affected environmental concern

(β = 0.41, p = 0.001), attitude toward sustainable travel (β = 0.36, p = 0.002), and low-carbon travel intention (β = 0.29, p = 0.004). The results showed that those who are more aware of personal health tend to be more inclined to engage in more environmentally sustainable travel habits and promote eco-friendly tourism activities. Concern about the environment also had positive significant effects on attitude towards sustainable travel (β = 0.33, p = 0.001) and low carbon travel intention (β = 0.27, p = 0.006), meaning that ecological awareness is a positive factor that intensifies tourists' intentions of sustainable travel among wellness tourists. The attitude towards sustainable travel was the most highly significant TPB construct (β = 0.45, p = 0.004) in predicting low-carbon travel intention. This finding highlights the pivotal role of positive attitudes toward eco-friendly travel in motivating tourists to engage in sustainable tourism activities. Subjective norms (β = 0.31, p = 0.003) and perceived behavioral control (β = 0.38, p = 0.001) also had significant effects on low carbon travel intention, suggesting that both social influence and perceived ability to change behavior is important for low carbon travel intention. Furthermore, the mediation analysis confirmed that environmental concern and attitudes toward sustainable travel serve as significant mediating pathways between health consciousness and low-carbon travel intentions. The results show that the indirect effect of health awareness towards sustainable travel behavior is mediated by forming environmental responsibility and positive travel attitudes. Multiple regression analysis was used to validate the robustness of the proposed model. The explanatory power of the combined effects of health consciousness, environmental concern, attitude, subjective norms, and perceived behavioral control for the intention to use low-carbon travel was 68% (R^2 = 0.68). The empirical findings support the premise that integrating health-conscious and environmental dimensions offers a more comprehensive understanding of sustainable tourist behavior compared to conventional behavioral constructs. Therefore, in regard to the theory application of this study, the incorporation of health consciousness and environmental concern as one of the important variables that affect the low-carbon tourism intention goes beyond the previous studies. Regarding its theoretical contributions, this study integrates health consciousness and environmental concern as pivotal determinants of low-carbon tourism intentions, thereby extending the scope of prior literature. The policy implications of this study are important to policy makers, tourism authorities, wellness tourism operators, and environmental planners. Medical tourism stakeholders need to boost sustainability programs and campaigns grounded in health approaches, which link health and environmental protection. In order to achieve this, the development of eco-friendly accommodation, sustainable transportation systems, wellness-oriented green tourism packages, and environmental education programs can stimulate tourists to shift towards intention on low carbon travel behavior. Furthermore, leveraging social influence and public awareness mechanisms can bolster the efficacy of sustainable tourism initiatives while fostering favorable attitudes and behaviors toward pro-environmental practices. The results also imply practical environmental benefits, as health awareness and environmental awareness could promote the selection of environmentally friendly travel options, which could help to lower the carbon footprint generated by tourism and promote sustainable tourism destination management and green tourism policies in Thailand. The findings demonstrate that enhancing sustainable tourism awareness alongside promoting eco-friendly travel behaviors serves as a key catalyst for establishing enduring,

responsible, and low carbon tourism destinations in Thailand. An approach to combining health awareness with environmental sustainability measures can contribute to the reinforcement of tourism policies through the promotion of environmentally-friendly travel, accommodation, medical tourism packages and environmental education.

AUTHOR CONTRIBUTIONS

W. Madhyamapurush, as the sole author, conceived the study, performed the analyses, interpreted the results, and drafted and revised the manuscript.

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CONFLICT OF INTEREST

The author declares 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/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
AI	Artificial intelligence
AT	Attitude toward sustainable travel
AVE	Average variance extracted
B	Unstandardized coefficient
CB-SEM	Covariance-based structural equation modelling
CFA	Confirmatory factor analysis
COVID-19	Coronavirus disease 2019
CR	Composite reliability
DG rho	Dijkstra–Henseler's rho
EC	Environmental concern
GHG	Greenhouse gas
HC	Health consciousness
IGSCA	Importance-gap satisfaction and competitive analysis
LCTI	Low-carbon travel intention
MCA	Multiple correspondence analysis
NAM	Norm activation model
PBC	Perceived behavioral control
SEM	Structural equation modelling
SN	Subjective norms
SOR	Stimulus–organism–response
SPSS	Statistical package for the social sciences

TPB	Theory of planned behavior
VIF	Variance inflation factor
VR	Virtual reality

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ORIGINAL RESEARCH ARTICLE

Balancing ecological stability and economic growth under oceanographic variability and coastal interventions in fisheries systems

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ABSTRACT

BACKGROUND AND OBJECTIVES: The advancement of coastal fisheries can lead to improved livelihoods, yet it may also heighten fishing pressure and create hidden ecological risks, particularly in data-limited small-scale systems where ecological responses are not immediately detectable. The study objectives were to assess the trade-offs and synergies between economic development and ecological health in a small-scale coastal fisheries system under the Kampung Nelayan Merah Putih intervention in Samber–Binyeri Village, Biak Numfor, Indonesia.

METHODS: An integrated framework combining the Ecosystem Approach to Fisheries Management, pressure-response analysis, field observations, interviews, secondary data, satellite-derived environmental indicators, and Generalized Additive Model analysis was applied to evaluate fisheries performance, fishing pressure, ecological conditions, and governance responses. To capture the environmental drivers impacting fisheries dynamics, oceanographic variability, such as sea surface temperature and chlorophyll-a, was taken into consideration.

FINDINGS: The intervention improved economic performance, with fisher income increasing by 88.8 percent in peak seasons, production by 121.2 percent, and fishing trips by 44.4 percent. The overall Ecosystem Approach to Fisheries Management composite index reached 78 percent, indicating good sustainability performance. Economic, social, and fishing technology domains scored highly, while habitat and ecosystem conditions remained moderate at 60 percent. The mean catch per unit effort recorded was 42.78 kilograms per trip, which did not display a steady decline. Nevertheless, factors such as juvenile catch, habitat restrictions, and increased effort point to developing ecological pressure. These patterns suggest a potential hyperstability condition, where stable catch rates may not fully reflect changes in stock condition. Consequently, management should therefore focus on controlling efforts, restoring habitats, monitoring adaptive Ecosystem Approach to Fisheries Management monitoring, strengthening institutional coordination, and integrating local knowledge systems.

CONCLUSION: Economic development in Samber–Binyeri has generated clear livelihood benefits, but stable catch per unit effort may mask underlying ecological risks caused by increasing fishing pressure. Indicators suggest the system is in a state of short-term ecological stability. To ensure long-term coastal fisheries sustainability amidst rising environmental variability and development, management must prioritize habitat restoration, adaptive strategies, and stronger institutional coordination.

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INTRODUCTION

Freshwater Coastal regions are complex socio-ecological systems where biophysical processes and human activities interact, particularly in small-scale fisheries. These systems link oceanographic processes, ecosystem structures, and resource-dependent livelihoods (Berkes *et al.,* 2003). Coastal ecosystems, including coral reefs, seagrass beds, and mangroves, support fisheries productivity through habitat provision, nutrient cycling, shoreline protection, and ecological functions (Barbier *et al.,* 2011). Nevertheless, they are subjected to escalating pressures due to coastal development, overfishing, and climate variability, which jeopardize ecosystem resilience and fisheries sustainability (Halpern *et al.,* 2015; Hoegh-Guldberg *et al.,* 2017). Coastal fisheries development interventions, such as infrastructure expansion, fisheries modernization, cold storage, market access, and improved technology, can enhance fisher income, production efficiency, and economic resilience (World Bank, 2012; FAO, 2024). Conversely, such measures risk expanding fishing capacity and access, potentially escalating the exploitation pressure placed upon marine ecosystems (Selgrath *et al.*, 2018). In small-scale fisheries, indicators such as catch per unit effort (CPUE), commonly used to assess fisheries' performance, may remain stable despite declining fish stocks because fishers can maintain catch levels through improved efficiency, spatial targeting, concentration on fish aggregations, or shifts in target species (Smallhorn-West *et al.*, 2022). This phenomenon, known as hyperstability, can mask underlying declines in fish abundance and delay the detection of ecological degradation (Harley *et al.,* 2001; Erisman *et al.*, 2011). visible economic growth and stable catch rates should not be mistaken for ecological sustainability. This is especially true in data-poor fisheries where comprehensive stock assessments are unavailable. The relationship between fisheries development and ecological stability is further mediated by environmental variability. Oceanographic drivers such as sea surface temperature (SST), chlorophyll-a concentration, salinity, currents, and monsoon variability strongly influence marine productivity, habitat suitability, fish distribution, and catch success (Lehodey *et al.*, 2006; Han *et al.*, 2022; González *et al.*, 2022). Variability in SST and chlorophyll-a has been shown to affect CPUE, fishing-ground distribution, and fisheries productivity across tropical and small-scale fisheries systems (Tangke and Senen, 2020; Putri *et al.,* 2024). Environmental factors often amplify or obscure the results of fisheries interventions, making it difficult to separate natural variability from human-induced stress. Fisheries sustainability therefore requires an integrated perspective that accounts for both human-induced pressures and oceanographic variability. The ecosystem approach to fisheries management (EAFM) provides a relevant framework by integrating ecological, economic, social, technological, and institutional dimensions (Muawanah *et al*., 2018). Climate-informed EAFM highlights how oceanographic variables—including sea surface temperature, productivity, and acidification—impact fish habitats and socio-economic stability. These variables directly influence fisheries yield and social vulnerability, requiring a management approach rooted in continuous monitoring and evaluation (Heenan *et al*., 2015). However, this approach remains largely conceptual and planning-oriented, with limited empirical assessment at the local fisheries scale. In contrast, Hidayat *et al*. (2025) applied EAFM to balance ecological and economic performance in small-scale fisheries in West Papua but did not explicitly account for oceanographic variability as a driver of fisheries performance and ecological response. Furthermore, a lack of understanding persists regarding the ways in which coastal development efforts alter fisheries systems amid environmental challenges and economic demands. This study addresses that gap by integrating climate-informed EAFM and ecology–economy balance assessment to examine how

oceanographic variability, modernization village intervention, fishing pressure, and ecosystem response interact. Rather than treating EAFM as a mere sustainability scoring mechanism, this study utilizes the framework to investigate how intervention-induced shifts in fishing capacity, income, and effort trigger ecological trade-offs. The analysis is conducted using a case study of Samber–Binyeri Village in Biak Numfor Regency, Indonesia, where a coastal development program under the Kampung Nelayan Merah Putih (KNMP) initiative has been implemented. This study site offers a pertinent empirical framework, characterized by a well-preserved ecological baseline, a high reliance on small-scale fisheries, and recent infrastructure and economic initiatives. This study aims to assess the trade-offs and synergies between economic development and ecological health in a small-scale coastal fisheries system. The study has been contacted in Samber–Binyeri Village, Papua, Indonesia in 2025.

MATERIALS AND METHODS

Study area

The study region is located in Samber–Binyeri Village, Papua, Indonesia (Fig. 1). This region constitutes a segment of a highly dynamic tropical marine system shaped by intricate interactions between oceanographic processes and atmospheric variability, rendering it especially appropriates for investigating socio-ecological dynamics in small-scale fisheries (Sprintall *et al*., 2014). The selection of this study area is based on three main considerations. First, the region represents a data-limited, small-scale fisheries system, where fishing activities are dominated by artisanal fleets with relatively low technological capacity, which is characteristic of coastal fisheries across Southeast Asia (Pauly and Zeller, 2016; Teh and Sumaila, 2011). Second, the area is subject to strong environmental variability, particularly driven by monsoonal systems and large-scale climate oscillations such as the El Niño–Southern Oscillation (ENSO), which are known to significantly affect marine productivity and fisheries outcomes in tropical regions (Bell *et al*., 2013). Additionally, the implementation of the KNMP program over the past two years allows for a timely evaluation of how the system responds to both management interventions and environmental stressors in the short term. The study area is dominated by small-scale artisanal fisheries with low capital, short trips, and near-shore operations. These fisheries support food security and local economies but are often underrepresented in official statistics and management (Zeller *et al.,* 2023; Pauly and Zeller, 2016). Their dependence on environmental conditions makes them vulnerable to climate variability and ecosystem change (Allison *et al.,* 2009). The ecological evaluation of the study area exhibits a moderate degree of resource exploitation, indicating that resources have not been entirely overexploited, though localized pressures could potentially arise. Many comparable small-scale tropical fisheries remain between sustainable use and overexploitation (Costello *et al.,* 2012; Hilborn *et al.,* 2020). This makes the area relevant for assessing early warning signals of fishing pressure and system stability. While fishing effort remains primarily small-scale, it is currently expanding. This growth is driven by variables such as capacity, access, and socio-economic conditions, alongside seasonal and environmental factors, rather than industrial scaling or formal regulatory frameworks (Cinner *et al.,* 2009).

Data collection and sources

This study utilized both primary and secondary data to evaluate the fisheries' performance, socio-economic conditions, governance, and environmental variability in Samber and Binyeri Villages. Primary data was collected through observations, interviews, and FGDs involving fishers, processors, village officials, fisheries

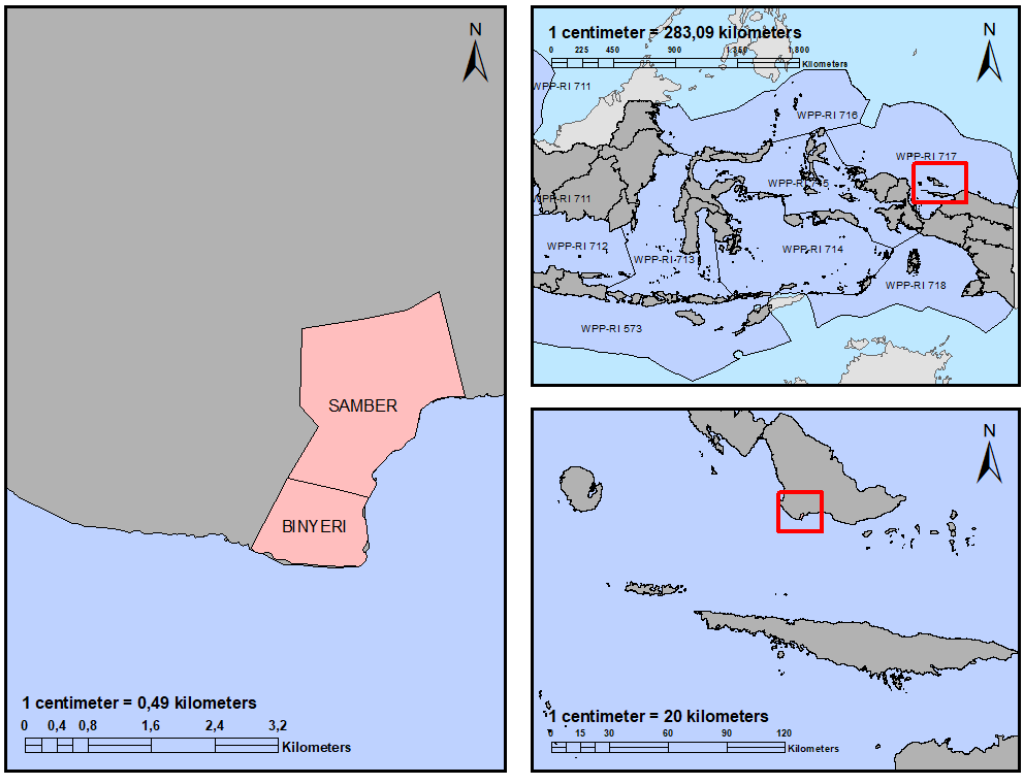

Fig. 1: Geographical location of the study area in Samber–Binyeri Village, Papua, in Indonesia

officers, extension officers, and local stakeholders. This data encompassed aspects such as production, prices, gear, infrastructure, distribution, income, assets, and business profiles. Data reliability was ensured through cross-checking and triangulation. Secondary data were obtained from the Biak Numfor Fisheries Office, BPS, policy documents, literature, and satellite datasets, including fisher numbers, production trends, institutional conditions, land status, demographic-economic indicators, and income statistics. This analysis merged geospatial and qualitative methodologies by employing image cropping, overlay analysis, satellite processing, and map interpretation. Oceanographic parameters, including SST, chlorophyll-a, salinity, currents, and depth, were derived from MODIS, GEBCO, and Copernicus datasets for 2019–2024 and processed using SeaDAS 8.3.0 and ArcGIS. MODIS Level 3 data were interpreted cautiously due to cloud cover, spatial resolution, shallow-water effects, coastal turbidity, and surface-only observation (Chassot *et al*., 2011; González *et al*., 2022). Satellite data reflects surface conditions and may not fully capture subsurface processes, nutrient dynamics, habitat variability, or short-term changes experienced by fishers. Thus, they were interpreted as environmental indicators of productivity, fishing-ground suitability, and CPUE, rather than direct measures of fish abundance. In the absence of in-situ validation data, satellite-derived indicators were rigorously cross-referenced with fisher knowledge, field observations, and secondary reports to ensure accuracy. Sustainability interpretation remains uncertain due to limited time-series data, CPUE-based abundance proxies, semi-quantitative EAFM scoring, and environmental variability, highlighting key methodological constraints (Cotter *et al*., 2009b).

Generalized additive model for effort–CPUE relationship

The relationship between fishing effort and CPUE was analyzed using a generalized additive model (GAM) to capture nonlinear patterns. The assessment of fishing effort involved the tally of fishers per landing, whereas CPUE (kg/trip) functioned as a surrogate for resource abundance. Both variables were log-transformed to reduce extreme values and heteroscedasticity. The GAM followed Eq. 1 (Han *et al*., 2022):

$$\log(CPUE_i) = \beta_0 + s(\log(Fisher_i)) + Month_i + \varepsilon_i \quad (1)$$

where, $\log(CPUE_i)$ represents CPUE, $\log(Fisher_i)$ represents fishing effort, s (·) is a smoothing spline, and $Month_i$ accounts for temporal variability. The model was fitted using Restricted Maximum Likelihood (REML) in the Mixed GAM Computation Vehicle (MGCV) package in R, with diagnostics based on residual checks and smoothness criteria. The anticipated values along with 95% confidence intervals were illustrated to evaluate the nonlinear effort–CPUE patterns and seasonal fluctuations (Han *et al.,* 2022; Coletto *et al.,* 2019). SST and chlorophyll-a were analyzed separately as environmental indicators within the EAFM framework.

EAFM-based analytical framework and scoring procedure

This study applies an integrated framework to examine coastal fisheries as a coupled socio-ecological system, linking ecological processes and human activities. EAFM conceptualizes fisheries as interactions among fish stocks, fishers, environmental conditions, and socio-economic and institutional systems. This methodology evaluates fisheries by moving beyond standard biological metrics, prioritizing resilience, adaptive management, and the integration of precautionary strategies (Heenan *et al.,* 2015). EAFM is also flexible and applicable at various scales, including the regency level (Hidayat *et al.,* 2025). The assessment covered six domains: fishery resources, fishing practices, habitat and ecosystem, economic, social, and institutional aspects. Each domain was weighted and scored using a three-point Likert scale: 1 = low, 2 = moderate, and 3 = high. Indicator scores were multiplied by their weights and summed to obtain domain scores, following Table 1. The three-point scale ensured consistent classification for both quantitative and qualitative indicators. To mitigate bias, data was triangulated using field observations, interviews, FGDs, and satellite products, alongside government statistics and existing literature. Furthermore, the use of standardized EAFM criteria and multi-stakeholder input improved scoring consistency beyond purely self-reported information. Robustness was strengthened by integrating EAFM scoring with pressure–response analysis and environmental indicators, enabling simultaneous ecological and socio-economic assessment (Heenan *et al.,* 2015; Muawanah *et al.,* 2018; Ye and Link, 2023). Each domain used relevant primary and secondary data. Fisheries resources relied on Biak Regency Fisheries Office data and fisher interviews. Habitat and ecosystem data were drawn from TNWL, DKP, surveillance reports, fisheries statistics, annual reports, and interviews. Fishing technology and economic sectors based their findings on official reports and research data, supplemented by interviews for the economic sector. Social data came from DKP officers and fishers, while institutional data combined DKP reports, statistics, and interviews with DKP, TNWL, and fishers. This multi-source integration improved data triangulation and reduced potential bias across domains, thereby strengthening reliability. Economic growth and ecological health were in trade-off when positive economic trends were offset by moderate ecological health, increasing environmental strain, or surfacing risks (Voss *et al.,* 2014). They were assessed by comparing livelihood gains with warning signs such as increased effort, juvenile catch, and moderate habitat performance. Detailed criteria and scoring scales are presented in Table 1.

Table 1: Conceptual Pressure-Response framework used in this study

Indicators		Criteria
1. Fisheries resources domain		
1.1.	Basic CPUE	1 = CPUE decreases sharply; 2 = CPUE decreases slightly; 3 = CPUE is stable or increasing
1.2.	Size trends in target species catch	1 = average size is decreasing; 2 = relatively stable; 3 = increasing
1.3.	Proportion of juvenile fish captured	1 = very high (>60%); 2 = moderate (30–60%); 3 = low (<30%)
1.4.	Species composition of the catch	1 = target species proportion is lower; 2 = equal proportion; 3 = target species proportion is higher
1.5.	"Range Collapse"	Fishing Difficulty: 1 = increasingly difficult; 2 = relatively unchanged; 3 = easier Fishing Ground Distance: 1 = very far; 2 = far; 3 = relatively close
1.6.	Bycatch of or other threats posed to ETP species by the fishery	1 = many ETP species caught; 2 = few ETP species caught; 3 = no ETP species caught
2. Habitat and ecosystems domain		
2.1.	Water quality	Pollution Level (visual/clinical identification): 1 = polluted; 2 = moderately polluted; 3 = not polluted Water Turbidity: 1 = high (>20 mg/m³); 2 = moderate (10–20 mg/m³); 3 = low (<10 mg/m³) Eutrophication (Chlorophyll-a concentration): 1 = >10 mg/m³ (eutrophic); 2 = 1–10 mg/m³ (potential eutrophication); 3 = <1 mg/m³
2.2.	Status of Seagrass ecosystems	Habitat Cover: 1 = low (≤29.9%); 2 = moderate (30–49.9%); 3 = high (≥50%) Biodiversity Index: 1 = low diversity (H' < threshold); 2 = moderate diversity; 3 = high diversity
2.3.	Status of Mangrove ecosystems	Mangrove Density: 1 = low (<1000 trees/ha, <50%); 2 = moderate (1000–1500 trees/ha, 50–75%); 3 = high (>1500 trees/ha, >75%) Biodiversity Index: 1 = low diversity (H' < threshold); 2 = moderate diversity; 3 = high diversity
2.4.	Status of coral reef ecosystems	Habitat Cover: 1 = low cover (<25%); 2 = moderate (25–49.9%); 3 = high (>50%) Biodiversity Index: 1 = low diversity (H' < threshold); 2 = moderate diversity; 3 = high diversity
2.5.	Special habitats	1 = no unique habitat identified; 2 = identified but poorly managed; 3 = identified and well managed
2.6.	Climate change impacts on habitat condition/resources	1 = no assessment 2 = impacts identified, no mitigation 3 = impacts and mitigation strategies
3. Fishing technology domain		
3.1.		
3.2.	Destructive and illegal fishing	1 = >10 cases/year; 2 = 5–10 cases/year; 3 = <5 cases/year
3.3.	Modification of fishing gear and ancillary equipment	1 = >50% below Lm; 2 = 25–50%; 3 = <25%
3.4.	Fishing capacity and effort	1 = R < 1; 2 = R = 1; 3 = R > 1
3.5.	Catch selectivity	1 = low (high use of non-selective gear); 2 = moderate; 3 = high
3.6.	Compatibility between fishing vessel function/size and legal documents	1 = low (>50% non-compliant samples); 2 = moderate (30–50% non-compliant); 3 = high (<30% non-compliant)
3.7.	Certification of fishing vessel crew in accordance with regulations	1 = Certification ownership <50%; 2 = Certification ownership 50–75%; 3 = Certification ownership >75%
4. Social domain		
4.1.	Stakeholder participation in fisheries management	1 = decreasing (>50% decline); 2 = relatively stable; 3 = fully maintained/increased
4.2.	Conflict in fisheries	1 = >5 times/year; 2 = 2–5 times/year; 3 = <2 times/year
4.3.	Utilization of local knowledge in fishery resources management	1 = none; 2 = available but ineffective; 3 = available and effective
5. Economic domain		
5.1.	Asset ownership of fishing households/ unit	1 = decreasing (>50% decline); 2 = relatively stable; 3 = fully maintained/increased
5.2.	Fishing household income	1 = below minimum wage; 2 = equal to minimum wage; 3 = above minimum wage
5.3.	Savings ratio of fishing households	1 = below interest rate; 2 = equal to interest rate; 3 = above interest rate

6. Institutional domain	
6.1. Compliance with fisheries regulations and responsible fishery principles	1 = frequent (>5 cases/year); 2 = occasional (2–4 cases/year); 3 = rare (<2 cases/year)
6.2. Comprehensiveness of fishery management rules and regulations	Non-formal Institutional Rules: 1 = none; 2 = exist but incomplete; 3 = complete Resource Availability Trend: 1 = decreasing; 2 = stable 3 = increasing
6.3. Demersal fishery decision taking mechanisms	Law Enforcement: 1 = none; 2 = exists but ineffective; 3 = exists and effective Monitoring Capacity: 1 = none; 2 = available but no action; 3 = available with active enforcement Institutional Mechanism: 1 = none; 2 = exists but ineffective; 3 = effective Policy Implementation: 1 = not implemented; 2 = partially implemented; 3 = fully implemented
6.4. Fishery management plan (RPP)	1 = not available; 2 = available but not fully implemented; 3 = fully implemented
6.5. Synergy between fisheries management policies and institutions	1 = conflict between institutions; 2 = weak communication; 3 = strong coordination
6.6. Stakeholder capacity building	1 = none; 2 = available but not utilized; 3 = available and utilized

This study operationalized the pressure–response framework by correlating the KNMP coastal intervention with assessable indicators of both fisheries and the broader ecosystem. Coastal intervention was represented by changes in infrastructure, market access, fishing capacity, and livelihood activities. Pressure indicators included fishing effort, fishing trips, gear use, production intensity, and spatial use of fishing grounds. Response indicators included CPUE patterns, juvenile catch, habitat and ecosystem condition, income changes, social participation, and institutional performance. These indicators were evaluated across the relevant EAFM domains to determine if economic gains were coupled with rising ecological pressure or new sustainability risks. Fig. 2 illustrates the Pressure-Response framework used to operationalize the EAFM-based analysis by conceptualizing coastal fisheries as an adaptive socio-ecological system. Evidence suggests that management interventions and infrastructure improvements can initially boost fishing capacity and effort. In the context of Indonesian fisheries, this often heightens anthropogenic pressure on ecosystems that are already suffering from overexploitation (Arta and Miranda, 2025). At the local scale, similar patterns in Biak Numfor indicate that increased production has led to more intensive exploitation and potential stock depletion (Katiandagho and Marasabessy, 2017). Nevertheless, certain ecological indicators might exhibit relative stability in the short term, despite an increase in fishing pressure, as CPUE may be affected by factors such as seasonal availability, fishing efficiency, spatial targeting, and environmental buffering. These hypothesized relationships are further examined using measurable indicators, including fishing effort, production, CPUE, juvenile catch, habitat condition, and GAM-based seasonal CPUE variability.

Statistical analysis

Statistical analysis was conducted using a data-limited fisheries approach, combining descriptive statistics, composite index analysis, and qualitative triangulation. Descriptive statistics, including mean, range, and percentage change, were used to summarize environmental variables, fisheries production, fishing effort, CPUE, and economic indicators. Fishing pressure was quantified using proxies such as fishing trips, production shifts, and fisher density per landing. However, these indicators were carefully evaluated to account for the influence of gear efficiency, fishing location, and individual fisher

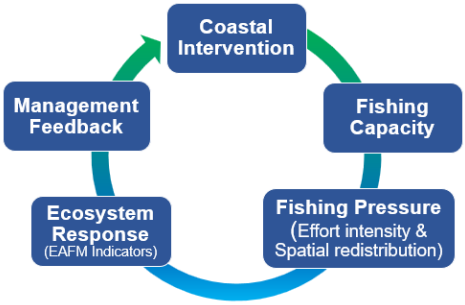

Fig. 2: Conceptual pressure-response framework used in the study

behavior on small-scale effort (Cinner *et al*., 2009; Selgrath *et al*., 2018). This approach is widely applied in small-scale fisheries assessments where data availability is limited and heterogeneous (Cotter, 2009a; Leitão *et al*., 2021). Where applicable, variability in key variables was interpreted based on observed ranges and temporal patterns rather than relying on extensive inferential statistics. EAFM scores were analyzed using a composite index approach by aggregating indicator scores into domain-level and overall sustainability scores. Composite indicators are commonly used in ecosystem-based fisheries assessments to integrate ecological, social, economic, technological, and governance dimensions (Ye and Link, 2023; Hidayat and Kurniawan, 2025). Qualitative triangulation was applied to validate quantitative findings by cross-checking EAFM scores with field observations, interviews, focus group discussions, and secondary data. This methodology minimizes potential bias by ensuring that quantitative findings are interpreted through a socio-ecological lens, specifically for indicators related to governance, social, economics, and fishing effort.

RESULTS AND DISCUSSION

Oceanographic variability, fisheries performance, and fishing pressure dynamics

Samber–Binyeri is influenced by a dynamic coastal oceanographic system in Biak waters, where seasonal monsoon forcing and ENSO variability affect currents, waves, sea surface temperature (SST), chlorophyll-a, salinity, and potential fishing grounds. These findings align with established satellite-based EAFM applications, in which SST and chlorophyll-a serve as standard proxies for assessing habitat suitability and ecosystem productivity within fisheries (Chassot *et al*., 2011). During 2019–2024, Biak waters experienced strong interannual variability. La Niña influence in 2020, with current velocity reaching 0.35–0.6 meters per second (m/s) during December-January-February (DJF) and 0.4–1.0 m/s during June-July-August (JJA), while 2023 was affected by moderate–strong El Niño, with generally weaker currents around 0.04–0.3 m/s, although northern Biak reached 0.8–1.5 m/s during JJA. In 2024, current velocity shifted toward neutral ENSO conditions, ranging from 0.04–0.6 m/s across seasons. Wave conditions also varied strongly, with maximum average wave height declining from approximately 1.6 m in 2019 to 0.6 m in 2021, equal to a 62.5% decrease. Data analysis reveals an inverse relationship between SST and chlorophyll-a; specifically, elevated sea surface temperatures correlated with a decline in chlorophyll-a concentrations, whereas lower temperatures were associated with increased productivity. The strongest anomaly occurred in 2022, when chlorophyll-a increased alongside a sharp SST decline, likely reflecting La Niña-related nutrient enrichment and increased productivity. This inverse relationship indicates that primary productivity is regulated by oceanographic variability, which may facilitate temporary

increases in fish availability and spatial aggregation. However, mounting pressure risks compromising recovery potential, particularly when exploitation levels surpass the ecosystem's inherent buffering capacity (Erisman *et al*., 2021). Similar studies have demonstrated that SST and chlorophyll-a significantly influence CPUE and the spatial distribution of fishing grounds, with optimal environmental ranges determining areas of high catch potential (González *et al*., 2022). This indicates that seasonal and interannual oceanographic variability likely influences fish availability and catch success, contributing to the observed temporal variability in CPUE. Fisheries' performance improved after KNMP implementation. In peak season, net income increased from United States Dollar (USD) 381.78 to USD 720,63/month, equal to 88.8%, while monthly production increased from 552 kg to 1,221 kg, equal to 121.2%. Fishing trips also increased from 9 to 13 trips/months, or 44.4%, indicating higher fishing pressure after the intervention. CPUE was estimated at 42.78 kg/trip based on the updated trip-level dataset, with monthly mean CPUE ranging from 32.7 kg/trip in June to 58.3 kg/trip in April. Monthly CPUE exhibits moderate seasonal variability, peaking in April and September, without a clear declining trend over the study period. However, this apparent stability warrants a cautious interpretation, as it may stem from hyperstability—where fishing efficiency, spatial concentration, and aggregation targeting mask underlying changes in stock abundance (Harley *et al*., 2001; Erisman *et al*., 2011). This pattern suggests that catch success is influenced not only by stock abundance but also by environmental variability, spatial patchiness, and fishing efficiency, as commonly observed in small-scale fisheries systems where CPUE responds to both ecological and operational factors (Coletto *et al*., 2018). The absence of long-term stock assessment data, historical biomass estimates, and fisheries-independent ecological monitoring limits the ability to determine whether current CPUE stability reflects true stock stability or shifting ecological baselines (Cotter *et al*., 2009b; Pauly *et al*., 2002). The statistics indicate a clear economic increase after KNMP, but the updated CPUE analysis does not provide sufficient evidence to claim long-term ecological improvement or severe resource decline. The primary indicator of mounting pressure is the 121.2% growth in production outstripping the 44.4% increase in trips, signaling shifts in fishing efficiency and heightened exploitation levels. This condition may indicate an early stage of pressure accumulation, where increasing fishing effort and efficiency have not yet resulted in detectable declines in CPUE, potentially masking underlying ecological changes. These results suggest that transient economic growth can mask mounting ecological pressure, particularly when increases in fishing capacity and effort outpace the detectable response of the ecosystem (Selgrath *et al*., 2018). Therefore, the ecological interpretation should remain precautionary: short-term fishery performance improved but increasing effort may add pressure to fish stocks that is not fully captured by CPUE if not controlled through EAFM-based monitoring.

Fishing effort–CPUE relationship analysis (GAM)

The results of the GAM analysis indicate that the relationship between the number of fishers (as a proxy for fishing pressure) and CPUE in Samber–Binyeri Village is relatively weak and does not exhibit a consistent declining pattern. In several months, as seen in Table 2 and Fig. 3, a slight decrease in CPUE is observed at low to moderate levels of fishing effort; however, this pattern does not persist at higher effort levels. This suggests that increasing fishing effort has not yet resulted in a substantial decline in catch productivity. Therefore, there is no strong evidence of overfishing based on the CPUE indicator. On the other hand, the relatively high variability in CPUE across nearly all levels of fishing effort suggests that fish resources are distributed in a patchy manner.

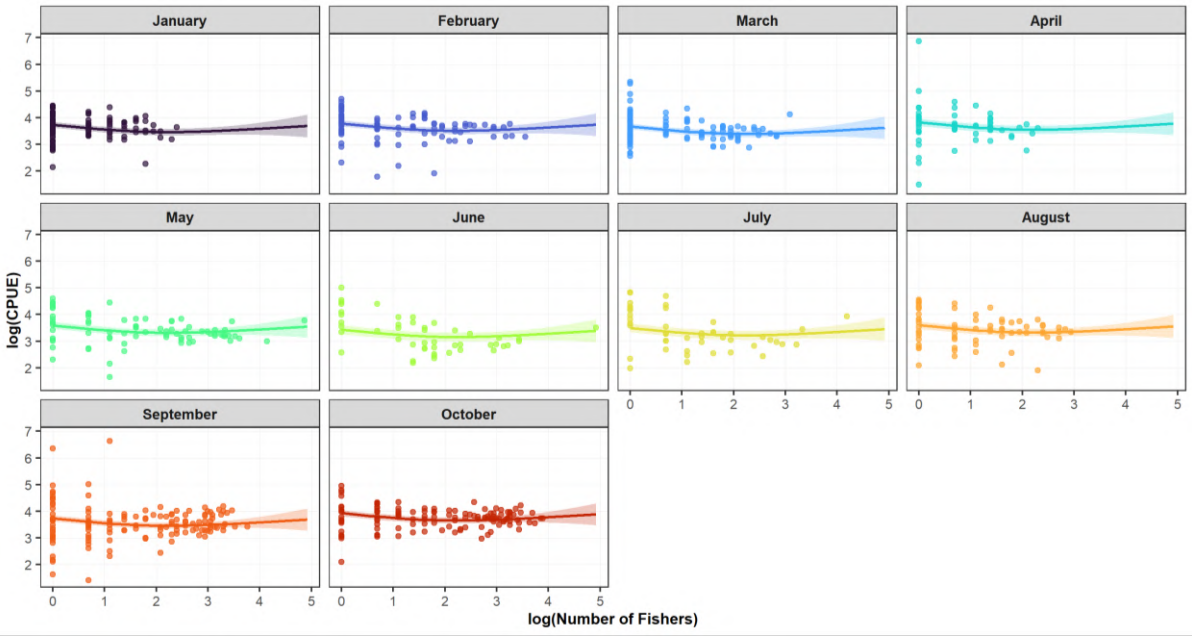

Fig. 3: GAM-based relationship between log-transformed fishing effort and CPUE across months in the Samber–Binyeri fisheries. Shaded areas represent 95% confidence intervals

Table 2: Parametric coefficients of the GAM model

Term	Estimate	Standard error (SE)	t value	p value	effective degrees of freedom (edf)	Deviance explained	Adjusted R^2
(Intercept)	3.589	0.054	66.162	<0.001	0.000	0.00%	0.000
Month February	0.047	0.078	0.606	0.545	1.541	11.10%	0.096
Month March	-0.069	0.074	-0.921	0.357	1.944	5.03%	0.033
Month April	0.087	0.086	1.009	0.313	0.000	0.00%	0.000
Month May	-0.147	0.083	-1.767	0.078	5.204	17.73%	0.119
Month June	-0.306	0.097	-3.142	0.002	3.326	45.34%	0.411
Month July	-0.241	0.098	-2.467	0.014	2.110	25.08%	0.213
Month August	-0.139	0.086	-1.621	0.105	1.009	5.85%	0.044
Month September	-0.003	0.074	-0.038	0.97	0.000	0.00%	0.000
Month October	0.193	0.075	2.558	0.011	0.000	0.00%	0.000

This pattern suggests that catch success is primarily driven by spatial dynamics and the aggregative behavior of the resource, rather than being determined strictly by the total number of fishers. Furthermore, the consistency of the observed patterns across months indicates the absence of extreme seasonal fluctuations in resource availability, suggesting that stock conditions remain relatively stable throughout the observation period. According to the results, within the context of EAFM, the condition of fisheries resources in Samber–Binyeri Village can be classified as moderately exploited. The CPUE indicator does not show a consistent declining trend, although there are early signs of competition among fishers at certain effort levels. The results from the GAM analysis further suggest that the variability in CPUE is partially affected by seasonal dynamics. June showed the strongest negative and statistically significant effect on CPUE (estimate = -0.306, p = 0.002), with the highest deviance explained (45.34%) and adjusted R^2 (0.411), followed by July, which also showed a significant negative effect (estimate = -0.241, p = 0.014). In contrast, October showed a significant positive effect on CPUE (estimate = 0.193, p =

0.011), suggesting relatively higher catch performance during this period. The findings suggest that fluctuations in CPUE are influenced not only by fishing pressure but also by seasonal environmental variability, especially during changes in oceanographic conditions associated with the monsoon. The edf values also suggest that several monthly effects, particularly May, June, and July, follow non-linear patterns, indicating that seasonal changes in CPUE may be shaped by complex interactions between environmental conditions, fishing behavior, gear efficiency, and spatial targeting. Therefore, the moderate exploitation status should be interpreted cautiously. The absence of a strong declining CPUE trend does not necessarily indicate stock stability or the absence of overfishing, because CPUE may be influenced by seasonal availability, fisher adaptation, and potential hyperstability. Consequently, weak or non-significant statistical relationships were interpreted as an indication of limited explanatory power, rather than as definitive evidence of ecological stability or long-term sustainability. In this study, CPUE was treated as a fishery performance indicator rather than a direct proxy for stock abundance. Therefore, stable or non-declining CPUE was not interpreted as evidence of stock sustainability. Instead, CPUE was evaluated together with fishing effort, juvenile catch, habitat condition, seasonal variability, and potential hyperstability to provide a more cautious interpretation of fisheries resource conditions.

EAFM-based assessment of ecological and socio-economic performance

The results of the EAFM scoring analysis indicate that fisheries sustainability in Samber–Binyeri shows variation across domains and indicators. Data presented in Fig. 4 indicates that while the social, economic, and technological domains are performing well, the habitat and fisheries resource domains show only moderate levels of success. This pattern is consistent with the EAFM principle that fisheries sustainability should be assessed through multiple ecological, social, economic, technological, and institutional dimensions rather than through biological indicators alone (Muawanah *et al*., 2018). The EAFM assessment of Samber–Binyeri fisheries indicates generally favorable conditions, although several sustainability concerns remain. In the realm of fish resources, tuna was identified as the main target species and was evaluated using six indicators: CPUE, fish size, juvenile proportion, species composition, range collapse, and the presence of endangered, threatened, and protected (ETP) species. Average CPUE reached 42.78 kg/trip and showed seasonal variation, with relatively higher values observed in April (58.3 kg/trip) and September (48.7 kg/trip), and lower values in June (32.7 kg/trip) and May (34.9 kg/trip), without a consistent declining trend. Catch composition was dominated by tuna, with low bycatch, minimal ETP interaction, and stable fishing grounds, suggesting relatively selective and efficient fishing practices. Corroborating existing evidence, the findings suggest that while utilization pressure in Biak Numfor is moderate, fisheries resources remain abundant and have not reached the threshold of overexploitation (Likumahua and Nifaan, 2020). However, the occurrence of juvenile and sub-adult individuals, together with variable CPUE, indicates emerging fishing pressure and the need for precautionary effort control, particularly in months such as April and September. GAM analysis results placed the fish resource domain in the intermediate category (score 2–3), identifying a productive system that requires cautious oversight to prevent future overexploitation. The habitat and ecosystem domain showed mixed ecological performance. Water quality in southern Biak remained within established thresholds (KEPMEN No.51/2004), with high clarity (12–20 m), low turbidity (<1–3 NTU), and low chlorophyll concentrations (0.12–0.4 µg/L), indicating oligotrophic conditions and limited sediment input associated with karst-dominated geomorphology (Msen *et al*., 2023; Adams *et al*., 2022).

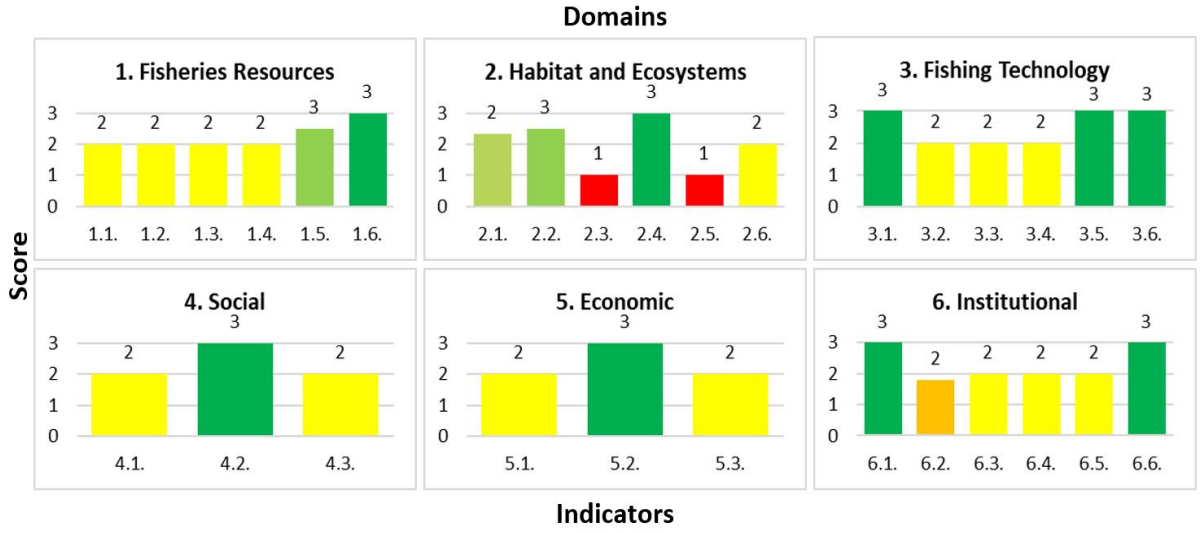

Fig. 4: EAFM Scoring Method

The extent of seagrass coverage was quite significant, falling within the range of 60% to 80%, and comprising 8 to 9 species, indicating a robust ecosystem (Dewi *et al*., 2017). Coral reef cover reached 56%, categorized as good, suggesting that ecological function remains relatively intact. In contrast, mangrove cover was low at 37%, indicating fragmentation and localized ecological pressure. Although climate-related impacts have not been comprehensively assessed, shallow reef habitats may be vulnerable to bleaching under increasing sea surface temperatures and local environmental stressors. Scoring in the fishing technology domain reflects the low-impact nature of local small-scale fisheries, which typically result in minimal direct ecological disturbance. Local fleets are dominated by small vessels below 5 gross tonnage (GT), mainly outboard motorboats and canoes, consistent with small-scale fisheries in Southeast Asia (Pauly and Zeller, 2016; Teh and Pauly, 2018). Fishing effort remains moderate, averaging around 13 trips per month based on data from the Ministry of Marine Affairs and Fisheries, although it varies with weather and wind conditions. In 2024, only a single instance of destructive fishing involving explosives was documented, and notably, this incident occurred beyond the territorial of Samber–Binyeri waters. Nevertheless, random sampling of tuna catches shows that many individuals remain below gonadal maturity size, suggesting a juvenile to sub-adult, indicates a potential risk to stock regeneration if fishing intensity increases. Formal compliance was notably robust, as vessel specifications aligned with legal documentation and 99% of the surveyed fishers held valid fisher competency certificates (SKN). The social and economic domains showed strong performance. KNMP Samber–Binyeri has received substantial state support by multiple stakeholders, with the Ministry of Marine Affairs and Fisheries playing a central role through the provision of key fisheries infrastructure through cold storage, ice plants, landing facilities, boatyards, training centers, and capacity-building programs facilitated by Agency for Marine and Fisheries Extension and Human Resources (BPPSDM-KP), which can improve efficiency, market access, and competitiveness in small-scale fisheries (World Bank, 2012). The absence of reported conflicts suggests a high degree of social stability within the fishery, largely attributed to well-functioning customary institutions and effective internal communication. This supports evidence that social cohesion and

collective action strengthen fisheries governance (Ostrom, 2009; Cinner *et al*., 2012). Local ecological knowledge can facilitate the early detection of seasonal shifts, habitat variations, and changes in fish distribution, gradual environmental degradation may remain obscured if catch rates appear stable (Berkes *et al*., 2000; Johannes *et al*., 2008). Economically, most households own key productive assets, including boats, engines, gear, and navigation equipment, which are central to fishing capacity and livelihood resilience. In recent years, asset ownership has increased among some fishers, mainly through government assistance from the Ministry of Marine Affairs and Fisheries. While such support has improved both the volume and caliber of fishing assets, it does not inherently reflect a strengthening of independent investment capacity within the local sector. Approximately 90% of fishers earned above the regional minimum wage and reported an increase in average monthly income from USD 274.30 million before KNMP implementation to USD 487.30 million after its inauguration, suggesting a positive effect on local economic welfare. This finding is consistent with global evidence that small-scale fisheries contribute significantly to income, employment, food security, and rural livelihoods, particularly in developing coastal communities (World Bank, 2012; FAO, 2024). Elevated income levels have expanded the capacity of fishing households to accumulate savings and bolster financial resilience. Furthermore, this trend enables more effective risk management and the reinvestment in productive assets, thereby advancing long-term economic sustainability within the EAFM framework. However, rising income and asset ownership may also increase fishing capacity if not balanced by effective management controls (FAO, 2015; Bavinck *et al*., 2023). Continued expansion of fishing effort may increase socio-economic vulnerability through income dependence on fisheries, resource competition, unequal access to fishing opportunities, and reduced resilience to environmental or market shocks (Pomeroy *et al*., 2016a). Market demand, enhanced market access, and price incentives collectively influence local fishing effort by incentivizing intensified production and the expansion of operations beyond subsistence-level activities (Prosperi *et al*., 2019). The institutional domain indicates that formal governance structures are established but unevenly implemented. Samber–Binyeri is located within Fisheries management area (WPP) 717, supported by KEPMEN KP No. 123/KEPMEN-KP/2022 and Papua Provincial Regulations No. 9/2016 and No. 6/2023, reflecting Indonesia's commitment to ecosystem-based and decentralized fisheries management (KKP, 2022; FAO, 2015). These regulations have been introduced and communicated to fishers through relevant national and provincial fisheries institutions. Nevertheless, enforcement efficacy is limited by inadequate compliance mechanisms and documented instances of informal cooperation between violators and certain enforcement officials—a systemic challenge frequently observed in the governance of small-scale fisheries (Pomeroy *et al*., 2006; FAO, 2015). According to the 2024 report of the Directorate General of Marine and Fisheries Resources Surveillance, one destructive fishing incident using explosives was recorded during the previous year, although the incident occurred outside the administrative waters of Samber–Binyeri. This indicates that destructive fishing pressure was not frequently recorded within the village waters, but enforcement risks remain relevant at the wider seascape scale. Decision-making procedures involving fishers, village authorities, and government agencies exist but are not fully effective, indicating persistent challenges in aligning formal governance with local practices and community needs (Berkes, 2009; Cinner *et al*., 2012). Interviews indicated that SOPs and fisheries management mechanisms already exist, including discussions among fishers, village authorities, and government institutions regarding fishing spots or fishing-point areas, but these mechanisms have

not been effectively implemented. Institutional effectiveness is further constrained by fragmented coordination between government agencies, fisher groups, and the KNMP cooperative. This is exacerbated by a prevailing preference for direct market sales, driven by significant price disparities that disincentivize cooperative participation. This price gap has reduced fishers' willingness to sell their catch through the KNMP cooperative and has weakened the alignment between program objectives, market behavior, and local compliance. Such fragmentation can reduce compliance and weaken governance outcomes (Ostrom, 2009; Jentoft, 2007). Thus, formal rules alone are insufficient without stronger enforcement, coordination, and integration of local actors (FAO, 2015; Pomeroy *et al*., 2006). The enduring success of EAFM implementation is contingent upon robust institutional capacity, necessitating seamless coordination among governance actors, consistent enforcement, active stakeholder participation, and rigorous compliance with fisheries regulations (Fortnam, 2019; Mozumder *et al*., 2020). The EAFM composite index indicated good performance at 78%. The economic, social, and fishing technology domains scored highest at 90%, 82%, and 81%, respectively, reflecting strong livelihood outcomes, community stability, and relatively sustainable fishing practices. Institutional and fish resource domains were also categorized as good, with scores of 77% and 76%. However, the habitat and ecosystem domain scored only 60%, identifying ecological sustainability as the main constraint. The findings presented in Table 3 indicate that while the Samber–Binyeri fisheries currently exhibit productivity and social resilience, long-term sustainability is contingent upon the implementation of more robust habitat protection, effort regulation, and institutional coordination. The EAFM composite results indicate that fisheries management in Samber–Binyeri is generally in good condition, as high economic, social, technological, and institutional scores compensated for lower habitat and ecosystem performance within the composite index structure (Muawanah *et al.,* 2012). Fisheries resources appear stable, but CPUE, fish size, and juvenile catch still require monitoring because apparent stability may hide underlying risks (Hilborn *et al.,* 2020). The habitat and ecosystem domain represents the weakest area of performance, primarily driven by insufficient mangrove cover. This deficiency persists despite the favorable condition of seagrass and coral reef habitats, underscoring the critical role of comprehensive habitat quality in ensuring fisheries sustainability (Barbier *et al.,* 2011). Fishing technology, economic, and social domains show strong performance, reflecting improved livelihoods and stable community conditions (FAO, 2015), although effort control, asset capacity, and participation need improvement. The institutional domain is also relatively good, but coordination, human capacity, and implementation remain challenges (Riandi *et al.,* 2026). Overall, ecological-economic system models provide a useful foundation for EAFM, but long-term effectiveness depends on stronger habitat management, regulated fishing effort, and adaptive participatory governance to support compliance, sustainable fisheries, and healthy fish stocks fish stocks (Voss *et al.,* 2014). Changes in fisheries and ecological indicators show that the Samber–Binyeri coastal system is currently stable but under emerging pressure. Fish stock indicators, including CPUE, size structure, juvenile proportion, and species composition, suggest stable productivity, although moderate CPUE changes and sub-mature fish indicate possible stress on regeneration. This supports the view that CPUE may mask stock decline and should be interpreted carefully in small-scale fisheries (Erisman *et al.,* 2011). Persistent harvesting of juvenile individuals poses a significant risk to future recruitment potential; should fishing pressure continue to escalate, the long-term resilience of the stock may be critically undermined (Mason *et al*., 2024; Kamikawa *et al*., 2019).

Table 3: EAFM composite Index

Domain	Composite index (%)	Description
Fisheries resources	76	Good
Habitat and ecosystems	60	Moderate
Fishing technology	81	Excellent
Social	82	Excellent
Economy	90	Excellent
Institutional	77	Good
Aggregate all domain	78	Good

Habitat conditions are generally favorable, with good water quality, high seagrass cover, and intact coral reefs, but low mangrove density and limited climate-impact assessment reveal ecological vulnerability. Since mangroves, seagrass, and coral reefs are essential for fisheries productivity and resilience, their degradation may affect fish stocks and ecosystem stability (Unsworth *et al*., 2019). Although fishing practices remain typical of small-scale fisheries, gear selectivity and juvenile catch require continued monitoring and adaptive management (Brodziak and Link, 2002). The documented shifts illustrate the multifaceted interactions between development, fishing pressure, ecological feedback, and governance frameworks. While enhanced infrastructure and market access have bolstered fishing capacity and economic outcomes, they simultaneously risk escalating fishing effort and exploitation intensity. This pattern is common in small-scale fisheries when capacity growth is not matched by effective management (Trimble and Berkes, 2015). Therefore, although current performance appears stable, long-term sustainability depends on governance capacity to control effort, ensure compliance, and support adaptive management (Schultz *et al*., 2015). The relative stability of certain ecological indicators during the study period is noteworthy; however, it does not provide a sufficient basis for concluding that the ecosystem has achieved long-term stability.

Pressure–response dynamics in environmental stability

The results show that fishing pressure increased while several ecological indicators remained relatively stable, creating a potential mismatch between short-term catch performance and longer-term ecological risk. The pressure component is characterized by metrics such as increased fishing effort, frequency of fishing trips, and total production; conversely, the response component is defined by CPUE patterns, habitat performance, and the prevalence of juvenile catch. Quantitatively, fisheries production increased by 121.2% and fishing effort increased by 44.4%, indicating higher exploitation intensity after KNMP implementation. These pressure indicators were compared with ecological response indicators, including the absence of a consistent declining CPUE trend, the presence of juvenile catch, and the moderate habitat and ecosystem score of 60%. Although economic performance and fishing capacity have improved, EAFM indicators suggest that ecological conditions have remained relatively stable in the short term. Nevertheless, this stability is occurring alongside an escalation in fishing effort, evidenced by increased trip frequency and enhanced access to fishing grounds. Increasing fishing effort may also intensify localized exploitation and habitat-level disturbance through repeated concentration of fishing activities in productive areas, effects that are not fully captured by CPUE alone (Griffeth *et al*., 2023; Chiarini *et al*., 2018). Such non-linear pressure-response relationships are well documented in fisheries systems, where catch indicators may remain stable despite increasing exploitation due to aggregation effects and fishing efficiency (Erisman *et al*., 2011). Similar patterns have been observed in Indonesian small-scale fisheries, where increasing effort does not

immediately result in declining catch indicators, masking early signs of overexploitation (Campbell *et al*., 2020). In this instance, the evidence regarding pressure and response indicates a rise in ecological risk instead of an immediate ecological deterioration, as both fishing trips and production saw an increase following the implementation of KNMP (Simonson *et al*., 2022).

Ecological stability and emerging risks under increasing fishing pressure

The results indicate that the Samber–Binyeri system currently exhibits apparent ecological stability, as reflected by relatively stable CPUE, moderate-to-good EAFM scores in fisheries resources (76%) and habitat (60%), and the absence of major ecological degradation signals. However, this stability should not be interpreted as ecological safety. Rather than indicating stability, these findings may reflect a latency period where underlying ecological risks have yet to fully manifest. Continued escalation in fishing pressure could push the system toward critical ecological thresholds, beyond which intensified resource depletion and habitat degradation become increasingly unmanageable (Pauly *et al*., 2002; Mullon *et al*., 2005). One key mechanism explaining this condition is hyperstability, where catch rates remain stable despite declining fish abundance due to improved fishing efficiency, spatial targeting, or aggregation behavior of fish stocks (Harley *et al*., 2001). In these coastal interventions, production increased by 121.2% while fishing effort increased by 44.4%, suggesting that improved efficiency and access to fishing grounds may partially mask underlying stock pressure. A steady CPUE does not always equate to a stable fishery. The ability of fishers to maintain yields under pressure can create a false sense of security, drive further expansion and obscuring the reality of increasing ecological strain (Golden *et al*., 2022). In addition, the system shows characteristics of a delayed ecological response, where ecosystem degradation occurs gradually and may not be immediately detectable through conventional indicators (Essington *et al*., 2015). Several early warning signals have already emerged, most notably the prevalence of juvenile fish in catches and moderate performance within habitat and ecosystem domains. These concerns are specifically tied to the degraded condition of mangroves and a lack of comprehensive climate impact assessment. Such patterns suggest that ecological responses may lag increases in fishing effort, especially in systems with relatively high initial resilience. The combination of stable CPUE, increasing effort, juvenile catch, moderate habitat condition, and absence of severe stock decline suggest a transitional state between apparent stability and potential ecological degradation (Mullon *et al*., 2005; Pauly *et al*., 2002). Therefore, the current ecological condition should be interpreted cautiously. The absence of immediate degradation not imply long-term sustainability, but highlights incorporating pressure indicators, such as fishing effort and capacity, alongside ecological metrics. Absent implementation of effective effort controls and adaptive management strategies, fishery system risks transitioning from a state of apparent stability toward a trajectory of ecological decline.

Environmental implications for sustainable coastal fisheries development

Governance and local knowledge remain important because fishing pressure is increasing while formal monitoring and coordination are still uneven. The EAFM assessment shows relatively strong performance in institutional (77%) and social (82%) domains, indicating the presence of formal regulatory frameworks, fisher compliance, and relatively stable social conditions. These governance structures are reinforced by KNMP interventions, specifically through infrastructure development and capacity-building initiatives. Such programs serve to bolster economic performance while simultaneously ensuring a necessary level of institutional oversight. However, such improvements are accompanied by a clear increase in fishing pressure, as indicated by

rising fishing trips (44.4%) and production (121.2%), which introduces a growing risk of overfishing if not properly controlled. At the community level, local knowledge systems play an important role in regulating resource use. Practices resembling sasi, a traditional marine management system widely applied in eastern Indonesia, involve temporary restrictions on resource extraction in specific areas or for specific species, allowing stock recovery and preventing overexploitation (Halim *et al*., 2020; Muin and Rakuasa, 2023). Such institutions serve as vital informal governance structures, providing the framework to manage access, maintain compliance, and harmonize local fishing efforts with seasonal ecological patterns. The combination of formal governance (EAFM, KNMP) and informal local systems (sasi-like practices) creates a multi-layered governance structure that contributes to coastal system resilience. This explains why the system has not yet experienced substantial ecological decline despite increasing fishing effort. Nevertheless, governance effectiveness remains inconsistent, characterized by fragmented institutional coordination, lack of enforcement uniformity, and poor integration between fisher groups and formal management frameworks. Similar challenges have been observed in small-scale fisheries systems, where governance gaps can reduce the long-term effectiveness of management interventions and increase vulnerability to overfishing (Stacey *et al*., 2021). From an ecological perspective, these conditions raise concerns regarding the carrying capacity of the coastal system. Carrying capacity represents the maximum level of exploitation that can be sustained without degrading ecosystem structure and function. Although the relatively good condition of coral reefs and seagrass suggests that the system maintains some buffering capacity, the moderate habitat scores of 60% coupled with evident ecosystem pressure—indicate that this resilience is reaching its functional limits. The long-term resilience of ecological indicators may decline under cumulative climate-driven oceanographic variability and sustained anthropogenic pressure, particularly in habitat systems already showing moderate ecological performance (Hoegh-Guldberg *et al*., 2017; Halpern *et al*., 2015). When fishing pressure approaches or exceeds this threshold, the system may shift toward degradation, even if short-term indicators such as CPUE remain stable. The trajectory analysis (Fig. 5) further reinforces this interpretation. The system initially occupies a position between restoration strategy and social development strategy, indicating that ecological, social, and institutional conditions are not yet fully stable. The incremental transition toward conservation management, combined with the retention of existing strategies, represents a pragmatic yet protracted pathway for improvement. However, the relatively moderate position of the system even after two years suggests that current interventions have not yet produced strong ecological or governance outcomes. This highlights that early-stage development interventions often improve economic indicators faster than ecological or institutional dimensions. The results highlight a threshold in sustainability: while ecological conditions still facilitate economic growth, this relationship is increasingly strained by rising pressure on the system. Early warning signals—such as increasing effort, moderate habitat condition, and reliance on stable CPUE—suggest that the system may be approaching these limits. Without intervention, this condition may increase the likelihood of overexploitation, particularly under conditions of hyperstability and delayed ecological response. To maintain balance between ecological sustainability and economic development, several management implications emerge. First, priority must be given to the active regulation of fishing effort; specifically, this entails the implementation of controls on trip frequency, total fishing capacity, and the management of spatial access to designated fishing grounds. Second, strengthening governance systems is essential, particularly through improved

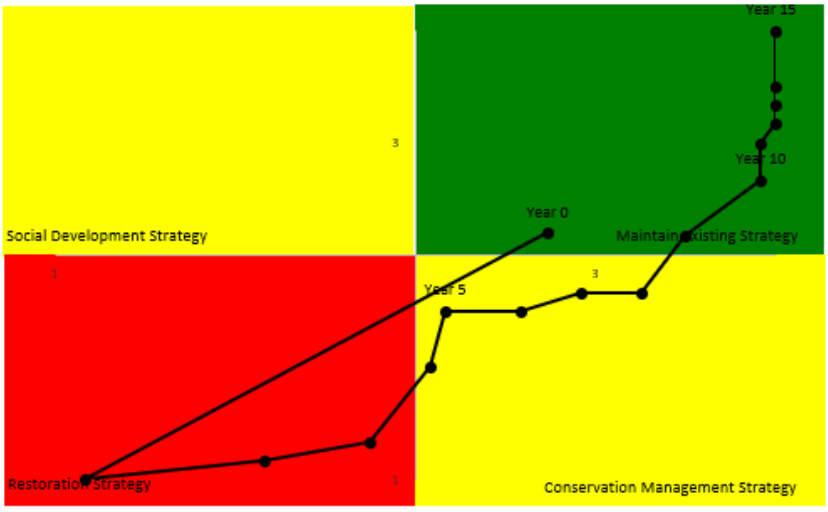

Fig. 3: Fisheries management improvement plan

enforcement consistency, institutional coordination, and integration between formal management and local knowledge systems. Third, local practices such as sasi should be formally recognized and integrated into fisheries management, as they provide effective mechanisms for regulating resource use at the community level. Fourth, habitat protection and restoration, especially mangrove ecosystems, should be prioritized to enhance ecological resilience. Finally, adaptive EAFM-based monitoring must be enhanced through the integration of environmental indicators, such as SST and chlorophyll-a, with fisheries and effort data. This holistic approach is essential for the timely detection of emerging ecological shifts. Although this study is site-specific, the integrated climate-informed EAFM and pressure–response framework may be applicable to other tropical small-scale fisheries experiencing similar interactions among environmental variability, increasing fishing pressure, and socio-economic dependence on fisheries resources (Pomeroy *et al.*, 2016b). While current governance arrangements help prevent immediate substantial ecological decline, their long-term effectiveness will depend on the ability to control fishing pressure, strengthen institutional performance, and align development interventions with ecosystem-based sustainability principles.

CONCLUSION

This study indicates that the Samber–Binyeri coastal fisheries system is currently in a transitional state, where economic gains from the KNMP intervention coexist with increasing fishing pressure and emerging ecological risks. The integration of climate-informed EAFM and pressure–response analysis demonstrates that fisheries sustainability must be assessed beyond the narrow lenses of economic growth or short-term catch stability. Oceanographic variability influences fish availability and catch performance, while development-driven improvements in infrastructure, market access, and fishing capacity reshape exploitation patterns and increase pressure on coastal resources. The results suggest that the KNMP intervention has generated contributed to livelihood benefits, reflected in increased fisher income, production, and fishing trips. However, these gains are accompanied by increasing fishing pressure. Notwithstanding an EAFM composite index of 78% and a stable CPUE trend, ecological sustainability continues to be hindered by moderate habitat performance, the prevalence of juvenile catch, and escalating effort

intensity. This suggests that severe ecological degradation was not clearly detected from the available indicators, but pressure is accumulating and may not be fully captured by conventional indicators. Stable CPUE should not be interpreted as definitive evidence of stock sustainability, as it may reflect hyperstability, improved fishing efficiency, spatial targeting, or delayed ecological response. These findings highlight that apparent ecological stability does not necessarily reflect long-term sustainability. While the current state of coral reefs and seagrass suggests the system may still possess ecological buffering capacity, this conclusion is constrained by the limitations of available indicators and the short-term nature of the dataset. If fishing capacity continues to increase without effective regulation, the current balance between economic growth and ecological integrity may shift toward resource depletion and habitat degradation. Therefore, sustainability assessment must consider not only current system status, but also the direction and intensity of fishing pressure over time. In light of this comprehensive evaluation, the present study offers policy-oriented suggestions designed to fortify the implementation of KNMP. These measures are essential for securing long-term sustainability in marine and fisheries development within the region. Management priorities should include controlling fishing effort and capacity, improving gear selectivity, regulating spatial access to fishing grounds, and strengthening habitat protection and restoration, particularly mangrove ecosystems. Adaptive management should combine effort regulation, habitat protection, climate-informed monitoring, institutional coordination, and integration of local ecological knowledge to balance economic development and ecological stability under increasing fishing pressure and environmental variability. It is essential to enhance adaptive EAFM-based monitoring by synthesizing fisheries indicators with environmental variables, specifically SST and chlorophyll-a. This integration facilitates the proactive detection of emerging ecological shifts before they impact stock stability. Monitoring systems should integrate CPUE, fishing effort, juvenile catch, habitat condition, fisher observations, and oceanographic indicators to detect early degradation signals that may remain hidden under stable or hyper stable CPUE patterns. In addition, stronger institutional coordination, consistent enforcement, and better alignment between formal governance systems and local knowledge are needed to maintain community resilience and prevent unsustainable exploitation. This study's central contribution is the empirical evidence that coastal fisheries are coupled with socio-ecological systems, where economic gains and fishing pressure interact dynamically with environmental shifts and ecosystem responses. For Samber–Binyeri, management should focus on controlling effort growth, improving catch-effort monitoring, protecting mangrove habitats, and aligning KNMP economic targets with ecological limits.

AUTHOR CONTRIBUTIONS

W.I. Sakti contributed to the conceptualization of the study, drafted the original manuscript, and conducted the literature review. I. Meilano supervised the writing process and provided critical revisions to the manuscript. H. Latief supervised the study and supported the refinement of the manuscript. I.M. Radjawane supervised and provided critical revisions to the manuscript. S.W. Trenggono contributed through critical review of the manuscript. R.A. Wahyudin contributed to the critical revision and final editing of the manuscript. S.D. Diantara contributed to the literature review. N.F. Gusmawati and D.G.K. Ketaren contributed to the study conceptualization and interpretation of results. Syamdidi supported the refinement of the manuscript. T. Yuwono contributed to the data analysis and strengthened the literature review. F.Y. Arthatiani and I.N.P. Winata assisted with data collection and interpretation. I.N. Radiarta contributed to the study conceptualization and the literature review. N.D. Fahira assisted with

data collection. S. Maharani contributed to data analysis and interpretation. K. Kasim contributed to manuscript preparation, data analysis, and interpretation. All authors reviewed and approved the final version of the manuscript for 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, 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
<	Less than
µg/L	Microgram per liter
BPPSDM-KP	Badan Penyuluhan dan Sumber Daya Manusia Kelautan dan Perikanan (Agency for Marine and Fisheries Extension and Human Resources)
BPS	Badan Pusat Statistik (the Central Bureau of Statistics)
CPUE	catch per unit effort
DJF	December-January-February
DKP	Dinas Kelautan Perikanan (Departement of Marine Affairs and Fisheries)
EAFM	Ecosystem Approach to Fisheries
ENSO	El Niño–Southern Oscillation
ETP	Endangered, Threatened, and Protected
FGDs	focus group discussions
GAM	Generalized additive model
GEBCO	General bathymetric chart of the oceans
GT	Gross Tonnage
JJA	June-July-August
kg	Kilogram
kg/trip	Kilogram per trip
KNMP	Kampung Nelayan Merah Putih
m	Meter
m/s	Meter per Second
MGCV	Mixed GAM Computation Vehicle

MODIS	Moderate Resolution Imaging Spectroradiometer
NTU	Nephelometric Turbidity Unit
REML	Restricted Maximum Likelihood
s	Second
SeaDAS	SeaWiFS data analysis system
SKN	Sertifikasi Kecakapan Nelayan (Fisher Competency Certificate)
SST	Sea surface temperature
SE	Standard error
TNL	Taman nasional laut (Marine National Park)
TNWL	Taman Nasional Wilayah Laut (Marine National Park Area)
USD	United States Dollar
WPP	Wilayah Pengelolaan Perikanan (Fisheries management area)

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ORIGINAL RESEARCH ARTICLE

Integrating hydrodynamic modeling and multi-criteria decision support for flood risk management in coastal systems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Flood management in low-lying coastal and peatland regions is not only a technical challenge but also a governance issue. While there have been significant advancements in hydrodynamic modeling and geographic information system-based multi-criteria analysis that aid in identifying flood-prone areas, these findings often fail to connect with the institutional realities that affect the execution of interventions. In decentralized systems, fragmented mandates, limited fiscal capacity, and uneven technical resources frequently constrain effective action. The study objectives were to propose a comprehensive decision-support framework to bridge spatial flood risk assessment with governance-sensitive implementation sequencing in coastal systems vulnerable to climate change.

METHODS: Aceh Singkil District, Indonesia, a compound riverine–tidal floodplain characterized by extensive peatlands, was selected as the case study. Multi-return-period (2–50 year) hydrodynamic simulations were used to quantify spatial variations in flood depth and duration. These hazard layers were combined with exposure and vulnerability indicators using spatial multi-criteria evaluation and the analytic hierarchy process, utilizing weights derived from stakeholders. In order to transcend static prioritization, an implementation readiness index was created to evaluate technical feasibility and institutional capacity. Interventions were then organised into phased short-, medium-, and long-term pathways.

FINDINGS: The results indicate that the highest flood risk is concentrated in coastal and peatland settlements where inundation depth and duration are prolonged. Nonetheless, a distinct spatial discrepancy arises between the intensity of hazards and the preparedness of governance. Several high-risk sub-districts demonstrate limited capacity for immediate large-scale intervention, while some moderate-risk areas exhibit higher readiness due to more stable institutional and infrastructural conditions. By combining structural measures and nature-based solutions within a phased framework, the recommended sequencing strategy enhances the alignment of flood intensity with implementation feasibility, thus lowering the risk of delayed or maladaptive responses.

CONCLUSION: This study contributes to environmental management by embedding governance capacity within spatial flood risk assessment. By transitioning from a static prioritization model to a sequencing-based strategy, the framework connects where interventions are needed with when they can be realistically implemented. The readiness-based sequencing model provides a transferable framework for decentralized and climate-vulnerable regions to convert scientific risk assessments into adaptive, executable, and contextually relevant policies.

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67	5	8

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INTRODUCTION

Flooding is a pervasive hazard in low-lying coastal and deltaic regions, driving ecological degradation, infrastructure damage, and socio-economic vulnerability (Dottori *et al*., 2016). It is progressively recognized as the result of interrelated socio-ecological processes, which encompass land-use change, wetland degradation, peatland drainage, and climatic variability. These processes intensify flood dynamics in tropical monsoon regions such as Indonesia, where fluvial–tidal interactions and rapid settlement expansion exacerbate compound flooding (Bennett *et al.,* 2023; Fitriyani *et al*., 2021; Zevenbergen *et al.*, 2020). Climate change exacerbates these risks by causing sea-level rise, intensifying rainfall, and increasing the frequency of extreme weather events, which challenges traditional evaluations and highlights the necessity for adaptive frameworks. Flood risk is therefore increasingly framed as a governance challenge. In decentralized systems, responsibilities are distributed across multiple institutions, often resulting in fragmented mandates and limited coordination. While structural measures are extensively utilized (Kundzewicz *et al*., 2018; Raška *et al.*, 2019), they can lead to long-term ecological trade-offs. Nature-based solutions (NbS) offer more sustainable alternatives (Brillinger *et al.*, 2021; Seddon *et al*., 2020), yet their integration remains constrained by institutional limitations (Lo and Jim, 2021; Fitriyani *et al.,* 2021; Meilianda *et al.*, 2023). Advances in spatial modelling, particularly spatial multi-criteria evaluation- Analytic Hierarchy Process (SMCE–AHP), enhance risk assessment and prioritization (de Brito and Evers, 2016; Gigović *et al*., 2017; Khosravi *et al.*, 2019; Gün and Yılmaz, 2026), but often overlook implementation under governance constraints, creating a persistent gap between analysis and action. Recent studies also highlight the role of socio-environmental, demographic, and urban form factors in shaping flood resilience and susceptibility (Díaz-Ponce *et al.,* 2026; Depari, 2026; Srivanit *et al.,* 2024). Flood risk maps are primarily characterized by their descriptive nature, with little application in planning and decision-making processes. Existing studies rarely integrate institutional capacity, implementation feasibility, and temporal sequencing within spatial decision-support frameworks, and governance variables in MCDA typically refine prioritization rather than address implementation timing. This study seeks to fill this void by proposing a readiness-oriented sequencing approach via the Implementation Readiness Index (IRI), associating spatial risk with both institutional and temporal feasibility. Integrating hydrodynamic modelling with SMCE–AHP and validated simulations in Aceh Singkil (Alfian *et al.*, 2023), the framework shifts from static prioritization to implementation-oriented sequencing. Using Aceh Singkil as a case study, it identifies risks, prioritizes locations, and aligns interventions with governance capabilities, redefining flood risk management as a staged, policy-relevant process. This study has been conducted in Aceh Singkil District within the Singkil River Basin, Indonesia from 2022 until 2024.

MATERIALS AND METHODS

Study area

Singkil district lies at the downstream of the 133 km Singkil River Basin (Alfian *et al*., 2023), draining approximately 10,090 km² into the Indian Ocean. As depicted in Fig. 1, the area of study is characterized by a low-gradient deltaic–estuarine plain, which is interspersed with meandering channels and tidal outlets. The figure delineates administrative and hydrographic boundaries and presents flood-prone zones derived from 2D hydrodynamic simulations (Alfian *et al*., 2023), highlighting concentrated flood intensity along riparian corridors and peat-dominated lowlands. It additionally illustrates the spatial arrangement of household surveys and focus group discussion (FGD) sites, signifying that the collection of primary data was integrated within areas that experience recurrent flooding.

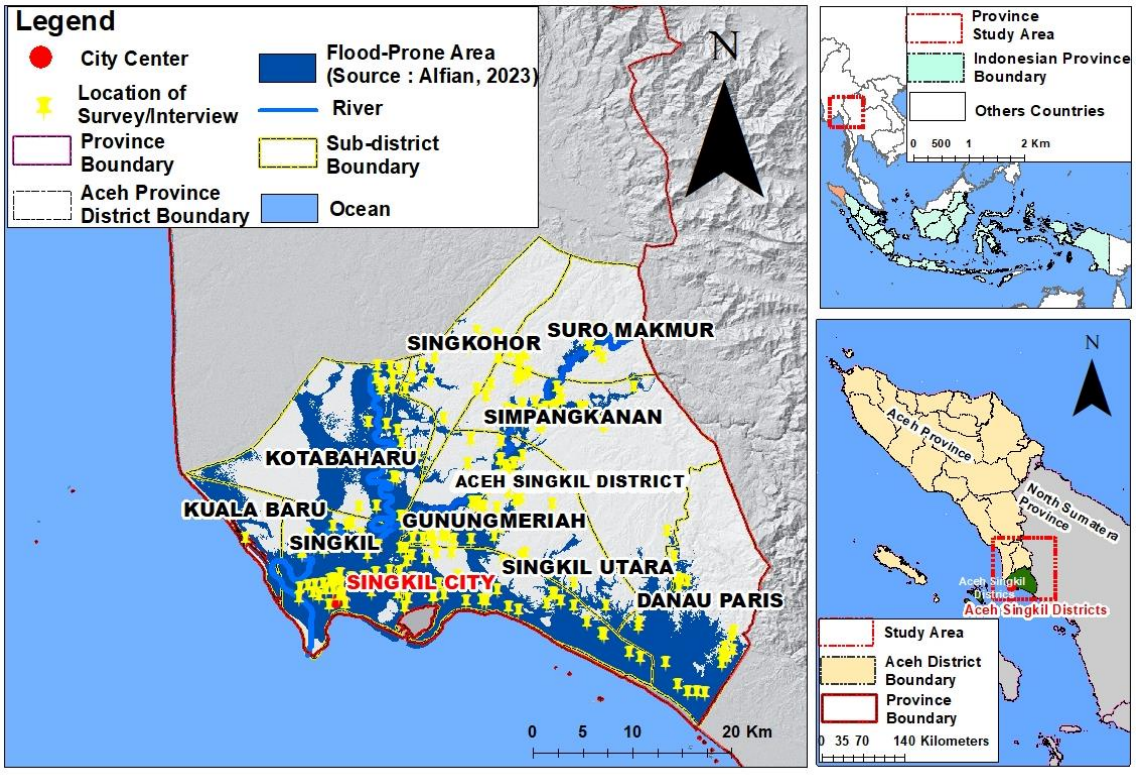


Fig. 1: Geographic location of the study area of Aceh Singkil District within the Singkil River Basin, showing major river networks, coastal interface, modeled flood-prone zones derived from 2D hydrodynamic simulations and the spatial distribution of household survey and FGD sampling locations (Alfian *et al*., 2023)

Geomorphologically, active sedimentation and channel migration (Narulita *et al.*, 2022) interact with peat-rich substrates characterised by low permeability and bearing capacity (Wijedasa *et al*., 2020). Ongoing peat subsidence further reduces land elevation relative to tidal levels (Opdyke *et al*., 2025), thereby reinforcing ongoing inundation patterns. Climatic forcing includes high annual rainfall with 3,000–4,500 millimeter per year (mm/y) with monsoonal concentration (BMKG, 2022), modulated by ENSO and IOD variability, generating substantial upstream discharge. During the occurrence of spring tides, the effects of tidal backwater extend inland, limiting drainage and extending the duration of flooding (Narulita *et al*., 2022). Ecological degradation intensifies these pressures. Wetlands and peat swamp forests that formerly supplied natural retention (Seddon *et al*., 2020) have been fragmented as a result of land conversion (Wijedasa *et al*., 2020), which has diminished their storage capacity. Meanwhile, settlement concentration along riverbanks—particularly in Singkil City, Singkil Utara, and Gunung Meriah (BNPB, 2021)—places over 75% of the population below 5 m elevation, overlapping with flood-prone zones. Historical data record at least 27 major floods between 2009 and 2022, with depths reaching 2–3 m (Alfian *et al*., 2023).

Data and methods

Developing meaningful flood management scenarios necessitates more than technical modelling alone; it requires a framework that integrates physically grounded hazard analysis with participatory planning and organized decision-support tools (Nasiri *et al*., 2023; Nguyen *et al*., 2024). In this study, flood hazards provide spatially distributed information on flood depth,

velocity, and duration across multiple return periods (Alfian *et al*., 2023). The results generated by these models, underpinned by field observations and supplementary datasets, facilitated a precise identification of areas susceptible to flooding and established a reliable physical foundation for grasping the spatial and temporal dynamics of flooding within the study region (Opdyke *et al*., 2025). By building upon an already calibrated modelling framework, methodological continuity was maintained, enabling this study to concentrate on integrating hazard layers within a multi-criteria decision environment for scenario formulation rather than re-estimating hydrodynamic behaviour. Although further hydrodynamic modeling or re-validation could enhance the accuracy of hazard representation, this was not the main aim of the current study. The hydrodynamic model developed by Alfian *et al*. (2023) has already undergone calibration and validation using field observations and historical flood data, providing a reliable and consistent basis for hazard characterization. The significance of this study is found in its ability to broaden the use of validated hydrodynamic outputs into a governance-oriented decision-support framework. Specifically, this study advances beyond previous work by integrating hazard modelling with SMCE–AHP and introducing the IRI, which incorporates institutional capacity and implementation timing into flood risk planning (Alfian *et al.,* 2023). In order to maintain the assessment's contextual relevance and operational significance, the physical hazard analysis was enhanced by an evaluation of the direct and cascading consequences of flooding on local communities. A mixed-methods approach was adopted, combining semi-structured interviews and FGD with key stakeholders, including government officials, community leaders, and technical practitioners in hydrology and disaster management. These engagements provided both qualitative insights and structured information regarding historical flood characteristics, exposure patterns, socio-economic disruptions, and the perceived effectiveness of existing mitigation measures. Participants were additionally encouraged to pinpoint key challenges, evaluate institutional and infrastructural limitations, and recommend practical intervention pathways that are in accordance with local governance realities. Fig. 2 illustrates the conceptual framework for integrated flood management scenario development. A summary of the key information collected to support scenario development is presented in Table 1.

Stakeholder evaluation and scenario structuring

Building on interviews and FGDs, stakeholders evaluated existing flood-response mechanisms, including early warning, shelters, embankment maintenance, and evacuation at community and government levels (Sarkheyli *et al.*, 2022). The discussions revolved around the effectiveness, coordination bottlenecks, and institutional constraints, refining essential hazard parameters—flood depth, duration, and return period—as significant risk determinants (Mudashiru *et al*., 2022). The process identified management options reflecting local perceptions and adaptive capacities (Seddon *et al.*, 2020). Inputs were synthesized within an SMCE framework to formulate context-sensitive scenarios (Gigović *et al*., 2017), thereby improving transparency and stakeholder ownership (Van Voorst, 2016). Scenarios were classified by timeframe, governance responsibility, and risk-reduction performance (Narayan *et al*., 2017).

Flood hazard profile

The modelling methodology employed by Alfian *et al*. (2023) utilized a two-dimensional hydrodynamic simulation framework that effectively captures floodplain flow processes, overbank inundation, and multi-channel routing dynamics, consistent with established coastal–fluvial flood modelling practices. The model generated spatial layers of flood depth and flood duration for return periods of 2, 5, 10, 25, and

Table 1: Key information collected for the development of flood management scenarios

No.	Information Category	Data type	Purpose / function	Source / method
1	Flood hazard profile (depth, velocity, duration)	Primary	Provides key physical parameters used to define hazard severity and classify scenario conditions	2D hydrodynamic simulation (Alfian *et al.*, 2023) and field observations
2	Flood-related issues and impacts	Primary and Secondary	Supports identification of priority problems, cascading impacts, and factors influencing scenario selection	Semi-structured interviews; FGD; technical reports
3	Existing flood management measures and institutional arrangements	Primary and Secondary	Assesses current programs, their performance gaps, and opportunities to enhance scenario design	Stakeholder consultation; technical documents; on-site assessment
4	Government policies and regulations on flood management	Secondary	Identifies regulatory frameworks and compliance requirements guiding scenario formulation	National/regional policy documents; National Disaster Management Agency (BNPB)/Regional Disaster Management Agency (BPBD) guidelines

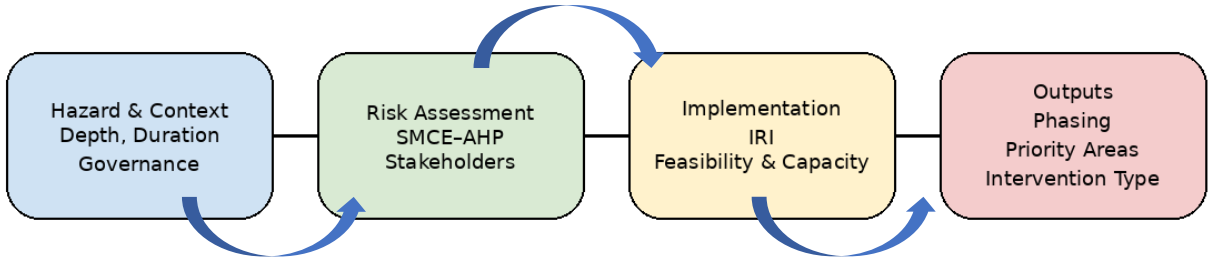


Fig. 2: Conceptual framework for integrated flood management scenario development

50 years. In addition, Monte Carlo techniques and two-dimensional flood simulation models have been widely integrated with GIS frameworks to support comprehensive flood risk assessment and spatial uncertainty analysis (Wang *et al.*, 2020; Teng *et al.*, 2020). The characteristics of rainfall frequency were obtained from historical time-series data obtained from Meterological, Climatological and Geophysical Agency of Indonesia (BMKG), employing the Log-Pearson Type III distribution for the estimation of return periods (England *et al.*, 2018; Sharma *et al.*, 2020). Model calibration was conducted by comparing simulated flood extents with field observations and stakeholder-reported inundation conditions, demonstrating good qualitative agreement. This validation approach aligns with commonly applied practices in data-limited floodplain environments (Mudashiru *et al.*, 2022). The ultimate results comprise raster-based surfaces that depict the maximum flood depth (m) and flood duration (days) for each return period scenario. The model results reveal that simulated flood depths exceeding 5.00 m and inundation durations greater than 14 days are consistently observed along settlement corridors in Singkil, Singkil Utara, and Gunung Meriah. These patterns illustrate the cumulative impact of significant monsoonal runoff, minimal floodplain gradients, and tidal backwater influences (Fig. 3 and Table 2). The model outputs in raster layers were directly adopted as hazard inputs within the present SMCE–AHP analytical framework. Given that the hydrodynamic modelling component has been extensively developed, calibrated, and validated, the current study emphasizes the integration of these hazard layers with residential exposure data within a SMCE framework and deriving stakeholder-informed criteria weights through the AHP process to prioritize intervention areas effectively and systematically for improved decision-making outcomes.

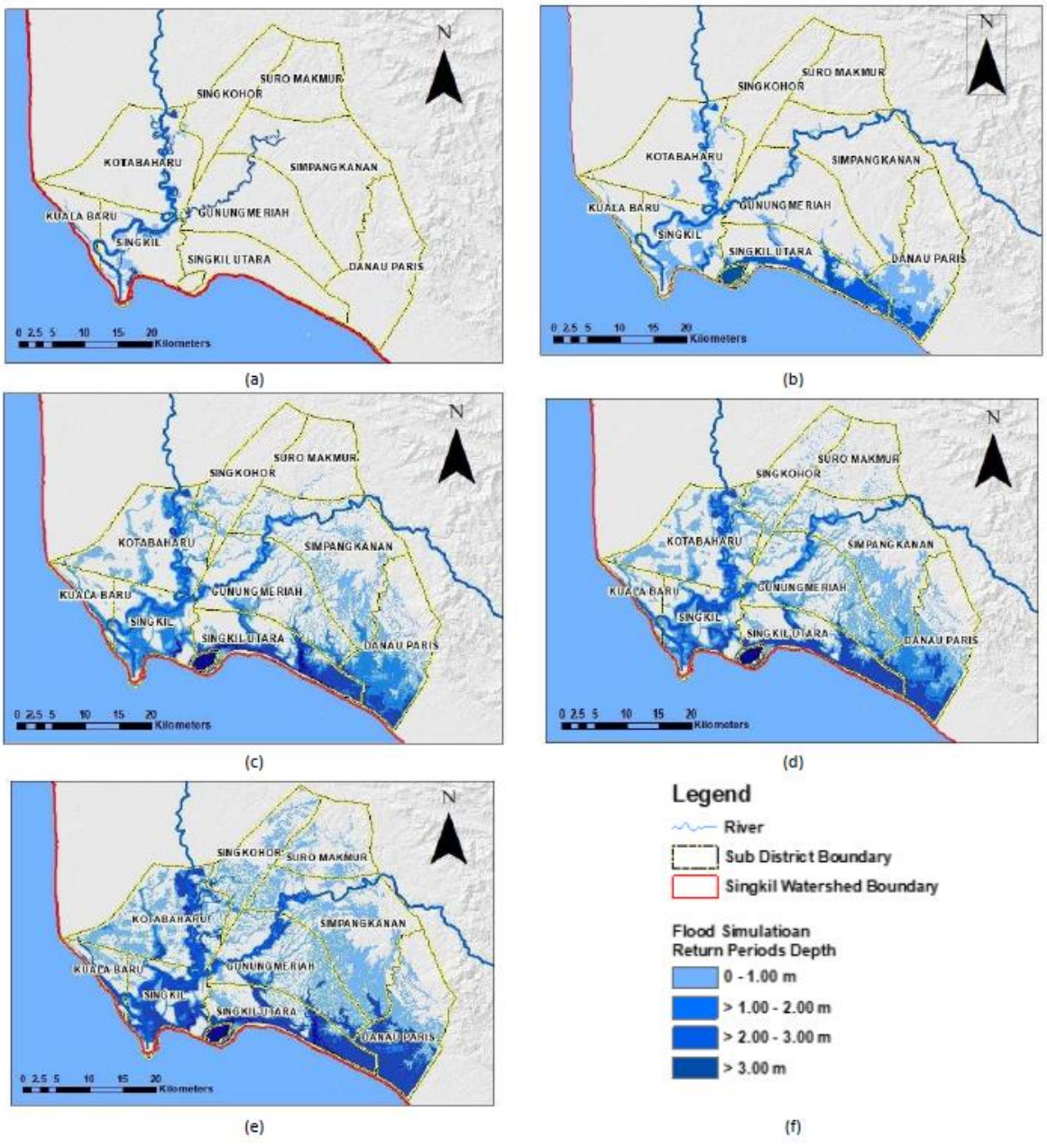


Fig. 3: Flood depth map of 2D hydraulic flood simulation with (a) 2 years return periods, (b) 5 years return periods, (c) 10 years return periods, (d) 25 years return periods, and (e) 50 years return periods (Alfian *et al.,* 2023)

Table 2: Summary of flood simulation results for different return periods (Alfian *et al*., 2023)

Return Periods (years)	Flood Extent (km^2)	Height (m)	Duration (day)
2	238.14	2.53	4.12
5	408.12	3.01	5.43
10	545.97	3.48	6.52
25	679.47	3.97	8.32
50	866.94	5.29	15.78

Climate change scenario consideration

To enhance long-term relevance, simplified climate change scenarios were incorporated into baseline hydrodynamic outputs using a sensitivity-based method that takes into account sea-level rise and heightened rainfall intensity (Vousdoukas *et al*., 2018; IPCC, 2021; Hirabayashi *et al.,* 2021; Alfieri *et al*., 2017). Sea-level rise elevates downstream boundaries, reduces hydraulic gradients, and intensifies tidal backwater, increasing flood depth and duration in low-lying areas (Nicholls and Cazenave, 2010; Vousdoukas *et al*., 2018). Increased rainfall intensifies upstream discharge and runoff, amplifying flood magnitude and extent (IPCC, 2021; Hirabayashi *et al*., 2021). Even though it is simplified, this strategy accounts for climate uncertainty while preserving consistency with verified baseline models.

Data acquisition

Primary data were collected through 249 household surveys across eleven sub-districts (5–20 January 2022), capturing socio-ecological exposure and governance perspectives. Surveys covered flood exposure, housing, impacts, coping, and mitigation, using CAPI via KoBoToolbox to ensure consistency. Locations aligned with modeled flood-prone areas (Alfian *et al*., 2023). A FGD comprising 35 participants analyzed flood characteristics, institutional roles, and adaptation strategies, following thematic saturation principles (Ahmed, 2025; Moore *et al*., 2026). Secondary data from Balai Wilayah Sungai (BWS), BPBD, Public Works, and Bappeda provided hydrological and policy context, while hydrodynamic parameters were derived from Alfian *et al*. (2023) and BWS datasets.

Spatial multi-criteria evaluation (SMCE)

SMCE was applied as the principal spatial decision-support tool to assess and prioritise flood hazard conditions in Singkil District. This approach enables the integration of heterogeneous spatial datasets including hydrodynamic model outputs, exposure layers, and socio-environmental indicators within a unified analytical framework (Luu *et al*., 2021; Gün and Yılmaz, 2026). Flood hazard layers that represent both depth and duration were generated from validated two-dimensional hydrodynamic simulations under multiple return periods (2, 5, 10, 25, and 50-year) (Alfian *et al*., 2023; Akay, 2021). These were integrated with a residential exposure layer created by spatially overlaying building data, which served as a proxy to depict population density and possible social vulnerability, especially in areas that are both densely populated and susceptible to flooding. Together, these parameters represent the key components of flood hazard: intensity (depth), persistence (duration), and exposure (residential impact), capturing the spatial variability of flood severity (Hadipour *et al*., 2020; Gün and Yılmaz, 2026). To ensure comparability, all criteria were preprocessed, resampled to a consistent spatial resolution, and normalised using fuzzy linear membership functions ranging from 0 (very low) to 1 (very high). This transformation illustrates the evolving characteristics of flood hazards, where greater depth and longer duration are associated with elevated risk levels. The linear membership function is defined as: The linear increasing membership function is expressed, using Eq. 1 (FEMA, 2022; World Bank, 2021):

$$\mu(x) = \begin{cases} 0 & if\ x \le a \\ \frac{x-a}{b-a} & if\ a < x < b \\ 1 & if\ x \ge b \end{cases} \quad (1)$$

where: $\mu(x)$ represents the membership value ranging from 0 to 1, x denotes the input parameter (such as flood depth, duration, or exposure), and a and b define the lower and upper thresholds that represent increasing levels of hazard severity. Three indices were derived flood depth index, using Eq. 2 (Dodangeh *et al*., 2020; Khosravi *et al*., 2019):

$$Flood\ Depth\ Index_{(x)} = \frac{D_x - D_{min}}{D_{max} - D_{min}} \quad (2)$$

where: D_x represents the simulated flood depth at pixel *x*, *Dmin* denotes the minimum flood depth observed in the dataset, and *Dmax* = 1.5 m represents the upper severity threshold beyond which inundation is associated with significant structural and economic damage (FEMA, 2022). Although these threshold values are based on recognized guidelines (FEMA, 2022; World Bank, 2021), their use in this study was further analyzed against the local flood characteristics identified in Aceh Singkil. Hydrodynamic simulation findings suggest that flood depths often surpass 2–3 m and inundation periods potentially lasting several days, particularly in low-lying peatland regions. Therefore, the selected thresholds represent conservative benchmark values that illustrate the transition from moderate to severe flood impacts while maintaining consistency across various return period scenarios. The resulting index ranges from 0, indicating the lowest flood hazard level, to 1, representing the highest level of risk. This index were derived as flood duration index, using Eq. 3 (Dodangeh *et al*., 2020; Khosravi *et al*., 2019):

$$Duration\ Index_{(x)} = \frac{T_x - T_{min}}{T_{max} - T_{min}} \quad (3)$$

where: T_x denotes the flood duration at pixel *x*, *Tmin* represents the shortest recorded inundation period, and *Tmax* = 3 days, which corresponds to the threshold beyond which prolonged inundation can lead to severe disruption to settlements and local activities. In a similar vein, the 3-day threshold for flood duration signifies a crucial juncture, beyond which extended flooding starts to markedly interfere with household operations, the functionality of infrastructure, and the livelihoods of the local community, as validated by field observations and discussions with stakeholders, utilizing Eq. 4 (World Bank, 2021):

$$Residential\ Impact\ Index_{(x)} = \frac{R_x - R_{min}}{R_{max} - R_{min}} \quad (4)$$

where: R_x represents the number of buildings inundated within each grid cell, while *Rmax* = 100 units per village defines the upper threshold of residential exposure (FEMA, 2022). Regions with elevated concentrations of impacted structures signify increased susceptibility owing to the buildup of exposed resources and the likelihood of more substantial economic losses.

AHP-based weighting and prioritization of flood management options

AHP was applied to determine the relative importance of flood-related criteria and to prioritise suitable flood management strategies for Aceh Singkil. As a complement to the SMCE framework, AHP allows for the organized transformation of qualitative judgments provided by experts into numerical weights, which supports structured decision-making (Gholami *et al*., 2025; Rahmati *et al*., 2019). AHP has been extensively utilized in flood risk assessments to evaluate mitigation options, climate adaptation strategies, and participatory planning processes (Aidinidou *et al*., 2023; Herbanu *et al*., 2024). While alternative multi-criteria decision-making (MCDM) methods such as VIKOR and entropy-based weighting exist, AHP remains one of the most commonly applied approaches in flood risk prioritization (Malekian and Azarnivand, 2016).

AHP weighting of flood hazard criteria

Pairwise comparisons of flood hazard criteria (flood depth, duration, and residential impact) were conducted with 35 stakeholders, including hydrologists, Badan Penanggulangan Bencana Daerah (BPBD) officers, spatial planners, and community representatives. To enhance transparency, the pairwise comparison process adhered to Saaty's established AHP methodology, in which stakeholders evaluated criteria on a 1–9 scale. Individual assessments were combined using the geometric mean to derive a group consensus matrix. While individual matrices are not presented due to space limitations, all

aggregated matrices satisfied the acceptable consistency threshold (CR ≤ 0.1), ensuring logical coherence in stakeholder judgments. Although consistency ratio (CR) evaluation ensures internal logical consistency, it does not fully capture uncertainty arising from variability in stakeholder judgments. Subsequent studies should consequently integrate formal sensitivity analysis methods, including weight perturbation or scenario-based testing, to assess the effect of weighting changes on spatial prioritization results. Participants were selected based on technical expertise, institutional roles, and experience with flooding. Evaluations were performed using Saaty's 1–9 scale and aggregated using the geometric mean to derive group-level comparison matrices. These matrices were normalised to obtain the priority weights. The weighted criteria were integrated into the SMCE framework using the weighted linear combination (WLC) approach, using Eq. 5 (Luu *et al*., 2021):

$$S_i = \sum_{j=1}^{n} W_j X_{ij} \quad (5)$$

Consistency Ratio (CR) was calculated using the following expressions, using Eq. 6 (Gigović *et al*., 2017; Mosadeghi *et al*., 2015):

$$CR = \frac{CI}{RI}, \qquad CI = \frac{\lambda_{max} - n}{n-1} \quad (6)$$

All matrices produced CR ≤ 0.1, indicating acceptable consistency (Gigović *et al*., 2017; Griffiths *et al.,* 2024; Şener *et al*., 2018). The resulting composite Flood Hazard Index (FHI) was classified into five categories (very low to very high) using the Jenks Natural Breaks method.

Prioritization of flood management options

AHP was further applied to prioritise structural, non-structural, and nature-based flood management strategies. The decision hierarchy consisted of three levels:

(1) Objective (selection of appropriate strategies),
(2) criteria (hazard, exposure, and vulnerability), and
(3) alternatives (e.g., embankments, drainage, relocation, wetland restoration, early warning systems (EWS), and community preparedness).

Pairwise comparisons of alternatives were conducted in FGDs involving 35 stakeholders. Judgments were compiled using the geometric mean and confirmed through CR analysis, ensuring coherence between criterion weights and strategy assessment. The integration of SMCE and AHP enables flood management scenarios by combining spatial hazard assessment with stakeholder-informed prioritization. This approach ensures proposed interventions are technically grounded in hydrodynamic conditions while aligned with institutional and community contexts, enabling feasible and implementable flood risk strategies.

Development of flood management scenarios

Flood management scenarios integrate SMCE–AHP outputs with institutional realities using a multi-source, participatory approach (Dewulf *et al*., 2019). Field observations and stakeholder consultations (BPBD, Public Works, Bappeda) identified drainage limitations and recurrent flooding, requiring combined structural and non-structural measures. Policy alignment followed RPBD and RTRW (UNISDR, 2015; World Bank, 2021), while hydrodynamic modelling supported risk identification (Alfian *et al*., 2023) and long-term strategies (Rusmanansari *et al*., 2022). Community input enhanced feasibility (Lechowska, 2018). IRI-based sequencing links interventions to hazard and governance capacity, progressing past static prioritization approaches (Luu *et al*., 2021) toward adaptive, implementation-focused flood risk management. Table 3 presents a comparison of the proposed SMCE–AHP–IRI framework with existing flood risk assessment approaches.

Table 3: Comparison of the proposed SMCE–AHP–IRI framework with existing flood risk assessment approaches

Approach	Main Focus	Strengths	Limitations	This study contribution
Hydrodynamic modelling	Physical flood processes	Accurate hazard representation	No decision support for planning	Integrated as hazard foundation
MCDA (SMCE–AHP)	Spatial prioritization	Incorporates multi-criteria and stakeholders	Static ranking, no implementation logic	Extended with governance dimension
Cost–Benefit Analysis (CBA)	Economic efficiency	Supports financial decision-making	Requires reliable cost data, ignores institutional capacity	Not used due to data constraints
Nature-Based Solutions frameworks	Ecosystem-based mitigation	Long-term sustainability	Weak implementation pathway	Integrated into phased strategy
Proposed SMCE–AHP–IRI	Risk + governance + timing	Links hazard, stakeholders, and feasibility	Requires stakeholder input	Enables sequencing-based, implementable planning

The IRI is defined using Eq. 6 (Luu *et al.*, 2021):

$$IRI_k = 0.5 \times F_k + 0.5 \times C_k \quad (6)$$

where F_k represents the technical feasibility of intervention k, and C_k represents institutional capacity, including coordination, financial readiness, and implementation capability. Both components were scored on a scale of 1 (very low) to 5 (very high) based on stakeholder evaluation and subsequently normalised to a 0–1 range. Equal weighting was implemented after obtaining stakeholder consensus throughout the consultation process. The technical feasibility component (F_k) was assessed based on criteria including engineering complexity, required infrastructure, implementation time, and operational requirements. The component of institutional capacity (C_k) encompasses governance-related factors, including inter-agency coordination, financial preparedness, regulatory support, and the ability to implement at the local level. Both components were evaluated by stakeholders using a structured scoring system during focus group discussions, which were aided by guiding questions and established criteria to maintain consistency across responses. Equal weighting (0.5–0.5) was applied following stakeholder consensus, reflecting the assumption that both technical feasibility and institutional capacity are equally critical in determining implementation readiness in decentralized contexts. In contrast to traditional feasibility indices, the IRI is not designed to reorder interventions solely based on their suitability. Rather, it serves as a sequencing tool that identifies the appropriate timing for implementing interventions given the current governance conditions. Based on the IRI values, interventions were classified into three implementation phases: short-term (IRI ≥ 0.67), medium-term (0.34–0.66), and long-term (IRI < 0.34). This classification enables a transition from static prioritization toward a dynamic and staged planning approach, aligning flood risk reduction strategies with both hazard intensity and institutional readiness.

Uncertainty and model validation

The trustworthiness of hydrodynamic modelling and multi-criteria evaluation is shaped by multiple uncertainties. In the hydrodynamic component, uncertainty arises from boundary conditions, DEM resolution, surface roughness, and fluvial–tidal interactions. As outputs were adopted from a calibrated study (Alfian *et al.*, 2023), uncertainty mainly relates to baseline simulations. In AHP, uncertainty stems from stakeholder subjectivity, reduced through geometric mean aggregation with acceptable consistency (CR ≤ 0.1). Nonetheless, fluctuations in preferences could still influence weighting results, and it is advisable to conduct a sensitivity analysis. Model validation showed good qualitative agreement with observed flood patterns (Alfian *et al.*, 2023). Overall, the framework is robust, though further uncertainty and sensitivity analysis would improve reliability.

RESULTS AND DISCUSSION

Spatial flood risk zoning

The SMCE produced a composite Flood Risk Index (FRI) representing spatial flood risk variation across Aceh Singkil. The index incorporates flood depth, flood duration, and residential exposure, all of which are normalized via fuzzy membership functions and amalgamated using a weighted linear model. For interpretation, FRI was classified into five categories: Very Low (0–0.20), Low (0.20–0.40), Moderate (0.40–0.60), High (0.60–0.80), and Very High (0.80–1.00). Residential exposure was the dominant factor (weight = 0.54), followed by flood depth (0.30) and duration (0.16), reflecting stakeholder priorities and established findings that densely populated low-lying areas exhibit higher vulnerability. The AHP weighting (Table 4 and Table 5) followed Saaty's 1–9 scale, with judgments aggregated using the geometric mean. The calculated consistency ratio (CR = 0.005) is well below the acceptable threshold (CR < 0.10), demonstrating a high level of internal consistency and reliability of the obtained weights. While CR confirms logical coherence, it does not fully capture uncertainty from stakeholder variability. Although group aggregation was applied, formal sensitivity analysis was not conducted. Future studies ought to include sensitivity testing to assess the resilience of spatial prioritization across various weighting scenarios. Flood depth and flood duration layers were generated from two-dimensional hydrodynamic simulations representing 2, 5, 10, 25, and 50-year return periods. Residential exposure was subsequently measured by conducting a spatial overlay analysis of building footprints within the simulated inundation zones. Prior to the normalization process, the minimum and maximum values for each parameter were established to reflect the range of variability in flood depth, flood duration, and residential exposure across the different return periods. These values were subsequently used as threshold limits in the fuzzy membership transformation. Table 6 provides a summary of the parameter ranges used in the normalization procedure.

As return periods increase, the spatial patterns of flood risk components exhibit distinct yet complementary dynamics (Alfian *et al.,* 2024). Flood depth remains concentrated along the coastal fringe and lower Singkil River, intensifying under higher return periods. In contrast, the duration of flooding spreads further inland in low-gradient regions, which reflects a limited capacity for drainage. Residential exposure is spatially clustered but increasingly overlaps with expanding hazard zones, particularly in Singkil, Singkil Utara, and Kuala Baru. This convergence results in a progressive increase in spatial risk intensity, reflected in the composite FRI (Fig. 4), which shows a systematic expansion of high- and very high-risk areas. Climate-related influences imply that increases in flood depth and duration will intensify hazard indices, which may result in moderate-risk regions being reclassified into higher-risk categories, particularly in areas with inadequate drainage. This may also influence AHP-based prioritization as stakeholder risk perceptions evolve. As such, results represent baseline-to-near-term conditions; incorporating dynamic projections (for instance, sea-level rise, rainfall intensification, storm surge) would likely further expand high-risk zones. This highlights the necessity for regular updates to hazard and risk classifications. In scenarios characterized by extreme conditions over a 50-year timeframe, large lowland areas are observed to reach critical risk levels, especially in Singkil, North Singkil, and Danau Paris. Subdistrict rankings (Table 7) consistently emphasize Singkil and Singkil Utara, followed by Gunung Meriah and Simpang Kanan, following, demonstrating a strong relationship between hydrodynamic exposure and settlement patterns. These findings are consistent with regional studies (Haque *et al.*, 2022; Kumar *et al.*, 2024; Lo and Jim, 2021) and historical flood events

Table 4: Pairwise comparison matrix

Criteria ↓ vs →	Flood depth (C1)	Flood duration (C2)	Residential Impact (C3)
Flood Depth (C1)	1	2	1/2
Flood Duration (C2)	1/2	1	1/3
Residential Impact (C3)	2	3	1

Table 5: Normalized Pairwise Comparison Matrix and Priority Weights for Flood Criteria

Criteria ↓ vs →	C1 (Norm)	C2 (Norm)	C3 (Norm)	Row Avg. (Weight)
C1 (Depth)	1.00/3.50 ≈ 0.29	2.00/6.00 ≈ 0.33	0.50/1.83 = 0.27	(0.29+0.33+0.27)/3 = 0.30
C2 (Duration)	0.50/3.50 ≈ 0.14	1.00/6.00 ≈ 0.17	0.33/1.83 = 0.18	(0.14+0.17+0.18)/3 = 0.16
C3 (Residential Impact)	2.00/3.50 ≈ 0.57	3.00/6.00 ≈ 0.50	1.00/1.83 = 0.55	(0.57+0.50+0.55)/3 = 0.54

Table 6: Parameter ranges used for normalizing flood depth, duration, and residential impact across return periods

Parameter	Flood depth (m)		Duration (day)		Residential impact (Number of buildings)	
	Min value	Max value	Min value	Max value	Min value	Max value
2 - Year return period	0.00	2.53	0.00	4.12	0	581
5 - Year return period	0.00	3.01	0.00	5.43	0	1576
10 - Year return period	0.00	3.48	0.00	6.52	0	1696
25 - Year return period	0.00	3.97	0.00	8.32	0	1849
50 - Year return period	0.00	5.29	0.00	15.78	0	1940

Table 7: Consolidated priority ranking of sub-districts for flood risk reduction across all return period scenarios in Aceh Singkil District

Priority rank	Sub-district	Risk trend (2–50 Years)	Key characteristics
1	Singkil	High → Very high	Coastal zone, densely populated, low elevation, tidal and riverine flood-prone
2	Singkil Utara	High → Very high	Coastal estuarine zone, limited infrastructure, high residential exposure
3	Gunung Meriah	Moderate → Very high	Inland floodplain, significant exposure, agricultural land at risk
4	Simpang Kanan	Moderate → high	Transitional zone, growing settlements, exposed infrastructure
5	Danau Paris	Moderate → high	Inland-riverine interface, moderate flood depth and duration
6	Suro	Moderate → high	Mixed-use land, moderate residential exposure
7	Kota Baharu	Low → Moderate	Peripheral area, moderate risk under extreme events
8	Kuala Baru	Low → Moderate	Limited flood extent, lower population density
9	Singkohor	Low → Moderate	Limited flood extent, lower population density

(Cai *et al.*, 2019; Eryani *et al.*, 2024). Validation against historical records and stakeholder reports substantiates that identified high-risk zones correspond to regions experiencing recurrent flooding. Moreover, the AHP weighting shows strong consistency (CR = 0.005), with residential exposure emerging as the dominant risk driver.

From spatial risk mapping to environmental governance

While the IRI has not undergone quantitative validation, its categorization of intervention phases corresponds with the institutional conditions observed, including variations in coordination capacity, infrastructure, and resource distribution among sub-districts. Stakeholder feedback from FGDs further supports the plausibility of these classifications. Overall, the integrated SMCE–AHP–IRI framework produces results consistent with observed flood behaviour, documented impacts, and governance conditions. However, future research should incorporate quantitative validation using damage datasets, time-series observations, and policy performance indicators to enhance robustness. The findings also highlight the importance of socio-economic disparities. While residential exposure captures population distribution, it does not fully reflect differences in income, land tenure, or marginalization. High-risk areas often coincide with communities of limited adaptive capacity, increasing vulnerability. These aspects were partially addressed through stakeholder consultations but not explicitly quantified,

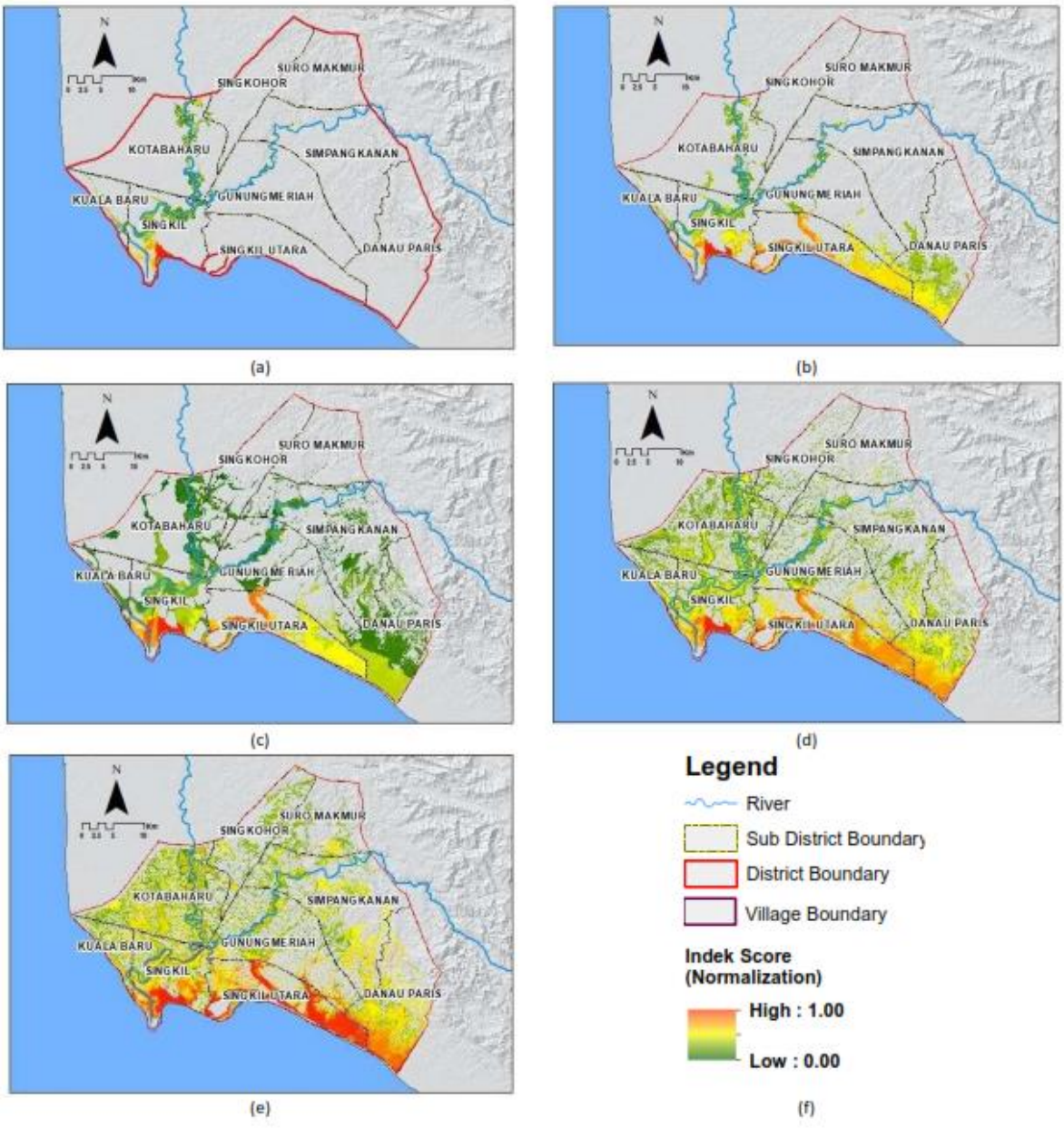


Fig. 4: Composite FRI Derived from SMCE : with (a) 2 years return periods, (b) 5 years return periods, (c) 10 years return periods, (d) 25 years return periods, and (e) 50 years return periods

suggesting the need to integrate more detailed socio-economic and equity-based indicators in future applications. In addition, indigenous and local ecological knowledge provides valuable insights into flood dynamics, complementing hydrodynamic models. In this study, such knowledge informed interpretation through consultations and interviews. However, more systematic integration such as participatory mapping and community-based monitoring would enhance both accuracy and legitimacy, particularly in data-constrained environments.

Flood risk reduction strategies and readiness-based sequencing

Flood risk reduction strategies in Aceh Singkil were identified through an integrated analysis combining hydrodynamic modelling, spatial vulnerability assessment, and stakeholder consultation. This multi-layered approach aligns with established frameworks for integrated flood risk planning in riverine and coastal systems (Dottori *et al*., 2016; Luu *et al*., 2021; Sayers *et al*., 2022). Hydrodynamic simulations across multiple return periods (2–50 years) reveal diverse flood typologies, including fluvial overflow, tidal backflow, pluvial flooding, and wetland degradation. These patterns provide the basis for distinguishing areas requiring immediate intervention from those needing longer-term structural or ecosystem-based measures (Teng, 2020). The SMCE framework further integrates exposure, sensitivity, and environmental degradation indicators to identify appropriate intervention types. Consistent with previous GIS-based flood risk studies (Luu *et al*., 2021; Khosravi *et al*., 2019), this approach enables spatial targeting of measures such as drainage improvement, EWS, wetland rehabilitation, and reforestation. Stakeholder consultations involving BPBD, PUPR, Bappeda, DLH, and local governments refine these options by incorporating institutional feasibility and operational constraints. This participatory process ensures that interventions are aligned with governance capacities and local priorities (Lebel *et al*., 2018; Trogrlić *et al*., 2019). To translate these findings into implementable strategies, the identified interventions were evaluated using an integrated SMCE–AHP–IRI framework. The resulting prioritization and readiness assessment is presented in Table 8, combines the relative significance of each intervention with its practicality within the current institutional circumstances. Unlike conventional intervention listings, this table explicitly links hazard-based prioritization with governance readiness, enabling a transition from static ranking to phased implementation planning.

Table 8 and Fig. 5 reveals a clear divergence between intervention priority and implementation readiness (Bubeck *et al.,* 2015). Community-based and non-structural measures such as EWS, enhancements to household drainage and preparedness consistently yield the highest IRI values (≥ 0.75), reflecting significant feasibility within prevailing institutional and financial limitations. Structural interventions, in contrast, such as levees, retention systems, and diversion canals, reveal a lower readiness level, despite their essential role in long-term risk reduction, which underscores the heightened technical, financial, and coordination demands. This mismatch indicates that feasibility is primarily shaped by governance capacity rather than hazard severity, highlighting the value of IRI-based sequencing. Spatial patterns reinforce this distinction. Structural interventions are necessary in coastal areas with high risk and in low-gradient floodplains; however, they entail considerable expenses and ecological compromises. Conversely, NbS, including wetland rehabilitation and peatland rewetting, are more suitable for moderate-risk and sensitive areas, offering long-term resilience and ecosystem co-benefits, albeit with slower impact. The proposed SMCE–AHP–IRI framework captures this trade-off by aligning intervention types with both hazard intensity and governance capacity. By incorporating both structural and nature-based approaches within a phased strategy, it creates a continuum that spans from immediate response to enduring resilience, thereby embedding the feasibility of implementation into flood risk governance. Interventions classified under the medium-term horizon, including zoning enforcement, tidal-control drainage systems, and retention ponds, exhibit moderate readiness (IRI ≈ 0.50–0.63) and require greater coordination, regulatory alignment, and financial mobilisation prior to implementation. Conversely, long-term strategies such as diversion canals and amphibious housing are characterised by lower readiness scores (IRI < 0.34), which reflect increased technical complexity and institutional requirements.

Table 8: Scenario-based prioritization of flood mitigation interventions integrating AHP–SMCE ranking and implementation readiness index

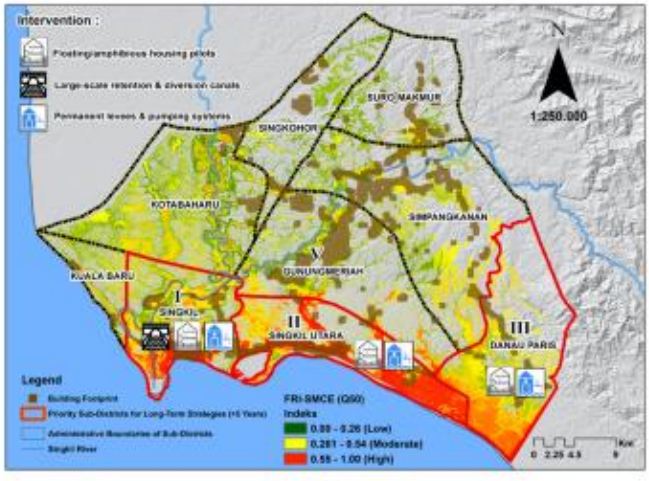
Code	Intervention name	$\tilde{F}_K$ (1–5)	$\tilde{C}_K$ (1–5)	$\tilde{F}_K$ Norm	$\tilde{C}_K$ Norm	IRI	Scenario	Sub-districts	Responsible stakeholder
NS1	Community-based EWS	5	5	1.00	1.00	1.00	Short-term (1–2 y)	Singkil, Singkil Utara, Gunung Meriah, Simpang Kanan, Danau Paris, Suro Makmur, Kota Baharu, Kuala Baru, Singkohor	BPBD and Village Government
S1	Improved household drainage	5	4	1.00	0.75	0.88	Short-term (1–2 y)	Gunung Meriah, Simpang Kanan, Suro Makmur, Singkohor, Kota Baharu	Public Works Department (PU)
S3	Drainage maintenance and natural swale rehabilitation	5	4	1.00	0.75	0.88	Short-term (1–2 y)	Gunung Meriah, Simpang Kanan, Suro Makmur, Kota Baharu	Public Works Department (PU)
NS2	Community preparedness and evacuation planning	4	4	0.75	0.75	0.75	Short-term (1–2 y)	Singkil, Singkil Utara, Kuala Baru	BPBD and Local Communities
A1	Elevated housing / Retrofitting	4	3	0.75	0.75	0.75	Short-term/ Medium-term (1–2 y)	Singkil, Singkil Utara, Gunung Meriah, Simpang Kanan, Danau Paris, Suro Makmur, Kota Baharu, Kuala Baru, Singkohor	Public Works Department (PU)
NS3	Land-use zoning enforcement (RTRW)	2	5	0.25	1.00	0.63	Medium-term (3–5 y)	Singkil, Singkil Utara, Gunung Meriah, Simpang Kanan, Danau Paris, Suro Makmur, Kota Baharu	Bappeda and Spatial Planning Agency
NbS1	Wetland rehabilitation and conservation	3	3	0.50	0.50	0.50	Medium-term (3–5 y)	Singkil, Singkil Utara, Danau Paris, Kota Baharu, Kuala Baru	Environmental Agency (DLH)
S2	Drainage with tidal-control valves	3	3	0.50	0.50	0.50	Medium-term (3–5 y)	Singkil, Singkil Utara, Danau Paris	Public Works Department (PU)
S6	Retention ponds	3	3	0.50	0.50	0.50	Medium-term (3–5 y)	Singkil, Singkohor	Public Works Department (PU)
S5	Earthen levees	3	3	0.50	0.50	0.50	Medium-term (3–5 y)	Gunung Meriah, Simpang Kanan, Suro Makmur, Kota Baharu	Public Works Department (PU)
NbS3	Upstream watershed reforestation	3	2	0.50	0.25	0.38	Medium-term (3–5 y)	Singkil, Singkil Utara, Gunung Meriah, Simpang Kanan, Danau Paris, Suro Makmur, Kota Baharu, Kuala Baru, Singkohor	Forestry Department
S4	Permanent levees and pumping systems	2	3	0.25	0.50	0.38	Medium-term / Long-term	Singkil, Singkil Utara, Danau Paris	Ministry of Public Works and Housing
NbS2	Peatland rewetting and conservation	3	2	0.50	0.25	0.38	Medium-term (3–5 y)	Singkil, Danau Paris, Kota Baharu, Kuala Baru	Environmental Agency (DLH)
A2	Floating/amphibious housing pilots	2	2	0.25	0.25	0.25	Long-term (>5 y)	Singkil, Singkil Utara, Danau Paris	Ministry of Public Housing
S7	Large-scale retention and diversion canals	2	2	0.25	0.25	0.25	Long-term (>5 y)	Singkil	Ministry of Public Works and Housing



(a)



(b)



(c)

Fig. 5: Priority locations of flood mitigation interventions across different time periods in Singkil District : (a) Short-Term (1–2 Years), (b) Medium-Term (3–5 Years), and (c) Long-Term (>5 Years)

The intensification of hazards due to climate change could diminish the short-term viability of interventions that are technically intricate and require substantial capital investment, thereby underscoring the importance of IRI-based sequencing to adaptively synchronize implementation timing with evolving risks. Nonetheless, such measures remain essential for extreme flood scenarios and long-term resilience. Spatial patterns of phased interventions (Fig. 5) show clear prioritization shifts: immediate measures concentrate on regions with high visibility (e.g., Singkil, North Singkil) that necessitate swift, cost-effective solutions; medium-term approaches aim at areas that are consistently flooded by employing a combination of structural and ecosystem-oriented strategies; while long-term measures tackle regions that are critically vulnerable, demanding significant adaptation efforts. This confirms that flood risk management is an adaptive, staged governance process rather than a one-off optimisation. The proposed framework integrates hydrodynamic modelling, SMCE–AHP, and IRI into an iterative system using flood depth, duration, residential exposure, FRI, and IRI as monitoring indicators. Scheduled updates (every 3 to 5 years) and input from stakeholders facilitate ongoing improvements, with the possibility of extending to real-time applications via remote sensing, AI, and IoT. Methodologically, this integration addresses key gaps: hydrodynamic models capture hazard dynamics but lack decision context; SMCE–AHP supports spatial prioritization but remains static; and IRI introduces governance feasibility and temporal sequencing, linking “where” and “when” interventions occur. Empirical findings indicate a discrepancy between the severity of hazards and the preparedness of institutions, calling into question the belief that prioritizing risks leads directly to actionable measures (Dottori *et al.*, 2016; Kumar *et al.*, 2024; Luu *et al.*, 2021). High-risk peatland and coastal areas often face limited capacity, while some moderate-risk areas show higher readiness due to stronger governance alignment. Structural measures in such contexts may also generate ecological trade-offs (e.g., habitat loss, altered hydrology), highlighting the need to integrate nature-based solutions. The IRI-based sequencing enables balanced strategies by combining immediate structural responses with longer-term ecosystem-based interventions, explicitly accounting for trade-offs between effectiveness, environmental impact, and system sustainability. Furthermore, despite existing limitations (for instance, the lack of sensitivity analysis and the subjective aspects of IRI scoring), the framework facilitates a risk assessment that is geared towards practical implementation. The integrated nature of the framework supports its conceptual applicability to various coastal regions, although it requires calibration to accurately represent local environmental and governance conditions. For instance, urban settings require additional parameters (e.g., pluvial flooding, impervious surfaces), while centralized governance may reduce reliance on participatory weighting. Overall, the findings demonstrate that integrating hydrodynamic modelling, SMCE–AHP, and IRI provides a more operational approach to flood risk management in decentralized coastal systems such as Aceh Singkil. Unlike conventional approaches that rely on static prioritization (Dottori *et al.*, 2016; Kumar *et al.*, 2024; Luu *et al.*, 2021), this framework incorporates governance readiness, showing that flood risk is co-determined by physical processes and institutional capacity (Lo and Jim, 2021; Haque *et al.*, 2022). Its primary contribution lies in the incorporation of temporal and governance aspects via IRI-based sequencing, redirecting evaluation towards implementation-focused planning and broadening the concepts of extending adaptive flood management concepts (Opdyke *et al.*, 2025).

From spatial risk mapping to environmental governance

Spatial flood risk mapping improves identification of hazard intensity, exposure, and priority areas; however, previous studies show that these factors alone cannot explain implementation outcomes in decentralized systems (Dottori *et al*., 2016; Kumar *et al*., 2024). Contrary to assumptions of direct translation from prioritization to action (Luu *et al*., 2021), results reveal a persistent mismatch between hazard severity and institutional readiness, indicating that flood risk is co-determined by physical processes and governance capacity. This is especially crucial in coastal areas and peatland ecosystems that are situated at low elevations, where environmental susceptibility is exacerbated by institutional limitations, influencing both the efficacy and timing of interventions. The findings extend existing frameworks by embedding implementation pathways within spatial analysis. Empirically, the study demonstrates that identifying high-risk areas does not ensure implementable interventions. Locations with similar hazard intensity exhibit divergent readiness due to differences in institutional capacity, coordination, and financial resources. High-risk areas, usually located in physically susceptible coastal and peatland regions, frequently encounter considerable governance limitations, while moderate-risk zones might exhibit greater preparedness owing to enhanced administrative capacity and alignment with development programs. This reinforces that risk intensity alone is insufficient for prioritization; governance feasibility and timing are equally decisive. The identified discrepancy is influenced by a combination of physical and institutional elements, such as geomorphological exposure, infrastructure limitations, and resource constraints. Bridging this gap requires adaptive governance strategies, such as enhanced inter-agency coordination, improved financial access, and policy alignment. Short-term prioritization of low-cost, community-based, and nature-based interventions can deliver immediate benefits while building capacity for more complex measures. The readiness-based sequencing method tackles this issue by synchronizing hazard intensity with institutional viability, thus facilitating phased implementation pathways. By integrating governance conditions into spatial risk assessment, the framework transforms risk mapping into a more operational, adaptive, and policy-relevant decision-support system for decentralized flood management.

Readiness-based sequencing as a governance innovation

The readiness-based sequencing framework shifts flood risk planning from static prioritization approach to a decision-making process focused on implementation, taking into consideration institutional constraints. In decentralized contexts such as Aceh Singkil, implementation is shaped by limited capacity, fragmented mandates, financial uncertainty, and weak coordination, which are often overlooked in conventional MCDA and cost–benefit approaches. Therefore, cost–benefit analysis was not conducted because of insufficient data and the uncertainty surrounding the monetization of ecosystem benefits. Implementation readiness is influenced by governance structures, where overlapping responsibilities among BPBD, Public Works, Bappeda, and environmental agencies create coordination challenges. These factors were incorporated into the institutional capacity component of the IRI, capturing coordination, financial readiness, and feasibility, though political dynamics were not explicitly modelled.

Limitations

This study advances a governance-oriented framework for flood risk management while highlighting areas for improvement. The enhancement of hydrodynamic modeling, which relies on validated simulations, could be achieved through dynamic recalibration and uncertainty analysis under climate change. AHP weighting reflects stakeholder priorities but may benefit from sensitivity testing, broader participation, and data-driven approaches. Climate change was integrated using simplified scenarios; future efforts should incorporate downscaled projections to more accurately reflect compound flooding. The framework mainly addresses physical and institutional aspects, and could be strengthened by including socio-economic indicators. Applying the framework across diverse contexts would further improve its adaptability and broader applicability.

CONCLUSION

Flood risk management in low-lying coastal peatland systems requires not only robust hazard modelling but also governance-aligned strategies that integrate hazard intensity, stakeholder priorities, and institutional readiness. The SMCE–AHP–IRI framework offers a pragmatic approach to harmonizing technical analysis with implementation capabilities, thereby facilitating more realistic and adaptive flood risk reduction strategies in decentralized coastal systems. This study demonstrates that integrating hydrodynamic modelling with SMCE–AHP provides a robust basis for spatial flood risk assessment in complex coastal environments. Nevertheless, the evidence suggests that relying solely on hazard intensity does not adequately gauge the feasibility of interventions, exposing a significant misalignment between the severity of floods and the preparedness for implementation within decentralized environmental management systems. To address this gap, this study introduces IRI, which integrates governance capacity into spatial risk assessment. More importantly, the IRI enables a shift from conventional static prioritization toward a sequencing-based approach, where the timing of interventions is explicitly aligned with both hazard intensity and institutional capacity. By linking “where” interventions are most needed with “when” they can be realistically implemented, the proposed framework provides a more practical and governance-sensitive pathway for flood risk management. The findings further emphasize the significance of integrating structural (grey) solutions with NbS. While infrastructure interventions remain critical in high-risk areas, ecosystem-based approaches such as wetland restoration and peatland rewetting play a key role in enhancing long-term system resilience. The sequencing framework enables the execution of these measures in a coordinated and adaptive manner across different time horizons. The innovation of this study is in transforming feasibility from a ranking criterion into a sequencing mechanism within governance-oriented flood risk planning. This alters the approach to flood management, changing it from a static optimization challenge to a phased governance process. This integration enhances adaptive and context-specific flood risk management by allowing different types of interventions to respond to varying local conditions and constraints. Grey measures provide immediate protection in high-risk areas, while NbS support long-term ecological stability and system resilience. Within the phased framework, this combination guarantees that short-term risk mitigation is in harmony with long-

term sustainability, facilitating more adaptable, context-sensitive, and flexible responses in decentralized coastal systems. Conceptually, this study contributes to environmental management by demonstrating how spatial risk assessment can be integrated with governance-sensitive decision-making. The combined use of hydrodynamic modelling, participatory multi-criteria analysis, and readiness-based sequencing offers a transferable framework for other flood-prone regions, particularly in data-constrained and decentralized contexts. In governance structures that are more centralized, enhanced coordination can facilitate implementation and lessen dependence on participatory weighting. Therefore, although the framework is theoretically transferable, it must be adjusted to maintain its relevance across various socio-environmental and governance conditions. Overall, the framework contributes to bridging the gap between flood risk assessment and real-world decision-making by promoting adaptive, staged, and context-sensitive intervention planning under evolving environmental conditions. Ultimately, successful flood risk management relies not only on pinpointing the locations of hazards but also on assessing when and under what circumstances interventions can be executed.

AUTHOR CONTRIBUTIONS

D. Alfian conceived, designed, and conducted hydrodynamic modeling, as well as conducted fieldwork for primary flood data collection, and preparing the manuscript draft. E. Meilianda co-supervised the first author, contributed to methods and data analysis, paper draft review, and final revision. A. Ahmad supervised the first author and contributed to data analysis and reviewed the paper draft. M. Syukri also co-supervised the first author, contributed to data and output presentation, visualization, and results interpretation 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
1-D	1 – Dimension
2-D	2 – Dimension
A	Adaption
AHP	Analytic Hierarchy Process
a.s.l	Above SeaL Level
BAPPEDA	*Badan Perencanaan Pembangunan Daerah* (Regional Development Planning Agency)
BPBD	*Badan Penanggulangan Bencana Daerah* (District Disaster Management Agency)
BNPB	*Badan Nasional Penanggulangan Bencana* (National Disaster Management Agency)
BMKG	*Badan Meteorologi Klimatologi dan Geofisika* (Meteorological, Climatological and Geophysical Agency of Indonesia)
BWS	*Balai Wilayah Sungai* (River Basin Authority)
CAPI	Computer-assisted personal interviewing
CB	Community Based
CR	Consistency Ratio
DLH	*Dinas Lingkungan Hidup (Environmental* Agency)
ENSO	El Niño–Southern Oscillation
EWS	Early warning systems
FEMA	Federal Emergency Management Agency
FGD	Focus group discussions
FRI	Flood Risk Index
IOD	Indian Ocean Dipole
I	Innovation
IRI	Implementation readiness index
km	Kilometers
km^2	Square kilometer
M	Meter
Mm/y	Millimeter per year
MCDA	Multi-criteria decision analysis
NbS	Nature-based solutions
NS	Non-structural
PUPR	*Kementerian Pekerjaan Umum dan Perumahan Rakyat* ((MoPWH-Ministry of Public Works and Housing)
RIPBN	*Rencana Induk Pengendalian Banjir Nasional* (National Master Plan for Flood Control)
RPJMN	*Rencana Pembangunan Jangka Menegah Nasional* (Medium-Term National Development Plan)
RPBD	*Rencana Penanggulangan Bencana Daerah (*Regional Disaster Management Plan)
RTRW	*Rencana Tata Ruang Wilayah* (Regional Spatial Plan)
S	*Structural*
SMCE	Spatial multi-criteria evaluation
UNISDR	United Nations International Strategy for Disaster Reduction

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ORIGINAL RESEARCH ARTICLE

Provisioning ecosystem services through the sustainable management of fish resources extracted by small-scale fishers

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ABSTRACT

BACKGROUND AND OBJECTIVES: As an urban coastal, Jakarta Bay faces significant pressure from human activities. Such pressure might cause a decline in fish resources. The study objectives were to analyze the sustainability of small-scale fisheries in supporting the provisioning ecosystem services for coastal communities around Jakarta Bay.

METHODS: The study site was the Jakarta Bay area. Data were collected from informants' assessments of the relevance of using coastal and marine areas to ecological integrity and provisioning ecosystem services. Data pertaining to fisheries were acquired through a mix of field observations, direct measurements, and surveys. The data obtained encompassed the types of fish captured, the biomass of the fish, and the length and weight measurements for each fish. Primary data collection was conducted through six sampling sessions over three months. Length and weight measurements were taken during these sessions focusing on five main fish species: Planiliza subviridis, Osteomugil speigleri, Arius maculatus, Gerres filamentosus, and Scatophagus argus. Data analysis for mapping and assessing provisioning ecosystem services was conducted by assigning relevance scores to the capabilities of ecosystems of ecosystems. Fish data analysis included growth parameters, mortality and exploitation rates, and the spawning potential ratio.

FINDINGS: The evaluation of ecosystem service provisioning in Jakarta Bay reveals a favorable balance between supply and demand, with supply surpassing demand, especially in the areas of mangroves, aquatic environments, and marine resources. A total of 63 fish species were recorded at two fish landing sites. The population of Planiliza subviridis indicated that it is overfished, with exploitation rate value of 0.57. The spawning potential ratio of 0.15. The fishing mortality and natural mortality ratio values are 1.33 (length-converted catch curve) and 1.21 (Length-based potential ratio model), both exceeding the threshold of 1.0.

CONCLUSION: Jakarta Bay provides ecosystem services to surrounding communities, particularly those in coastal areas. The fishery stock status of Planiliza subviridis indicates overexploitation. Consequently, it is essential to implement effective fisheries management strategies to secure sustainability and the best delivery of ecosystem services in Jakarta Bay.

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INTRODUCTION

Jakarta Bay provides vital ecosystem services (ESs) to surrounding communities, which depend on fish resources for their daily consumption. Jakarta Bay, covering approximately 7,000 square kilometers (km^2) (Nugraha *et al.,* 2020), possesses significant potential in fisheries and marine resources. This potential is allocated throughout the coastal and marine ecosystems of Jakarta Bay (Patawari *et al.,* 2022), which encompass estuaries, coral reefs, and mangroves (Nugraha *et al.,* 2020). This ecosystem creates resources that can be employed by the community. For instance, the average fish biomass in Jakarta Bay is estimated at approximately 11,400 kilograms per square kilometers (kg/km^2) (Wagiyo, 2021). The highest fish stock density is in the Seribu Islands at 25,500 kg/km^2 (Nugraha *et al.,* 2020). These fish resources have the potential to aid in sustaining food security for the communities in the vicinity of Jakarta Bay. In particular, local communities demonstrate a high level of economic and nutritional dependence on dominant species in Jakarta Bay. One example is *Planiliza subviridis*, which serves as an affordable source of animal protein for coastal communities (Susilowati *et al.,* 2024). Consequently, the catches from Jakarta Bay, notably *P. subviridis*, are a significant source of income for fishermen's households and contribute to their daily food needs. This strong dependence can increase fishing pressure on certain dominant species (Susilowati *et al.,* 2024), particularly due to limited alternative livelihoods. As a result, the risk of overexploitation may increase if effective management measures are not implemented (Pauly and Zeller, 2016; FAO, 2020; Susilowati *et al.,* 2024). As an urban coastal area, Jakarta Bay faces high pressure from human activities (Sofian *et al.,* 2020). This pressure impacts marine regions, encompassing pollution, land reclamation, tourism, and fishing. Pollution, eutrophication, habitat degradation, and coastal development can significantly impact the condition of fish resources and the provision of ESs. The integrity and sustainability of ecosystems are compromised by pollution, particularly due to heavy metal contamination, which is a specific hazard that requires diligent oversight. Coastal reclamation also has several negative impacts, such as coastal ecosystems disruption, increased sedimentation rates (Azis *et al.,* 2022), increased potential for flooding, marine pollution, and degradation of fisheries productivity (Patawari *et al.,* 2022). The pressures on the environment influence water quality and contribute to the deterioration of important habitats like mangroves, estuaries, and coral reefs (Ault *et al.,* 2018). These ecosystems are indispensable as they serve as feeding, spawning, and nursery grounds (Guerreiro *et al.,* 2021; Yuliana *et al.,* 2024a; Carranza *et al.,* 2021). Such impacts can lead to a decline in fish abundance, shifts in species composition (Yuliana *et al.,* 2017), and ultimately a reduced capacity of ecosystems (Mujiyanto *et al.,* 2023) to provide services to coastal communities. A variety of fisheries governance structures and regulatory measures has been established to facilitate sustainable management, encompassing the ecosystem approach to fisheries management (EAFM), licensing regimes, and co-management (Yuliana *et al.,* 2019). These mechanisms are designed to regulate fishing pressure, curb resource overexploitation, and enhance the long-term sustainability of fisheries. Nonetheless, the execution of these measures has produced varied results owing to ongoing difficulties, including insufficient enforcement, prevalent illegal, unreported, and unregulated (IUU) fishing practices, restricted access to dependable fisheries data, and poor collaboration among stakeholder groups (Campbell *et al.,* 2021; FAO, 2020). Moreover, a significant share of small-scale fisheries operating in Jakarta Bay demonstrates low compliance with existing regulations and frequently operates without formal licensing (Halim *et al.,* 2020). Climate-related stressors, including increasing sea surface temperatures,

ongoing sea-level rise, and more frequent and intense extreme weather events, are increasingly recognized as structural drivers shaping marine ecosystem dynamics and fisheries outcomes (Kaczan *et al.,* 2023). These processes are anticipated to affect reproductive success and diminish overall fisheries productivity, with unequal effects noted in tropical coastal systems. In highly urbanized and environmentally pressured settings such as Jakarta Bay, climate change is likely to interact with existing human-induced stressors, amplifying ecological risks and further complicating fisheries governance and management responses (Cinner *et al.,* 2022; Kaczan *et al.,* 2023). In order to ensure ESs sustainability, the fisheries potential and pressures in the coastal and marine areas of Jakarta Bay must be accurately assessed to prevent ecological and economic losses (Bekova *et al.,* 2019). Subsequent studies have demonstrated that the application of an ecosystem approach to fisheries management (EAFM) facilitates the balancing of ecological and economic considerations (Yuliana *et al.,* 2020a). In addition, assessment of the balance of ESs can be evaluated through ESs mapping, which includes ecosystem supply, demand, and overall ecosystem balance (Burkhard *et al.,* 2012). ESs can be evaluated based on ecosystem functions, including provisioning, regulating, habitat functions (Lavialle, 2023; Burkhard *et al.,* 2014; Costanza *et al.,* 2017), supporting, and cultural services (Anand and Gupta, 2020). The provision of ESs for society is significantly shaped by human endeavors, especially modifications in land use intended to fulfill societal requirements (Burkhard *et al.,* (2009). Provisioning ESs play a crucial role in supporting human well-being and survival, and provisioning ESs also contribute to the national economy, as reflected in the recently introduced valuation system (Anand and Gupta, 2020). Provisioning ESs contribute to human well-being through nutrient cycling, fisheries, climate regulation, and natural disaster protection (Liquete *et al.,* 2013). Conversely, ESs demonstrate a notable relationship with the level of human disturbance in China's Guangdong–Hong Kong–Macao Greater Bay Area (He *et al.,* 2021). To minimize human interference, it is essential to incorporate ESs into regional policies and conservation initiatives (Schlemm *et al.,* 2025). Coastal bays are vital for ecological health and socio-economic stability, owing to their rich biodiversity and dense human populations (Liquete *et al.,* 2013). In the Baltic Sea, ESs mapping has effectively identified regions positively linked to fisheries provisioning services (Inácio *et al.,* 2024). Similarly, mangrove ESs on Rimau Island, which serve as fish habitats, demonstrate a balanced provision and demand for ESs (Yuliana *et al.,* 2020b). The previous studies also suggest that monitoring the sustainability of fish resources can be conducted in several ways, such as measuring the length and weight of fish caught to analyze the length-weight relationship (Mehanna and Farouk, 2021), and assessing fish stock structure (Yuliana *et al.,* 2024b). The size composition of the catch illustrates the progression of fish size over the years. The observed decline in fish size structure indicates a deterioration of fish resources. The novelty of this study lies in its integration of ESs assessment with species-based fisheries stock analysis, an approach that has rarely been applied simultaneously in previous research. This framework creates a direct relationship among biophysical indicators, fish stock assessments, and provisioning ESs, enabling a deeper comprehension of the social–ecological system (Chong *et al.,* 2020). By combining ESs mapping with fisheries sustainability indicators, the study offers a holistic and ecosystem-centered perspective on how small-scale fisheries both depend on—and actively influence—the long-term resilience of provisioning ESs. This approach provides a new scientific foundation for ecosystem-based policymaking that aligns livelihoods, food security, and ecosystem integrity within urban coastal systems. The objectives of this study are to examine the sustainability of

small-scale fisheries in their role in providing ESs for coastal communities in the vicinity of Jakarta Bay. The results can serve as a basis for authorities in formulating policies and recommendations for sustainable fisheries management. This study has been conducted in Jakarta Bay, Indonesia, from 2025 to 2026.

MATERIALS AND METHODS

Research Approach

This research was conducted by combining methods used by Burkhard *et al.* (2014) and Inácio *et al.* (2024), focusing on fisheries provisioning ESs. This study integrates the matrix-based ecosystem service capacity framework of Burkhard *et al*. (2009) with selected marine ecological assessment elements from Inácio *et al.* (2024) to evaluate fisheries provisioning ESs. The framework established by Burkhard *et al*. (2012) serves as the conceptual foundation for evaluating the supply capacity of ESs, whereas biophysical indicators related to fisheries, modified from Inácio *et al*. (2024), are employed to describe marine ecosystems. Spatial mapping is not applied; the assessment focuses on evaluating fish stock status as an indicator of fisheries provisioning capacity. This approach offers a concise, ecosystem-based assessment framework to support sustainable fisheries management. In this study, the approach proposed by Burkhard *et al.* (2014) is applied as the core conceptual framework for structuring and assessing ESs supply capacity, while the method developed by Inácio *et al.* (2024) is adopted to operationalize the assessment within a marine context, particularly for evaluating fisheries provisioning services. The combination of these methods leads to a standardized assessment framework based on ecosystems, which highlights the ability of marine ecosystems to sustain fisheries, thereby making it appropriate for analyses related to coastal and marine planning and resource management analyses.

Study area

The study site was the Jakarta Bay area, with data collection points located in Tarumajaya District, Bekasi Regency, and Cilincing, North Jakarta (Fig. 1). Sampling sites were identified utilizing a purposive, spatially focused stratified sampling strategy. The Jakarta Bay area was divided into several strata according to gradients of anthropogenic pressure and ecological conditions, including mangrove cover, water quality, and sedimentation levels. The two locations were selected to represent the ecological and socioeconomic variability of Jakarta Bay. Cilincing illustrates estuarine and urban fisheries that are subjected to significant anthropogenic pressure, while Segarajaya exemplifies mangrove-associated, semi-natural environments. Together, they capture the mangrove–estuary–open coastal continuum relevant to provisioning ESs. Catches from West Jakarta Bay were excluded because they are mixed with landings from distant fishing grounds in the Java Sea, reducing their representation of local ecological conditions.

Data Collection

The data collected are in the form of primary and secondary data. The variables and instruments for ESs refer to the instruments developed by Burkhard *et al.* (2009) and Inácio *et al.* (2024). Data were obtained from informants' judgments on the importance of employing coastal and marine areas to ecological integrity and provisioning ESs (Schlemm *et al.,* 2025). Informants were selected using a combination of purposive and snowball sampling techniques. The criteria for selection encompassed direct participation in the utilization of coastal resources (such as fishers, aquaculture practitioners, and coastal business representatives), familiarity with local environmental changes, and the inclusion of a variety of stakeholders, which comprised local government and coastal communities. This approach enabled the collection of

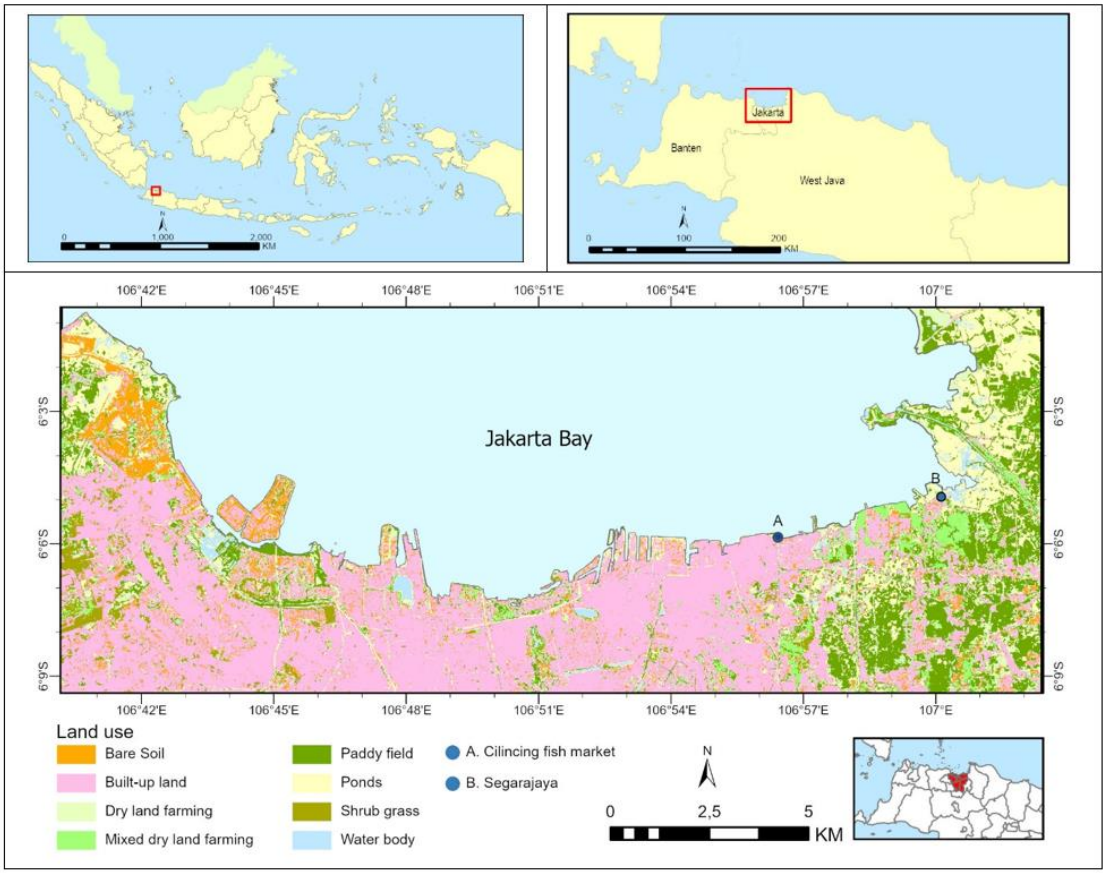


Fig. 1: Geographical location of the study area in the coastal and marine areas of Jakarta Bay, Indonesia

comprehensive information on human–environment interactions within the study area. ESs assessment data were provided by six resource individuals such as lecturers, researchers, and non-governmental organization (NGO) representatives, who are familiar with the coastal and marine characteristics of Jakarta Bay. The assessment used a 0–5 scale (0 = irrelevant; 1 = low relevance; 2 = relevant; 3 = moderate relevance; 4 = high relevance; 5 = very high relevance) for each combination of land-cover class and ecosystem service type (ecological integrity and provisioning ESs). Relevance scores for ESs provisioning were formulated using a comprehensive approach that integrates biophysical and socio-economic indicators alongside spatial analysis in the Jakarta Bay area. These relevance scores were designed to represent the relative importance and contribution of provisioning ESs to local communities. The development process involved normalizing indicators to a standardized scale (e.g. 1–5) to facilitate comparability among variables, succeeded by the weighting of indicators derived from a blend of literature review, expert assessment, and stakeholder viewpoints. The analytical framework was guided by the ESs concept of the Millennium Ecosystem Assessment, with adjustments to reflect local conditions. The indicators utilized encompassed biophysical factors, including the potential of fish stock potential, water quality, and the scope and

state of supporting habitats, including mangroves and coastal waters. To minimize sampling and perception bias, several data quality control measures were applied. These included spatial stratification to ensure representation across environmental gradients, data triangulation through the combination of field observations and interviews, and the standardization of semi-structured interview tools to improve consistency. The purpose of data collection for the management of fishery resources is to gather information that includes biophysical, spatial, social, and policy dimensions pertinent to coastal and marine ESs in Jakarta Bay. Data were collected through a combination of field observations, direct measurements, and surveys. The data collected included the species of fish caught, fish biomass, and the length and weight of each fish. The initial gathering of fish data took place during six sampling sessions aimed at recording all fish catch statistics. One limitation of this study is that data collection was conducted over a three-month period, which does not adequately represent seasonal variability (dry and wet seasons) within a full year. Future studies should thus guarantee that sampling encompasses various seasons to more effectively consider seasonal dynamics. Length and weight measurements were conducted in six sampling sessions focusing on five main fish species caught, namely: *P. subviridis*, *O. speigleri*, *A. maculatus*, *G. filamentosus*, and *S. argus*. These species have been prioritized owing to their prevalence in Jakarta Bay fisheries, characterized by relatively short life spans and swift growth rates, which facilitate the detection of their population dynamics detectable within shorter sampling durations. Secondary data were obtained from several fisheries agencies, and statistical data were obtained from the Ministry of Maritime Affairs and Fisheries (MMAF) of the Republic of Indonesia. The data collected were the number of catches of 10 dominant fish species over the past five years (from 2019 to 2023). To achieve precise and representative data, multiple data collection techniques were employed, customized to suit the specific attributes of each data type. Data were collected using the following techniques and procedures:

1. A stratified random sampling method was employed for fish sampling at the primary fishing sites to guarantee adequate representation of different habitats and types of fishing gear.
2. The total sample size comprised 1,073 individuals across five dominant species. Species identification followed Food and Agricultural Organization (FAO) taxonomic guidelines for tropical marine fishes, ensuring accuracy and consistency.
3. Fish length and weight measurements were taken using rulers and digital scales to obtain accurate biometric data.
4. Observations conducted in the field were employed to pinpoint anthropogenic activities, assess the state of ecosystems, and analyze the relationships between humans and the surrounding environment.

Data analysis

Provisioning ESs mapping

Data analysis for mapping and assessing provisioning ESs in Jakarta Bay follows the method used by Burkhard *et al.* (2009). The assessment entailed the allocation of relevance scores to the functions of coastal and marine ecosystems in delivering ESs, predicated on the utilization of coastal and marine regions. The assessment results are displayed in a bar chart, with color gradients indicating the level of relationship in provisioning ESs.

Life-history parameters and fisheries utilization conditions

The study focusing on life-history parameters and the state of fisheries stocks was undertaken to gain insights into the biological status and extent of exploitation of fish resources in Jakarta Bay. *P. subviridi*s was the most dominant species, with 341 individuals, followed by *S. argus* (204), *G. filamentosus* (202), *O. speigleri* (186), and *A. maculatus* (140).

1. Fish length distribution and length-weight relationship analysis

Fish length distribution was statistically analyzed to determine the dominant size, length range, and population size distribution. Differences in fish length between locations and species were tested using analysis of variance (ANOVA), with location and species as fixed factors, and their interaction included in the model. In instances where the assumptions of normality and homogeneity of variance for ANOVA were not satisfied, Mann–Whitney U tests were employed to assess the median lengths between locations for each species, conducted individually in R (Roberts, 2026). The length-weight relationship (LWRs) was analyzed using a regression model, using Eq. 1 Froese *et al.,* (2014):

$$W = aL^b \quad (1)$$

where: W = fish weight in grams (g); L = fish length in centimeters (cm); a = regression constant; b = growth exponent. The b value is used to determine the growth type. To test the model's suitability to the actual data, a chi-square test was performed between the actual weights and the scaled-down predicted weights.

2. Growth parameters

Fish growth parameters were analyzed using the Von Bertalanffy Growth Function (VBGF) model to describe fish length growth over time, using Eq. 2 (Sparre and Venema, 1998):

$$L_t = L_\infty\left(1 - e^{-k(t-t_0)}\right) \quad (2)$$

where: L_t = length of fish at age; L_∞ = asymptotic length; k = growth coefficient; t_0 = theoretical age at zero length. Growth parameters were estimated using the electronic length frequency analysis (ELEFAN) approach, method, particularly the ELEFAN genetic algorithm (ELEFAN-GA) executed in R. ELEFAN-GA was based on its superior ability to optimize the matching of growth curves to length-frequency data, achieving greater accuracy and efficiency compared to traditional techniques, thereby yielding the highest ELEFAN score (Rn_max) value as an indicator of the quality of the curve fit (Pauly, 1980; Taylor and Mildenberger, 2017).

3. Mortality and exploitation

Mortality and exploitation rate analyses were conducted to assess fishing pressure on fish stocks. The three main components analyzed were natural mortality (M), total mortality (Z), and fishing mortality (F). Z values were calculated using the Length Converted Catch Curve method (Sparre and Venema, 1998). This approach utilizes length-frequency data that has been transformed into age estimates, subsequently applying logarithmic regression to the cumulative catch frequency for age groups that have reached full catch size. M values were calculated using an empirical approach that evaluates various M estimation methods based on data from more than 200 fish species (Then *et al.,* 2015). F values and exploitation rates (E) were estimated using Eqs. 3 and 4 (Sparre and Venema, 1998):

$$F = Z - M \quad (3)$$

$$E = \frac{F}{Z} \quad (4)$$

where: an E value greater than 0.5 indicates that the stock is under high fishing pressure and has the potential to experience overfishing (Gulland, 1971).

4. Length-based potential ratio (LBSPR)

Analyzing the Spawning Potential Ratio (SPR) is a significant strategy in fish stock evaluation, which assesses the relative reproductive potential of populations that are being exploited. The LBSPR method is utilized for the estimation of SPR (Hordyk *et al.,* 2015). This model integrates biological parameters such as asymptotic length (L_∞), growth rate (K), natural mortality (M), and the lengths at which 50 percent (%) and 95% of individuals reach gonad mortality (L_{50} and L_{95}). SPR is calculated by comparing the remaining adult biomass under current fishing mortality (F) with

the adult biomass in an unfished population. SPR values range from 0 to 1 and are used as a biological reference point to assess stock exploitation status. If SPR < 0.2, it means the population is highly stressed and at risk of recruitment decline (Hordyk *et al.,* 2015).

RESULTS AND DISCUSSION

Provisioning ESs and ecological integrity

The ESs mapping based on expert assessments indicates that the supply capacity of provisioning ESs in Jakarta Bay is predominantly characterized by low to moderate relevance values (1–2), with only limited instances of irrelevance (Table 1). A significant relevance (value 5) is specifically identified for capture fisheries resources in mangrove and marine/ocean ecosystems, while crop yield provisioning exhibits a comparably strong link to wetland agriculture (Indrayanthi *et al.,* 2015). Demand assessment reveals very high relevance for biodiversity-related ecological integrity in mangrove and marine ecosystems only, reflecting strong societal dependence on these habitats (Table 2). Balance analysis shows that demand exceeds supply in certain land-use categories, particularly fishing boat harbors and energy-related uses, demand outstrips supply. In contrast, capture fisheries resources and aquaculture in marine ecosystems exhibit moderately positive balances (Table 3). Overall, provisioning ESs associated with capture fisheries exhibit moderately favorable but vulnerable conditions across mangrove, estuarine, and marine systems, highlighting the critical role of habitat availability in sustaining fishery resources and underscoring the need for effective habitat conservation to support long-term fisheries sustainability in Jakarta Bay (Medeiros-Leal *et al.,* 2023). A limitation of this study is the limited number of informants, which includes six experts. Future studies ought to include a more extensive group of experts, adequate respondents, and a wider participatory framework. These enhancements would aid in reducing possible bias and facilitate a more equitable and proportional understanding of the outcomes.

Table 1: Assessment matrix for capacity (supply) of coastal and marine ESs in Jakarta Bay

Use of coastal and marine areas	Ecosystem services (ESs)							
	Ecological Integrity		Provisioning ESs					
	Abiotic diversity	Biodiversity	Capture fish resources	Aquaculture	Livestock	Crop yields	Wood fuel	Energy potential
Residential settlements	1	2	1	1	2	2	1	0
Tourism/recreation	3	4	2	1	1	1	1	0
Mangrove	3	4	5	3	1	3	4	3
Fishpond	2	3	2	4	1	0	0	0
Freshwater body	3	3	3	4	2	2	1	3
Fishing boat harbor	1	1	2	2	1	1	0	0
Wetland farming	2	2	0	1	1	5	1	1
Dryland farming	2	2	0	1	3	4	3	1
Swamp	2	4	3	3	1	2	2	2
Bushes/empty land	2	3	0	0	3	2	2	0
Estuary	2	4	4	3	1	2	1	3
Marine/ocean	2	4	5	3	1	0	0	4

0	Not relevant
1	Low relevance
2	Relevant
3	Medium relevance
4	High relevance
5	Very high relevance

Table 2: Assessment matrix for demand for coastal and marine ESs in Jakarta Bay

Use of Coastal and Marine Areas	Ecosystem services (ESs)							
	Ecological Integrity		Provisioning ESs					
	Abiotic diversity	Biodiversity	Capture fish resources	Aquaculture	Livestock	Crop yields	Wood fuel	Energy potential
Residential settlements	1	2	1	2	2	2	2	2
Tourism/recreation	2	3	2	2	2	2	1	1
Mangrove	4	5	3	2	1	2	3	2
Fishpond	2	3	3	3	1	1	1	1
Freshwater body	1	3	2	2	2	1	1	2
Fishing boat harbor	2	1	3	2	1	1	1	3
Wetland farming	3	3	1	1	1	3	1	1
Dryland farming	3	3	0	0	2	3	2	2
Swamp	3	4	3	2	1	2	2	2
Bushes/empty land	1	2	0	0	3	2	2	1
Estuary	3	4	3	3	1	1	0	2
Marine/ocean	3	5	4	2	1	0	0	3

0	Not relevant
1	Low relevance
2	Relevant
3	Medium relevance
4	High relevance
5	Very high relevance

Table 3: Matrix for assessing the balance of supply and demand for coastal and marine ESs in Jakarta Bay

Use of Coastal and Marine Areas	Ecosystem Services (ESs)							
	Ecological Integrity		Provisioning ESs					
	Abiotic diversity	Biodiversity	Capture fish resources	Aquaculture	Livestock	Crop yields	Wood fuel	Energy potential
Residential settlements	0	0	0	0	-1	-1	-1	-2
Tourism/recreation	1	0	0	-1	-1	-1	-1	-1
Mangrove	-1	0	1	1	1	1	1	1
Fishpond	0	-1	0	1	0	-1	-1	-1
Freshwater body	2	1	1	1	0	1	0	1
Fishing boat harbor	-2	0	-1	0	-1	0	-1	-3
Wetland farming	-1	-1	-1	0	0	2	0	-1
Dryland farming	-1	-1	0	0	1	2	2	-1
Swamp	-1	0	1	1	0	0	0	-1
Bushes/empty land	1	1	0	0	0	0	0	-1
Estuary	0	-1	1	1	0	0	0	1
Marine/ocean	0	-1	2	2	0	0	0	1

-5	Demand	1	Supply
-4	Exceeds	2	Exceeds
-3	Supply	3	Demand
-2		4	
-1		5	

Fish diversity

Fish diversity is an indicator of the sustainability of fish resources. A total of 63 fish species were found at the research sites (Segarajaya and Cilincing), including both pelagic and demersal species (Table 4). The fish species identified at the research locations originated from various habitats: coastal waters, estuaries, rivers, coral reefs, mangroves, and brackish waters. Based on data from the MMAF, several fish species found at the Segarajaya and Cilincing fish markets (Table 4) were also among the top 10 catches in Bekasi Regency from 2019 to 2023 (Table 5). Among the coastal and estuarine fish species, *P. subviridis* and *S. argus* were consistently caught each year in relatively stable numbers, showing an overall increasing trend. Based on the data in Tables 4 and 5, this study focuses on five dominant species at the research site: *P. subviridis*, *O. speigleri*, *A. maculatus*, *G. filamentosus*, and *S. argus*. The fishing operations observed at the study sites were largely influenced by lift nets and gillnets, both of which featured a mesh size of approximately 1 inch. This relatively fine mesh results in low selectivity, increasing the likelihood of capturing juvenile fish and non-target species.

Fish length and weight distribution

Fish length distribution (Table 6) is an important indicator for understanding the population structure and growth patterns of captured species. This analysis was carried out on the five leading species at the site of study, obtained by fishermen in coastal and estuarine environments. A boxplot of fish length and weight (Fig. 2) shows that *A. maculatus* had the highest average length and weight. *P. subviridis* had the widest length range, with outliers above 35 cm, suggesting the presence of rarely captured adults. In contrast, *G. filamentosus* and *S. argus* had narrower and more homogeneous length distributions, indicating relatively uniform population sizes. *P. subviridis* and *A. maculatus* had higher median and maximum weights than the other species. The lengths of the five main species caught at two sites, Cilincing and Segarajaya, exhibited variations (Fig. 3). *P. subviridis* in Cilincing had higher median and maximum lengths than those in Segarajaya. This points to the possibility that the individuals located in Cilincing were larger, which could signify a more beneficial habitat for growth or diminished fishing pressure on adults. Statistical testing confirmed these observations with ANOVA revealed significant differences in fish length for the *P. subviridis* between locations (p-value < 0.001). Post-hoc Mann–Whitney U tests further showed that only *P. subviridis* exhibited a significant difference between locations (W = 3251, p-value < 0.01), while other species showed not differ significantly (p-value > 0.001). These results suggest that the variation in fish size is specific to each species, with *P. subviridis* particularly sensitive to ecological and anthropogenic factors, whereas *O. speigleri, A. maculatus, S. argus, and G. filamentosus* exhibited a more consistent size structures across locations.

Fish length-weight relationship

An analysis of the length-weight relationship was performed based on the length and weight data of five species. All species showed a statistically significant relationship ($p < 0.001$) (Table 7), with a high chi-square value, indicating that the regression model fits the field data (Fig. 4). The five species, namely *P. subviridis*, *O. speigleri*, *A. maculatus*, *S. argus*, and *G. filamentosus*, showed an allometric growth pattern, indicating disproportionate growth between length and weight. According to the chi-square test, which yielded a p-value of < 0.05, the growth pattern is classified as negative allometric. In this type of growth, the increase in length surpasses the increase in weight, resulting in a more slender body shape for the fish.

Table 4: List of fish species found at Segara Jaya and Cilincing fish market

Family	Species	Habitat	Segarajaya	Cilincing
Rajidae	*Rajidae* sp.	Coastal waters	Y	-
Dasyatidae	*Dasyatis* sp.	Coastal waters, estuary	-	Y
Elopidae	*Elops hawaiiensis*	Coastal waters, estuary	Y	Y
Megalopidae	*Megalops cyprinoides*	Coastal waters, estuary	Y	Y
Engraulidae	*Engraulis* sp.	Coastal waters	Y	Y
Chirocentridae	*Chirocentrus* sp.	Coastal waters, estuary	-	Y
Chanidae	*Chanos chanos*	Coastal waters, estuary	Y	Y
Ariidae	*Arius maculatus*	Coastal waters, estuary	Y	Y
Ariidae	*Hexanematichthys sagor*	Coastal waters, estuary	Y	Y
Ariidae	*Netuma thalassina*	Coastal waters	Y	-
Ariidae	*Osteogeneiosus militaris*	Coastal waters, estuary	Y	-
Hemibagridae	*Mystus* cf. *gulio*	Estuary, river	Y	-
Plotosidae	*Plotosus canius*	Coastal waters, estuary	-	Y
Mugilidae	*Liza* sp.	Coastal waters, estuary	Y	Y
Mugilidae	*Planiliza subviridis*	Coastal waters, estuary	Y	Y
Mugilidae	*Osteomugil speigleri*	Coastal waters, estuary	Y	Y
Belonidae	*Tylosurus crocodylus*	Pelagic, coastal waters	Y	Y
Hemiramphidae	*Hyporamphus quoyi*	Coastal waters	Y	Y
Latidae	*Lates calcarifer*	Coastal waters, estuary	Y	Y
Serranidae	*Epinephelus* sp.	Coral reef	-	Y
Sillaginidae	*Sillago sihama*	Coastal waters, estuary	Y	Y
Carangidae	*Carangoides* sp.	Coastal waters	-	Y
Carangidae	*Decapterus* sp.	Pelagic, coastal waters	-	Y
Carangidae	*Elagatis bipinnulata*	Pelagic	Y	Y
Carangidae	*Parastromateus niger*	Pelagic, coastal waters	-	Y
Carangidae	*Scomberoides tol*	Coastal waters	-	Y
Carangidae	*Scomberoides* sp.	Coastal waters	Y	-
Leiognathidae	*Leiognathus* sp.	Coastal waters	Y	Y
Lutjanidae	*Lutjanus fulviflamma*	Coral reef, mangrove	Y	Y
Caesionidae	*Caesio cuning*	Coral reef	-	Y
Gerreidae	*Gerres filamentosus*	Coastal waters, estuary	Y	Y
Haemulidae	*Pomadasys kaakan*	Coastal waters, estuary	Y	Y
Nemipteridae	*Nemipterus hexodon*	Demersal, benthic	-	Y
Nemipteridae	*Nemipterus* cf. *marginatus*	Demersal, benthic	-	Y
Polynemidae	*Eleutheronema tetradactylum*	Coastal waters, estuary	Y	Y
Sciaenidae	*Johnius carouna*	Coastal waters, estuary	Y	Y
Drepanidae	*Drepane punctata*	Coastal waters, estuary	-	Y
Terapontidae	*Terapon jarbua*	Coastal waters, estuary	Y	Y
Terapontidae	*Terapon theraps*	Coastal waters, estuary	Y	Y
Cichlidae	*Oreochromis mossambicus*	Brackish waters	Y	Y
Cichlidae	*Mayaheros urophthalmus*	Brackish waters	Y	-
Gobiidae	*Glossogobius* cf. *biocellatus*	Estuary	Y	-
Scatophagidae	*Scatophagus argus*	Coastal waters, estuary	Y	Y
Siganidae	*Siganus javus*	Coastal waters, estuary	Y	Y
Siganidae	*Siganus guttatus*	Coastal waters, estuary	Y	-
Sphyraenidae	*Sphyraena jello*	Estuary, murky waters	Y	Y
Trichiuridae	*Trichiurus lepturus*	Pelagic, benthic	-	Y
Scombridae	*Euthynnus affinis*	Pelagic	Y	Y
Scombridae	*Katsuwonus pelamis*	Pelagic	Y	Y
Scombridae	*Sarda orientalis*	Pelagic	-	Y
Scombridae	*Thunnus albacares*	Pelagic	-	Y
Scombridae	*Rastrelliger* sp.	Epipelagic	Y	Y
Paralichthyidae	*Pseudorhombus arsius*	Demersal	-	Y
Soleidae	*Pardachirus pavoninus*	Demersal	-	Y
Cynoglossidae	*Paraplagusia bilineata*	Demersal	Y	Y
Synbranchidae	*Monopterus* cf. *javanicus*	Estuary, mangrove	Y	-
Penaeidae	*Penaeus monodon*	Demersal, benthic	Y	Y
Penaeidae	*Penaeus merguiensis*	Demersal, benthic	Y	Y
Penaeidae	*Penaeus semisulcatus*	Demersal, benthic	Y	-
Penaeidae	*Penaeus* sp.	Demersal, benthic	Y	-
Portunidae	*Portunus pelagicus*	Demersal, benthic	-	Y
Mytilidae	*Perna viridis*	Demersal, benthic	Y	Y
Veneridae	*Meretrix meretrix*	Demersal, benthic	Y	-

Notes: Y = found; - = not found

Table 5: Production data of the 10 largest main fish catches in study site (2019-2023) from MMAF data

Species	Fish productions (tons)					Total (tons)
	2019	2020	2021	2022	2023	
Planiliza subviridis	240	227	325	343	356	1,491
Arius maculatus	204	64	47	50	53	418
Scatophagus argus	191	195	276	284	300	1,246
Portunus pelagicus	886	868	422	412	429	3,017
Penaeus sp.	420	236	380	395	415	1,846
Chanos chanos	289	256	368	414	423	1,750
Rastrelliger sp.	643	584	594	629	663	3,113
Loligo sp.	602	612	344	360	379	2,297
Lates calcarifer	1.055	519	380	396	407	2,757
Eleutheronema tetradactylum	698	498	278	288	301	2,063

Table 6: Distribution of dominant fish lengths in study site

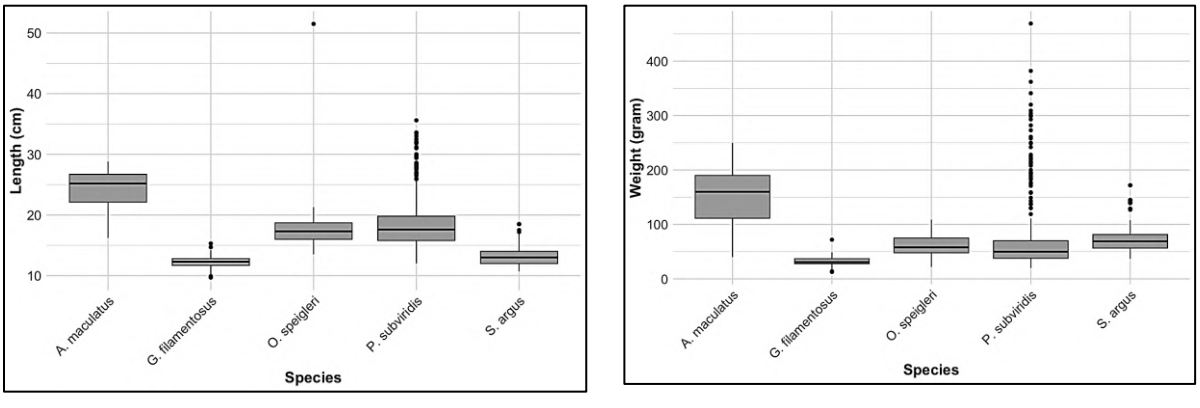
Species	n (ind)	Average length (cm)	Standard deviation	Fish Length min (cm)	Fish Length max (cm)
Planiliza subviridis	341	18.6	4.45	12.00	35.60
Osteomugil speigleri	204	17.4	2.97	13.50	21.30
Arius maculatus	140	24.4	3.10	16.20	28.80
Gerres filamentosus	202	12.2	0.89	9.70	15.30
Scatophagus argus	204	13.3	1.69	10.70	18.50

Notes: n = number of individuals; min = minimum; max = maximum

Table 7: Length-weight relationship of the five dominant fish species at the study site

Species	a	b	chi-square	p-value
Planiliza subviridis	0.1903	1.9488	151.76	<0.001
Osteomugil speigleri	0.0193	2.8206	202.30	<0.001
Arius maculatus	0.0940	2.3126	112.70	<0.001
Gerres filamentosus	0.3443	2.0538	232.58	<0.001
Scatophagus argus	0.0436	2.6312	102.43	<0.001

Notes: a = regression constant; b = growth exponent



(a) (b)

Fig. 2: (a) Boxplot of length (cm); (b) weight (g) of five dominant fish

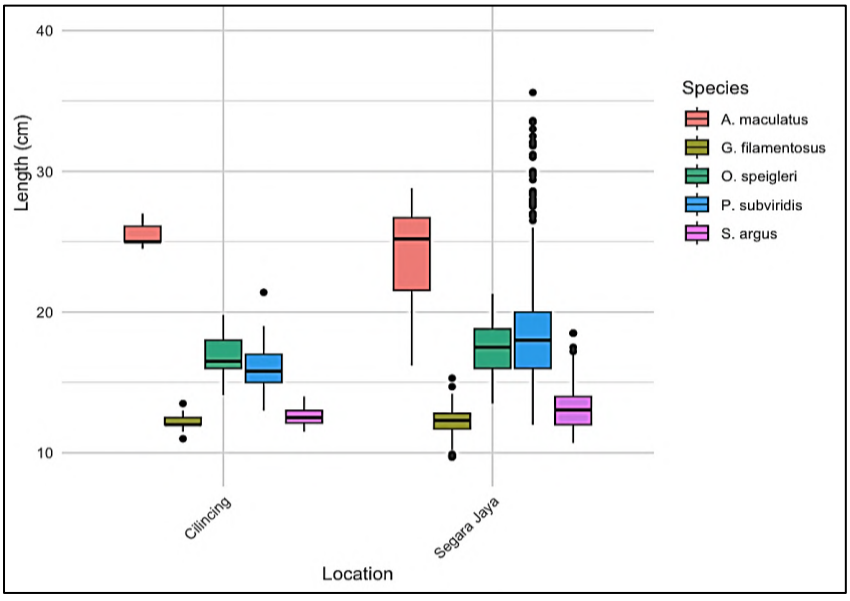


Fig. 3: Boxplot of dominant fish size based on data collection location

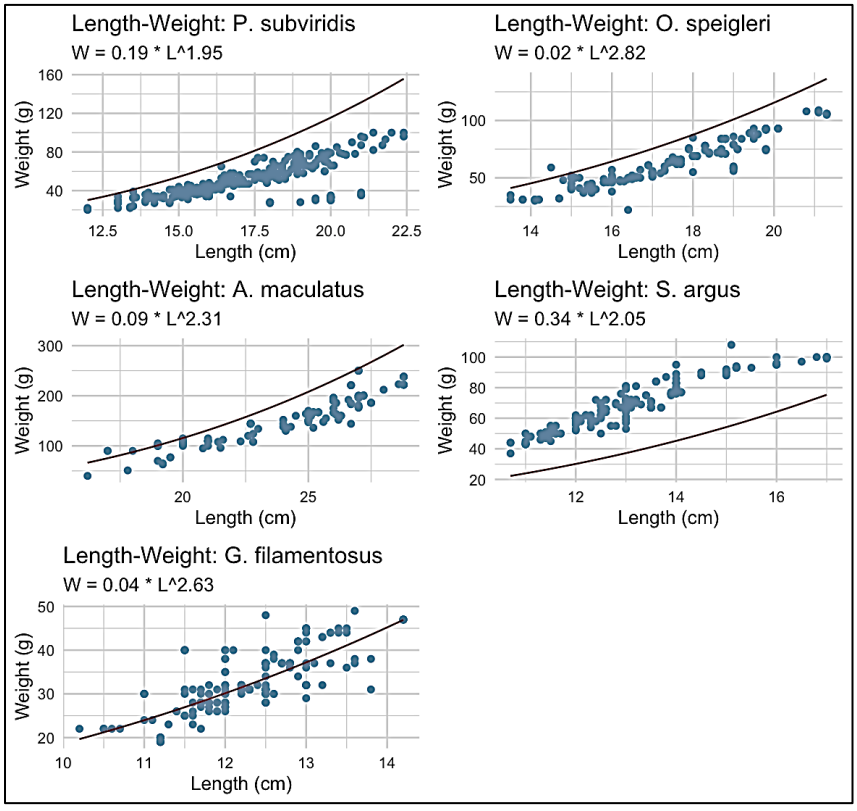


Fig. 4: Graph of the length and weight relationship of five dominant fish species. Blue points represent individual measurements of length (cm) and weight (g). The red line indicates the fitted length–weight regression curve for each species, derived from the equation

Growth parameters

The focus of this study's analysis on growth parameters, mortality, and utilization status was directed towards the *P. subviridis* species, as there were sufficient samples available, the samples was sufficient, the samples statistically represented the population size distribution, and the length distribution was even. The k (growth coefficient) value of the *P. subviridis* species was relatively high, at 0.69 per year (Table 8). In accordance with growth criteria, this value is categorized as fast-growing category (Froese and Binohlan, 2000). These growth parameters were obtained using the ELEFAN-GA method, selected for the highest Rn_max value, which indicates the best fit between the growth curve and length-frequency data (Pauly and David, 1981; Taylor and Mildenberger, 2017).

Mortality and exploitation rate

Based on the exploitation rate (E) value of 0.57 (Table 9), the greenback mullet (*P. subviridis*) stock is considered to be under high utilization, exceeding the conservation threshold of 0.5 (Gulland, 1971). This implies that the impact of fishing mortality on overall mortality is substantial, with 57% of the population's deaths linked to fishing activities. The ratio of Fishing Mortality (F = 1.34 per year) to Natural Mortality (M = 1.01 per year) is greater than 1.0, confirming that fishing mortality has surpassed natural mortality. This discrepancy is a distinct signal of heightened fishing pressure on the population and corresponds with recruitment overfishing, where reproductive capacity is greatly compromised (Hordyk *et al.,* 2015). Jakarta Bay is a coastal area rich in marine biodiversity, with essential ecosystems such as coral reefs, seagrass beds, and mangrove forests that support fisheries productivity. The evaluation results of the provisioning ESs assessment of Jakarta Bay reveal that the equilibrium between supply and demand is favorable (supply exceeds demand) in coastal land use for mangroves, water bodies, and marine/ocean zones. Unsatisfactory outcomes (where demand surpasses supply) are observed in land utilization for transportation and ports. These results indicate that provisioning ESs for capture fish resources is significantly reliant on mangrove, aquatic, and marine/ocean ecosystems (Tables 1, 2 and 3). Provisioning ESs for capturing fish resources are also related to transportation and port facilities. The evaluation findings suggest that the presence of such infrastructure yields unsatisfactory outcomes, as demand surpasses supply. This is closely related to detrimental human activities in coastal and marine areas, including reclamation, pollution, and overexploitation, which affect the quality of coastal habitats (Maisalda *et al.,* 2024). To minimize human interference, ESs should be incorporated into regional policies and conservation plans (Schlemm *et al.,* 2025). Therefore, local policies that consider provisioning ESs are essential for supporting ecosystem health and community well-being. Concerning capture fisheries, it was noted that small-scale fishers working near the shore utilize lift nets and gillnets, predominantly featuring a mesh size of approximately 1 inch. This fine mesh size results in low selectivity, increasing the likelihood of capturing juvenile fish and non-target species. From the catches recorded at Segara Jaya and Cilincing, 63 fish species from various families were identified, reflecting relatively high fish diversity. Fish diversity is an indicator of both the sustainability of fish resources (Mujiyanto *et al.,* 2023; Yuliana *et al.,* 2019) and the health of aquatic ecosystems (Mujiyanto *et al.,* 2023). Furthermore, the insufficient selectivity of gears significantly affects both the composition of the catch and the condition of the stock. As an illustration, *P. subviridis* and *S. argus* indicated stable or increasing trends, while *A. maculatus* exhibited a declining trend, consistent with vulnerability to juvenile exploitation. These findings emphasize the need for size-based fisheries management, habitat protection, and regular stock monitoring to sustain the ecological function of Jakarta Bay as a strategic fisheries area.

Table 8: Estimated growth parameters of the *P. subviridis*

Parameter	Unit	Value
Asymptotic length (L_∞)	cm	39.39
Growth coefficient (k)	/year	0.69
Theoretical age at zero length (t_0)	year	-0.85

Table 9: Estimation of mortality parameters and exploitation rate of mullet

Parameter	Unit	Value
Natural mortality (M)	/year	1.01
Total mortality (Z)	/year	2.35
Fishing mortality (F)	/year	1.34
Exploitation ratio (E)	-	0.57
Fishing pressure (F/M)	-	1.33

Communities around Jakarta Bay rely heavily on the bay's fishery resources. Fishing operations are mainly conducted by small-scale fishers utilizing traditional equipment and boats under 10 GT, leading to fishing predominantly occurring in coastal waters roughly 12 km from the shore. Moreover, traditional fishermen (small-scale fishermen) in Indonesia are not yet required to obtain permits. This situation could threaten the sustainability of fishery resources by allowing for the unreported increase in fishing fleets (Halim *et al.,* 2020). Unregulated fishing activities ultimately lead to the degradation of fish resources; therefore, it is important to monitor the sustainability of fish resources. The assessment of stock sustainability was carried out using length-based stock evaluation methods, which are well-regarded as effective strategies for small-scale and coastal fisheries, particularly in situations where long-term data on catch and effort time series is frequently lacking (Pauly, 1980; Sparre and Venema, 1998; Froese, 2006; Hordyk *et al.,* 2015). Such growth patterns are important because they affect stock resilience (Mehanna and Farouk, 2021) and assessing fish stock structure. The composition of the catch size illustrates the progression of fish sizes over the years. The decreasing trend in fish size structure suggests fish resource degradation. Fish size structure is a tool for analyzing fish diversity (Boll *et al.,* 2023) and is also related to fish stocks (Jaliadi *et al.,* 2017). In this study, the size structure was examined based on the annual catch trend from 2019 to 2023. The declining trend in biomass suggests degradation of the fish resource. Table 5 shows that two fish species (*P. subviridis* and *S. argus*) exhibit increasing catch trends, while one species, *A. maculatus*, exhibits a decreasing catch trend. This condition signifies that *A. maculatus* has undergone degradation. The outcomes underscore the importance of implementing size-based fisheries management, safeguarding habitats, and conducting regular stock assessments to maintain the resources and ecological integrity of Jakarta Bay as a strategic fisheries zone. Fish resource degradation is confirmed by the research results of Patawari *et al.* (2022), which indicate that capture fishery resources are not sustainable and are becoming less so. To assess biomass for various fish populations, it is essential to comprehend the length-weight relationships (LWRs) of the species being examined. LWRs play a crucial role in stock assessments for estimating biomass (Mehanna *et al.,* 2018; Mehanna and Farouk, 2021). At the study site, five species were identified as dominant based on abundance, and their length distributions and length-weight relationships were analyzed. The analysis showed a relatively narrow and homogeneous length distribution (Table 6 and Fig. 2) and a negative allometric growth pattern (Table 7 and Fig. 4), meaning that length increases faster than weight, resulting in the fish being relatively thin. Analyzing growth patterns is crucial

as they influence stocks (Mehanna *et al.,* 2018) and ultimately yield insights regarding resource sustainability. A more in-depth analysis of fisheries utilization conditions for *P. subviridis* was conducted based on the number of samples and their length distribution across various size classes. This approach allows for a more accurate estimation of population parameters. Growth parameter estimates indicate that mullet has an asymptotic length (L_∞) of 39.39 cm and a growth coefficient (k) of 0.69 per year. The relatively high k value indicates that *P. subviridis* is a fast-growing species, consistent with Froese and Binohlan's (2000) classification, which places a k value of ≥ 0.5 in the fast-growing category. Species exhibiting these traits typically possess a brief life cycle, attain sexual maturity at an early stage, and demonstrate a high rate of reproduction (Beverton and Holt, 1957). However, high growth rates can also indicate vulnerability to overexploitation, especially if individuals are caught before they have the opportunity to reproduce. Based on growth parameters, mortality parameters were evaluated to further analyze population dynamics. Total mortality (Z) was calculated using method by Sparre and Venema (1998). Mortality analysis revealed a total mortality (Z) of 2.35 per year, natural mortality (M) of 1.01 per year, and fishing mortality (F) of 1.34 per year. The exploitation rate (E = 0.57) exceeded the conservation threshold of 0.5, confirming that the stock is under high fishing pressure. Importantly, the fishing pressure (F/M ratio) (1.34/1.01 ≈ 1.33) exceeded 1.0, indicating that fishing mortality has outstripped natural mortality. This disparity acts as a reliable sign of excessive fishing pressure and is consistent with recruitment overfishing, significantly diminishes reproductive capacity (Hordyk *et al.,* 2015). The low SPR (0.15) further supports this conclusion, indicating that only 15% of the spawning biomass remains compared to an unfished population. Together, these indicators confirm that *P. subviridis* is overexploited and highlight the direct influence of fine-mesh gears on juvenile capture and stock depletion. Such stock conditions necessitate conservation-oriented management to maintain marine ecosystem health and biodiversity (Arthatiani *et al.,* 2026). The integration of exploitation indicators (E, F/M ratio, SPR) with gear selectivity observations provides a comprehensive understanding of stock dynamics in Jakarta Bay. Population sustainability also depends on preserving ecological adaptability and resilience under increasing environmental pressures (Nurfadillah *et al.,* 2025). Studies have demonstrated that the use of fine-mesh gears leads to higher rates of juvenile mortality and a decrease in spawning biomass, which ultimately weakens stock resilience (Pauly, 1980; Froese *et al.,* 2014). Therefore, adaptive management strategies are urgently needed, including increasing mesh size, promoting more selective gear types, and enforcing monitoring of small-scale fleets that currently operate without permits (Halim *et al.,* 2020). These measures further support blue economy objectives that balance fisheries productivity with environmental sustainability (Trenggono *et al.,* 2025). These measures would reduce juvenile exploitation, allow populations to rebuild, and sustain the provisioning ESs that coastal communities depend upon.

CONCLUSION

The provisioning ESs assessment of Jakarta Bay indicates that the balance between supply and demand for ESs is moderately favorable but vulnerable — supply exceeds demand — particularly for coastal land use associated with mangroves, water bodies, and marine/ocean resources. Conversely, inadequate balance outcomes (where demand surpasses supply) were noted for land use associated with transportation and ports, indicating that pressures related to infrastructure necessitate meticulous management. These findings confirm that the provisioning ESs of capture fish resources in Jakarta Bay are highly dependent on mangrove, water body, and marine/ocean ecosystems.

Consequently, it is imperative to uphold the sustainability of these ecosystems to secure the enduring sustainability of fishery resources. The fish consumption needs of coastal communities in Jakarta Bay can be met in the long term by maintaining ecosystem sustainability. A total of 63 fish species were recorded at two fish landing sites — Segara Jaya and Cilincing fish markets — representing a wide range of habitats including coastal waters, estuaries, mangroves, coral reefs, and brackish environments. The notable diversity of species identified at the research location emphasizes the substantial biodiversity and fishery opportunities present in Jakarta Bay as a vital coastal area. Fish diversity serves as an important indicator of both fish resource sustainability and aquatic ecosystem health. To uphold this diversity, it is essential to implement comprehensive habitat protection strategies, particularly for essential nursery and feeding grounds such as mangrove areas and estuaries. Analysis of catch trend data from 2019 to 2023 revealed that *A. maculatus* has experienced a declining catch trend, indicating early signs of resource degradation for this species. In contrast, *P. subviridis* and *S. argus* indicated relatively stable or increasing trends. Among the five predominant species, the assessment of the fishery status of P. subviridis revealed that the population is experiencing overfished. This is evidenced by an exploitation rate (E = 0.57) exceeding the sustainability threshold of 0.5, a SPR = 0.15 below the critical reference point of 0.20, and a fishing mortality to natural mortality ratio (F/M = 1.33) greater than 1.0. The length distribution of *P. subviridis* was dominated by juvenile-sized individuals, suggesting that fishing pressure is concentrated on young fish that have not yet had the opportunity to reproduce. LBSPR simulations further illustrated that an increase in the F/M ratio results in a decrease in SPR, thereby heightening the risk of recruitment failure if the existing levels of exploitation are not managed. Significantly, these stock indicators are inherently connected to the values of ecosystem services: overexploitation leads to a reduction in spawning biomass and recruitment potential, thus impairing the provisioning ESs of capture fisheries. In Jakarta Bay, the interaction between biological overfishing (high E, F/M > 1, low SPR) and habitat degradation (reclamation, pollution, mangrove loss) poses a serious threat to the long-term sustainability of fishery resources and the ESs they provide to coastal communities. In order to confront these challenges, a number of evidence-based fisheries management strategies are recommended. First, a minimum legal-size regulation for *P. subviridis* should be established and enforced to allow juvenile fish to reach reproductive maturity before capture. Second, the establishment of temporal fishing restrictions, including closed seasons, during spawning times should be taken into account to ensure the protection of reproductive stock. Third, integrated coastal management that incorporates ESs valuation into local policy frameworks is essential to balance ecological and economic objectives. Finally, regular stock monitoring programs utilizing length-based assessment methods — such as LBSPR — should be institutionalized to enable adaptive management responses to changing stock conditions. The outcomes of this study illustrate that the condition of fish stocks and the provision of ESs are closely intertwined: unsustainable fishing practices reduce ecological capacity, and deteriorated habitats further intensify the decline of fish stocks. This research indicated that the vulnerability of ESs themselves can act as an additional pressure on fisheries. When mangroves, estuaries, and seagrass beds lose their ecological function due to reclamation, pollution, and coastal development, the provisioning capacity of these ecosystems' declines, reducing recruitment success and weakening fish stock resilience. This ecological vulnerability directly leads diminished values of ESs, establishing a feedback loop in which the weakening of provisioning ESs exacerbates the pressure on fisheries. This pressure is further worsened by non-selective fishing practices,

particularly the widespread use of lift nets and gillnets with fine mesh sizes (~1 inch), which disproportionately capture juvenile fish before they reach reproductive maturity. The interaction between ecosystem degradation and non-selective fishing methods generates compounded risk, in which declining ESs diminish fish productivity, while unsustainable fishing practices exacerbate stock depletion. This integrated perspective, linking ESs vulnerability with biological exploitation indicators (E, F/M ratio, SPR) can provides a scientific basis for authorities to design adaptive, ecosystem-based fisheries management policies for Jakarta Bay and similar urban coastal areas in Indonesia and the broader tropical region.

AUTHOR CONTRIBUTIONS

E. Yuliana, the corresponding author, conceived, designed, and conducted research, as well as data analysis, preparing the manuscript draft, and finalizing the manuscript draft. M. Nurilmala supervised the first author, contributed to data sampling, especially for fish sampling, and data analysis. A. Rahadiati conducted interviews with informants, performed ESs data analysis and reviewed the paper draft. I. Farida developed research instruments and conducted fishers sampling. H. Kurniawati was responsible for data processing, fish sampling, and species identification. S. Agustina contributed to fish data analysis, sampling, and data processing. D.A. Difah contributed to fish data analysis, sampling, and data processing. P.R. Pertiwi also conducted fishers sampling and contributed to data analysis. B.E. Wicaksana contributed to data processing and fish sampling. R.V. Ramilo contributed to fish data analysis and preparing the manuscript draft. W.A. Djatmiko made contributions to fish identification, sampling activities, and data processing.

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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
a	Regression constant
b	Growth exponent
cm	Centimeter
E	Exploitation rate
EAFM	Ecosystem approach to fisheries management
ELEFAN	Electronic Length Frequency Analysis
ELEFAN-GA	Electronic Length Frequency Analysis Genetic Algorithm
ESs	Ecosystem services
F	Fishing mortality
FAO	Food and Agricultural Organization
g	Gram
ind	Individual
k	Growth coefficient
kg	Kilogram
kg/km²	Kilograms per square kilometers
km	Kilometer
km²	Square kilometers
L	Fish length
L_t	Length of fish at age
L_∞	Asymptotic length
L_{50}	Length at which 50% of the fish are mature
L_{95}	Length at which 95% of the fish are mature
LBSPR	Length-Based Potential Ratio
LWRs	Length-weight relationships
M	Natural mortality
max	Maximum
min	Minimum
MMAF	Ministry of Maritime Affairs and Fisheries
n	Number of individuals
NGO	Non-Governmental Organization
p	Probability
R	Programming language
Rn_max	Maximum ELEFAN score
SPR	Spawning potential ratio
t_0	Theoretical age at zero length
VBGF	Von Bertalanffy Growth Function
Z	Total mortality

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ORIGINAL RESEARCH ARTICLE

Community-based adaptation strategies to the impact of climate change in vector-borne diseases

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate change is driving the emergence and geographic expansion of vector-borne diseases globally, creating urgent public health challenges. This study explores the interplay between climatic elements—including elevated temperatures, changed precipitation patterns, and growing greenhouse gas emissions—and socioeconomic factors and institutional capabilities to influence community vulnerability. The study synthesizes secondary evidence to identify and evaluate adaptation strategies and develop an integrated thematic framework linking climatic, ecological, socioeconomic, and institutional dimensions of vulnerability and response.

METHODS: A thematic synthesis of secondary data was conducted using peer-reviewed journals, government reports, and publications from international organizations. Sources published in English from 2020 to 2025 were intentionally identified using structured yet non-systematic keyword searches that corresponded with the study's objectives. Thematic analysis was employed to integrate findings into analytically derived themes that correspond with the research objectives. An iterative coding process incorporating both deductive (objective-driven) and inductive (emerging) approaches was used to capture patterns across studies. Data collection from different source types enabled triangulation to strengthen interpretive validity.

FINDINGS: Four significant themes were identified: first, climatic and ecological drivers: increasing temperatures and changing precipitation patterns are associated with broader vector ranges and longer transmission seasons. Second, socioeconomic and environmental determinants: poverty, inadequate housing, limited access to water, and political marginalization increase vulnerability to vector-borne diseases. Third, institutional and policy gaps: fragmented surveillance, weak cross-sectoral coordination, and limited community participation restrict effective responses. Fourth, community-based adaptation strategies: community-led environmental management, surveillance, and health education can help reduce vector abundance and disease incidence, especially when backed by institutional integration, ongoing resources, and capacity building. Effectiveness varies across ecological and socioeconomic contexts.

CONCLUSION: Addressing climate-driven vector-borne disease risks require integrated approaches combining early warning systems, community-centered interventions, strengthened health system capacity, and cross-sectoral governance. The suggested thematic framework emphasizes the interdependence of climatic, ecological, and socioeconomic influences alongside the ability of institutions to respond. Sustained domestic funding, formal institutionalization of community roles, and equity-focused resource allocation are essential for scaling interventions to large populations. The study provides targeted, evidence-informed recommendations for policymakers, health system managers, community organizations, and international agencies, while identifying key gaps in evidence regarding scalability, long-term sustainability, and context-specific effectiveness. The results are founded on the synthesis of secondary data and should be interpreted regarding contextual variability.

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INTRODUCTION

Climate change is fundamentally altering environmental conditions that affect the global distribution and incidence of vector-borne diseases (VBDs) (Githeko *et al.,* 2000; Campbell-Lendrum *et al.*, 2015). These diseases—spread by vectors like mosquitoes, ticks, and sandflies—contribute to over one-sixth of the global burden of illness and disability, with more than half of the world's population currently exposed to risk (Campbell-Lendrum *et al.,* 2015; WHO, 2024). Significant pathogens include viruses (dengue, Zika, chikungunya), bacteria (Lyme disease, rickettsioses), protozoa (malaria, leishmaniasis), and many others (Socha *et al.,* 2022; Khan *et al.,* 2023). Accelerated global warming, increased greenhouse gas emissions, glacial melting, and unpredictable weather patterns have expanded the habitats and breeding seasons of disease vectors (de Souza and Weaver, 2024; Jibon *et al.,* 2024). Mosquito-borne diseases, such as malaria, dengue, chikungunya, and Zika, are specifically sensitive to microclimate variations in temperature and humidity, which drive their transmission intensity, seasonality, and geographic spread (Hussain *et al.,* 2024; Mertens, 2025; Anikeeva *et al.,* 2024). Other VBDs, including Lyme disease and rickettsial infections, have migrated and broadened into new ecological regions, suggesting that vectors are adapting to alterations in temperature and rainfall patterns (Abbasi, 2025). Vectors are ectothermic organisms, which means their physiology, reproduction, and survival are regulated by environmental conditions (de Souza and Weaver, 2024; Githeko *et al.,* 2000). Temperature plays a significant role in vector physiology and the progression of pathogens, as increased temperatures usually enhance transmission dynamics within biologically defined boundaries. Rising global average temperatures are predicted to expand risk zones northward and to higher elevations (Githeko *et al.,* 2000; Molina-Guzmán *et al.,* 2022), and this has already facilitated outbreaks in zones previously considered low-risk, including temperate regions (Anikeeva *et al.,* 2024). VBDs unevenly affect low- and middle-income populations in tropical and subtropical regions, driven by limited adaptive capacity, poor housing, and lack of access to essential health services (Campbell-Lendrum *et al.*, 2015; WHO, 2024; Wu and Huang, 2022). Recent estimates indicate that VBDs cause over 700,000 deaths annually, and approximately 80 percent (%) of the global population is now exposed to risk, as vectors move into new territories (UNDP, 2025; Wu and Huang, 2022). Climate, nonetheless, operates alongside social elements including urbanization, deforestation, migration, and water management practices, all of which affect the likelihood of outbreaks and the dynamics of transmission (Campbell-Lendrum *et al.,* 2015). Importantly, climate change has changed vector behaviors, such as host seeking and resting preferences, resistance to desiccation, and adaptation to higher thermal limits, enhancing survival and reproductive cycles in new environments (Abbasi, 2025). These alterations emphasize the need for ongoing evaluation of public health strategies and improving surveillance systems amidst swift ecological shifts (Campbell-Lendrum *et al.,* 2015; Jibon *et al.,* 2024). Despite extensive literature on climate-sensitive VBDs, existing studies often examine climatic, ecological, or socioeconomic factors in isolation or remain confined to single disease or region-specific analyses. There is a scarcity of thematic synthesis that associates these interacting drivers with the processes of community-level adaptation and the institutional response capacity in different environments (e.g., urban, peri-urban, and rural). In addition, many existing reviews remain predominantly descriptive, with insufficient critical structuring of how vulnerability, governance, and intervention effectiveness interact under different climatic and socioeconomic contexts. This study examines four interconnected domains: climatic and ecological

drivers of VBD transmission, community-level social and economic vulnerability, governmental and institutional responsibilities, and community-based adaptation strategies for mitigation. This study applies a qualitative thematic analysis of secondary data to amalgamate evidence from different geographic and socioeconomic environments, and it is not restricted to any specific geographic location. This study aims to critically assess the processes by which climate change increases community vulnerability to VBDs and to evaluate actionable strategies for minimizing these threats through the following objectives: 1) To analyze the influence of global warming, altered precipitation, increased greenhouse gas emissions, and ecosystem disruptions on vector and pathogen transmission patterns (Molina-Guzmán *et al*., 2022; Githeko *et al.,* 2000). 2) To investigate environmental, social, and economic determinants impacting VBD risk, such as poverty, housing quality, and water access (Campbell-Lendrum *et al.,* 2015; Statista, 2023). 3) To assess the effectiveness and limitations of existing policies and institutional methods addressing climate-driven VBD outbreaks (WHO, 2024; Takken *et al.,* 2021). 4) To evaluate community-based adaptation techniques and their scalability for reducing VBD impact (Rivera *et al*., 2023; Hiscox *et al.,* 2025).

Problem statement

The risk of VBD is increasing worldwide as climate and social changes move faster than current adaptation approaches (Babatuyi *et al.,* 2024; Chigudu, 2025). Numerous local health systems do not possess adequate surveillance, diagnostic resources, and participatory planning mechanisms necessary to effectively detect and respond to the growing challenges posed by burdens VBD (Githeko *et al.,* 2000; Campbell-Lendrum *et al.,* 2015). In addition, fragmented governance, insufficient funding, and weak cross-sectoral coordination constrain the implementation and sustainability of adaptation strategies, particularly in resource-limited settings. Furthermore, without such cohesive approaches, the challenges posed by outbreaks can escalate rapidly, leading to increased risks of transmission between species (Campbell-Lendrum *et al.,* 2015; Mertens, 2025).

Research significance and scope

This research addresses the urgent need for integrated evidence connecting climate change adaptation to improved control of VBDs, especially in vulnerable regions. It combines climatic, epidemiological, policy, and community perspectives to support decision-makers and practitioners (Campbell-Lendrum *et al.,* 2015; Rivera *et al.,* 2023). This study elucidates how identifying patterns, contextual variations, and implementation constraints can guide interventions across local, national, and international spheres to foster effective climate resilience in public health (UNDP, 2025; Cheong *et al.,* 2023). The study was carried out in Riyadh, Saudi Arabia in 2025 and it is based on secondary data obtained from peer-reviewed and institutional sources published between 2020 and 2025.

MATERIALS AND METHODS

Research method and design

This study uses a qualitative research methodology, specifically thematic analysis, to explore the relationship between climate change and the rise of VBDs, focusing on the assessment of community-based adaptation and mitigation strategies. (Cheong *et al.,* 2023; Chai *et al.,* 2021). Qualitative methodologies are ideally suited for tackling complex questions in environmental health, facilitating the incorporation of multiple perspectives and the synthesis of empirical as well as policy-focused literature (Campbell-Lendrum *et al.,* 2015). An exploratory research design was selected, as it allows examination of complex and emerging phenomena—such as shifting vector ecology and adaptation strategies—by drawing

from heterogeneous and sometimes incomplete data sources (Olawale *et al.,* 2023; Chapungu and Nhamo, 2021). This method is consistent with the latest advancements in methodology that combine qualitative synthesis with findings from epidemiological modeling and scenario-based analyses, effectively capturing the interactions among climate, vector biology, and community interventions (Sadeghieh *et al.,* 2021; Royal Society, 2021a; Royal Society, 2021b). By triangulating multiple types of secondary data (empirical studies, policy reports, and modeling evidence), the study develops an integrated understanding of adaptation pathways in diverse geographic and socioeconomic contexts (Schlunegger *et al.,* 2024).

Data sources and search strategy

Secondary data were obtained from a diverse range of peer-reviewed journal articles, grey literature, policy papers, and official reports found through databases such as PubMed, Scopus, Web of Science, and Google Scholar (Cheong *et al.,* 2023). A structured keyword-based search strategy was used, employing combinations of terms such as: "climate change," "VBDs," "malaria," "dengue," "community-based adaptation," "disease surveillance," and "public health" (Chai *et al.,* 2021). Articles published in English between 2020 and 2025 were considered, with attention to both global and region-specific analyses (Cheong *et al*., 2023; Wellcome, 2024). Relevant review articles reference lists and consensus documents (e.g., WHO, IPCC) were scanned for additional sources (IPCC, 2024). The search process was iterative rather than protocol-driven; studies were selected according to their relevance to the research objectives instead of through comprehensive database retrieval. Therefore, this study does not claim completeness of coverage but aims for conceptual depth and thematic representation. Approximately 45-50 sources were included in the final synthesis following screening for relevance and quality. Emphasis was placed on studies that offered empirical evidence, comparative analyses, or well-defined methodological descriptions, along with credible reports from global health organizations.

Inclusion criteria

Studies were included if they were published in English between 2020 and 2025; focused on the intersection of climate change and VBDs in humans; addressed either risk assessment, mitigation/adaptation strategies, policy, surveillance, ecological drivers, or community interventions; and provided transparent methodological detail to enable qualitative synthesis (Schlunegger *et al.,* 2024). Significant reports from agencies like the WHO and CDCP, as well as frequently referenced academic reviews, were utilized to support the findings based on current best practice (Campbell-Lendrum *et al.*, 2015; WHO, 2024).

Exclusion criteria

Studies were excluded if they were published prior to 2020 (unless frequently cited as seminal works in included research); focused exclusively on non-human animal or plant VBDs without clear public health interface; did not address climate or social determinants in VBD emergence; provided insufficient data; or were not available in English (Cheong *et al.,* 2023).

Data analysis

Thematic analysis was performed in accordance with the six-phase framework established by Braun and Clarke (2006), which has been recently modified for research in environmental health (Cheong *et al.,* 2023; Chapungu and Nhamo, 2021). This technique involved: 1) Familiarization with all included texts. 2) Systematic initial coding for emergent themes concerning climate-VBD interactions, community vulnerability, institutional designs, and adaptation strategies. 3) Grouping codes into major and minor themes that fit with research objectives. 4) Reviewing and refining themes for coherence, overlap, and validity with support from research team

discussions. 5) Defining and naming finalized themes with corresponding evidence. 6) Synthesizing results to highlight cross-theme insights and policy implications.

Themes were developed using a combination of deductive (objective-driven) and inductive (data-driven) approaches, ensuring that both anticipated and emergent patterns were captured. The input from each individual study related to the themes was monitored, focusing on repeated patterns, differing results, and contextual differences instead of singular assertions. Triangulation of findings from peer-reviewed studies, modeling papers, and agency reports increased reliability and addressed potential single-source bias (Schlunegger *et al.,* 2024). A structured quality appraisal was conducted using the critical appraisal skills program (CASP) checklist and relevant standards for modeling and policy studies to inform interpretation rather than strict exclusion, allowing critical consideration of study limitations while retaining diverse evidence sources (Royal Society, 2021a). The results were evaluated with regard to the quality of the study, the limitations of the methodology, and the contextual factors involved.

RESULTS AND DISCUSSION

Theme 1: Climatic drivers and ecological changes influencing VBD transmission

Climate change is a key factor contributing to the emergence and global proliferation of VBD, primarily functioning through variations in temperature, changes in precipitation patterns, and extreme weather phenomena (Githeko *et al.,* 2000; Ma *et al.,* 2022; Molina-Guzmán *et al.,* 2022). *Aedes aegypti* (mosquito responsible for dengue, Zika, yellow fever, and chikungunya) has expanded significantly (Stanford Doerr School of Sustainability, 2025). Fig. 1 illustrates how the duration and risk zones for these diseases have increased worldwide. Temperature profoundly impacts transmission through extrinsic incubation period (EIP) shortening. The patterns of precipitation are significant. Heavy rainfall establishes areas for mosquito breeding, whereas droughts cause vectors and hosts to cluster around minimal water sources (Yadav and Upadhyay, 2023; Palmer *et al.,* 2023). Both situations can spark outbreaks, especially in regions newly exposed to disease (Githeko *et al.,* 2000; Mojahed *et al.,* 2022). Major climatic phenomena, such as the El Niño-Southern Oscillation, have been directly linked to VBD outbreaks—Rift Valley fever epidemics in East Africa are often triggered by successive droughts and floods (Research Outreach, 2020). Ecological changes—like land use shifts, urbanization, and deforestation—compound climatic effects, creating new vector habitats (Campbell-Lendrum *et al.,* 2015; Molina-Guzmán *et al.,* 2022). Fig. 2 shows that climate change has been associated with the emergence of more than 200 infectious diseases, including both VBDs and climate-sensitive infectious diseases, linked to shifting temperatures, rainfall variability, and severe storms. Mosquito-borne illnesses (dengue, malaria, Zika) show highest responsiveness (Anoopkumar and Aneesh, 2022; CDCP, 2024). *Aedes aegypti* expansion and mosquito VBD sensitivity (dengue, malaria, Zika) confirmed by 22/45 studies—strongest evidence among VBDs (CDCP, 2024; Table 3). Nonetheless, the connection between climatic factors and the spread of disease is not consistent. Several studies highlight non-linear and context-dependent effects, where transmission efficiency may decline beyond upper thermal thresholds (20-35 °C optimal; >37 °C vector mortality) or under extreme drought conditions. This denotes that climate-disease interactions are complex and are influenced by local ecological conditions instead of being universally straightforward (Yadav and Upadhyay, 2023). Other VBDs, such as Lyme disease and hantavirus, have also shifted range (Mertens, 2025).

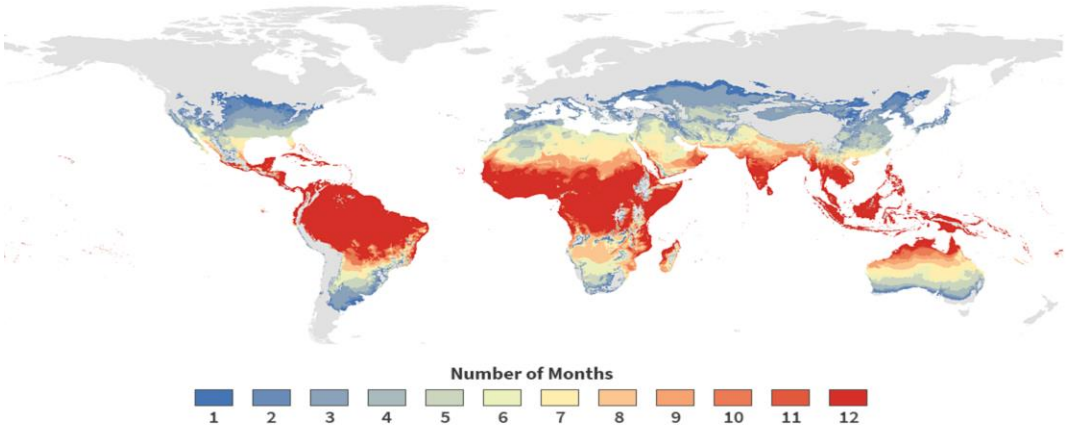

Fig. 1: Impact of climate change on transmission duration and geographic risk zones of major vector-borne diseases (Stanford Doerr School of Sustainability, 2025)

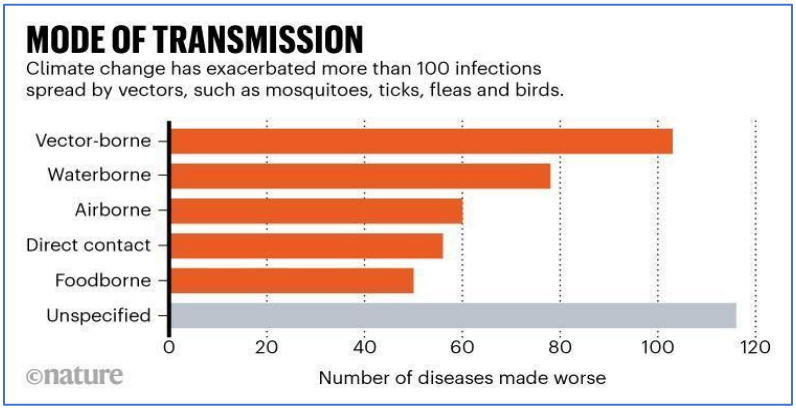

Fig. 2: Types of infectious diseases emerging due to climate change, showing highest responsiveness of mosquito-borne VBDs (Prillaman, 2022)

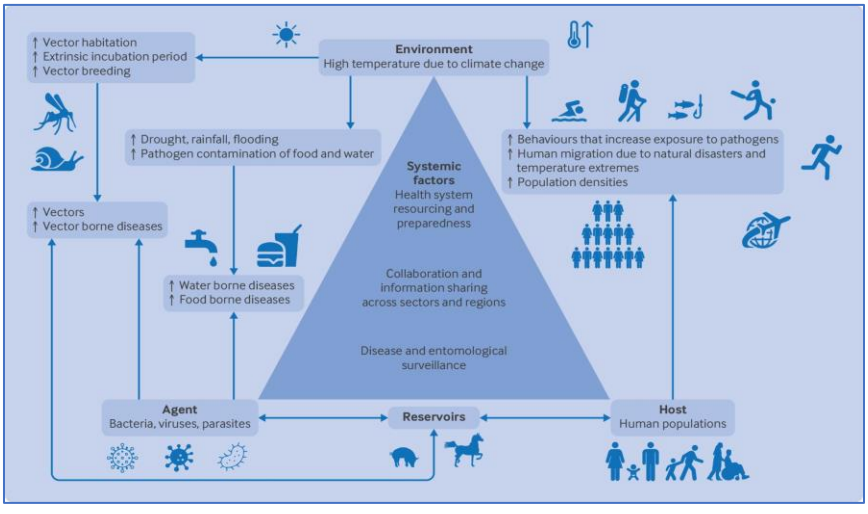

Fig. 3: Global warming impacts on emerging infectious diseases, including vector-borne disease range expansion (Anikeeva *et al.*, 2024)

Theme 2: Community-level social, environmental, and economic determinants

Social, economic, and environmental factors influence community resilience and vulnerability to VBDs (Alqassim, 2024; Yadav and Upadhyay, 2023). The concentration of burden occurs in regions where climate conditions interact with inadequate housing, economic hardship, and poor water management practices (Alqassim, 2024). Urbanization without planned infrastructure facilitates mosquito breeding and complicates disease control, particularly in informal settlements where drainage, sanitation, and housing quality are inadequate. The effectiveness of community-based adaptation strategies varies across urban, peri-urban, and rural contexts due to differences in population density, infrastructure, and environmental exposure (urban slums show 3-5× higher Aedes breeding rates) (Yadav and Upadhyay, 2023). Insufficient public education and awareness frequently exacerbate these risks, diminishing the effectiveness of behavioral interventions (Palmer *et al.,* 2023). Social determinants—poverty, gender roles, education, and migration—reduce preventive measures uptake by 30-35 % in low- and middle-income countries (Athni *et al.,* 2021). Fig. 4 highlights zoonotic spillovers: 73% of emerging infectious diseases (EIDs) are zoonotic, amplifying VBDs risks through human-animal-environment interfaces (Woolhouse and Gowtage-Sequeria*,* 2005; Buchholz, 2023). Communities with inadequate access to clean water, reliable waste management, and educational opportunities experience heightened disease risks, as ecological degradation and poverty drive exposure to breeding sites (Alqassim, 2024; Campbell-Lendrum *et al.,* 2015). Rapid urbanization, migration, and agricultural expansion can alter land use and bring people into interaction with animal reservoirs, increasing the risk of zoonotic spillovers (Prezode Initiative, 2025; CDCP, 2024). The synthesis also demonstrates that the effectiveness of adaptation strategies varies significantly across urban, peri-urban, and rural settings, where differences in infrastructure, population density, and environmental exposure shape both risk and intervention feasibility. Additional vulnerabilities encompass migratory labor trends and the political disenfranchisement of marginalized communities, both of which diminish access to public health interventions (Rivera *et al.,* 2023; Athni *et al.,* 2021). Barriers to adaptation persist in informal urbanization (limited institutional support reduces CBA effectiveness by 40-60%) (Rivera *et al.,* 2023). "One Health" approaches unify surveillance across human, animal, and environmental sectors for earlier detection and intervention (CDCP, 2024; Woolhouse and Gowtage-Sequeria*.* 2005; Prezode Initiative, 2025).

Theme 3: Institutional capacity, governance, and policy constraints

Policy and institutional response is crucial for managing VBDs under the stress of climate change (Ellwanger *et al.,* 2021; Takken *et al.,* 2021). One health strategies, uniting human, animal, and environmental health, are increasingly essential (Ellwanger *et al.,* 2021). International frameworks like the WHO, (2017) emphasize intersectoral policies (Fig. 5) and data sharing to enhance adaptive responses (Takken *et al.,* 2021; WHO, 2024). Furthermore, despite these endeavors, the disjointed health system infrastructure, lack of sufficient laboratory and diagnostic resources, and poor entomological surveillance, continue to be prevalent, especially in low-resource environments (Lyimo *et al.,* 2022; van den Berg *et al.,* 2021). Effective adaptation depends on integrating climatic, epidemiological, and vector surveillance data to enable early warning and timely response (Mertens, 2025; Anikeeva *et al.,* 2024). However, institutional barriers (limited resources, fragmented governance, weak coordination) constrain scalability—94-country survey confirms weak oversight undermines local control (van den Berg *et al.,* 2021). Community-led surveillance without formal support encounters

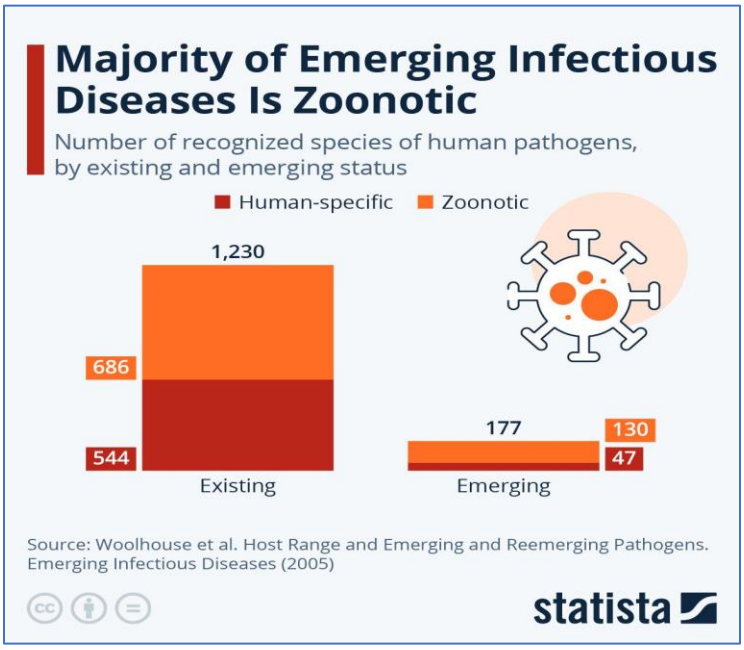

Fig. 4: Proportion of recognized human pathogen species by zoonotic status (existing vs. emerging), showing 73% of emerging infectious diseases are zoonotic (Buchholz, 2023)

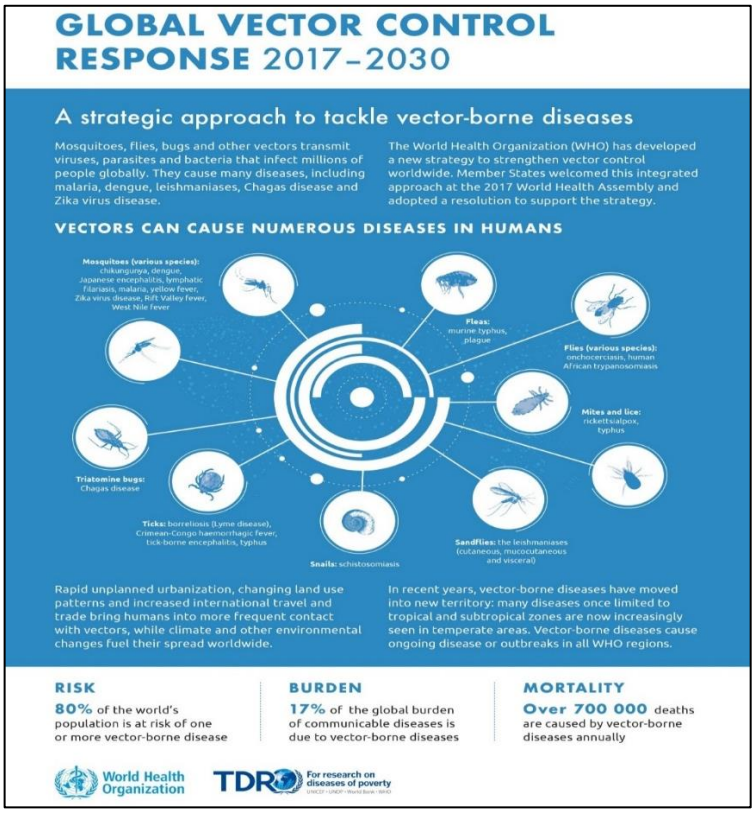

Fig. 5: Emphasizing intersectoral coordination and data sharing (ClimaHealth, 2025; WHO, 2017)

governance barriers: unclear stakeholder roles, overburdened volunteers (50-70% attrition within 2 years), data inconsistencies, and absent accountability structures (Sharp *et al.,* 2024; McGowan *et al.,* 2022; TC-WHO, 2019). These deficiencies compromise long-term effectiveness, given that volunteer attrition surpasses 50% within a two-year period without institutional integration (67-country CBS review) (Owusu *et al.,* 2023; Palmer and Duclos, 2023). Addressing these gaps requires robust governance systems, resource allocation, and cross-sectoral collaboration.

Theme 4: Community-based adaptation and intervention effectiveness

Global health initiatives are progressively acknowledging the importance of community-led adaptation, technological advancements, and inclusivity as essential components for the successful mitigation of VBD (Hiscox *et al.,* 2025; Rivera *et al.,* 2023). Larval source reduction achieves 60-95% vector reduction (Rivera *et al.,* 2023). Community engagement drives 40-65% adoption of preventive practices (vector control, hygiene) vs 8-12% from top-down messaging, with 16-25% sustained behavior change at 2-month follow-up (smoking cessation, bed net use) (Stover *et al.,* 2024; O'Mara-Eves, *et al,* 2015). Local leader-driven awareness campaigns secure compliance that is threefold higher, thanks to the cultivation of trust and the consideration of cultural specifics 90 (Aberese-Ako *et al.,* 2024; Gilmore *et al.,* 2020). Active community participation in planning achieves 2.3× greater sustainability and 40% higher intervention adherence vs top-down approaches (65% failure rate within 3 years). Bottom-up strategies foster local ownership essential for long-term adaptation success, while top-down interventions often lack community buy-in and collapse post-implementation (Sustainability Directory, 2025; Purinda, *et al.,* 2025). When institutional recognition and resources support community engagement and capacity-building, they contribute to the sustainability of intervention effectiveness (Rivera *et al.,* 2023). Community-led strategies like larval source reduction achieve 60-95% vector reduction during funding but collapse 1-2 years post-funding without institutional integration (73% Pacific Island CBA failure rate) (Westoby *et al.,* 2020). Sustainable vector management necessitates the incorporation of structured health system governance instead of intermittent external financial support (Wang *et al.,* 2025; Tye *et al*., 2021). Emerging tools such as mobile-based reporting systems, GIS mapping, and AI-supported early warning systems offer additional opportunities to strengthen community-level surveillance and response when effectively integrated with existing health systems. Fig. 6 demonstrates the partnership between public health agencies, local governments, and communities in upholding effective intervention (Rivera *et al.,* 2023; USDHHS and CDCP, 2024). Participatory interventions (environmental management, larval source reduction, health education) achieve 40-70 % incidence reduction in Brazil/India with institutional support (Athni *et al.,* 2021; Hiscox *et al.,* 2025). Despite this, interventions are still contingent upon short-term funding cycles and lack incorporation into established health systems (47% de-implementation resulting from funding loss) (McKay *et al*., 2021). These findings indicate that CBA requires institutional support, governance alignment, and long-term investment.

Cross-theme synthesis and comparative insights

The synthesis demonstrates that climate-driven VBD risk emerges from the interaction between climatic exposure, community-level vulnerability, and institutional capacity. The elevation in temperature along with fluctuations in rainfall establish favorable conditions for transmission; however, the scale and distribution of risk are moderated by the quality, governance systems, and social determinants

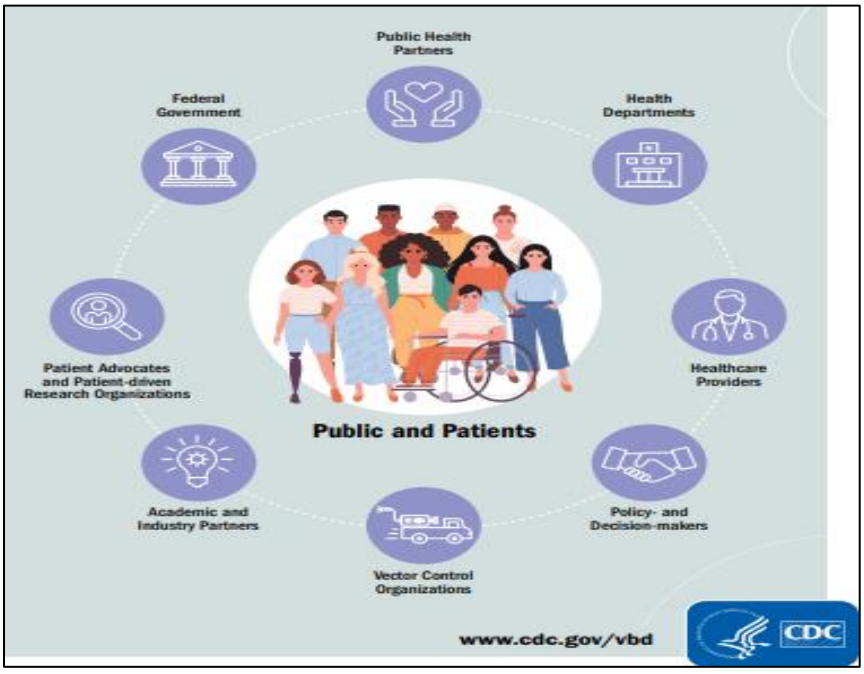

Fig. 6: Multi-sectoral collaboration model between public health agencies, local governments, and communities for sustainable VBD control (Rivera *et al.,* 2023; USDHHS and CDCP, 2024)

(Georgakopoulou et al., 2025; Yadav and Upadhyay, 2023). Comparative evidence suggests that:

- Regions with strong institutional coordination demonstrate earlier outbreak detection and more effective response.
- Community-based interventions yield better outcomes when combined with formal health system support.
- Resource-constrained settings face persistent challenges in sustaining adaptation strategies due to financial and infrastructural limitations.

Comparative analysis and study contribution

This study contributes to the existing literature by providing a cross-sectoral synthesis of biological, technological, and governance dimensions of climate-sensitive VBDs. Unlike previous reviews, which often focus on single diseases or specific geographic regions, this analysis adopts a multi-disease, global perspective and identifies context-specific transmission pathways. Prior studies have often highlighted the efficacy of community-based interventions, yet it has not adequately considered the institutional, financial, and governance limitations that hinder their scalability. In contrast, this synthesis demonstrates that CBA is not a standalone solution, but part of a broader system requiring sustained financing, institutional integration, and "One Health" governance frameworks to achieve long-term impact. Table 1 presents the comparative positioning of the present study in relation to previous reviews, highlighting its unique contributions, scope, and advancements within the existing body of literature.

Disease patterns, vectors, and environmental drivers

The synthesis indicates that increases in global temperature, irregular rainfall, and frequent extreme weather events are consistently associated with the expansion of vector populations and pathogen transmission dynamics (de Souza and Weaver, 2024; CDCP, 2024;

Table 1: Comparative positioning of the present study relative to previous reviews

Feature	Previous SLR / Narrative Reviews	Present Thematic Synthesis	Novelty / Strength
Scope	Often narrow (single disease or region)	Global, multi-disease, cross-context	Comparative across urban–rural gradients
Technological focus	Emphasis on primary control (e.g., bed nets)	Integration of digital tools (AI, GIS, EWS)	Links surveillance with decision systems
Social analysis	Descriptive mention of poverty	Analysis of migration, informal settlements	Identifies structural vulnerability modifiers
Policy direction	General recommendations for coordination	Explicit governance pathways	Actionable "One Health" integration framework

Georgakopoulou *et al.*, 2025). Based on the studies that have been reviewed, diseases transmitted by mosquitoes and ticks have been recognized as the most sensitive to climate changes, with substantial evidence indicating their geographic spread into highland, peri-urban, and temperate regions. Table 2 summarizes the causative agents and the key climatic and environmentally driven impacts for the principal VBDs affecting humans. Geographic expansion into highland, peri-urban, and temperate areas is already well documented for diseases like malaria, dengue, chikungunya, and Lyme disease as vectors adapt to newly suitable habitats (UNDP, 2025; Mertens, 2025). The synthesis emphasizes that prolonged breeding seasons and heightened incidence rates are prevalent in areas experiencing significant climate stress, swift urban expansion, and poor water management (APMEN, 2025). However, these patterns are not uniform across settings. The analysis indicates that climatic drivers interact with local environmental conditions—such as water storage practices, sanitation infrastructure, and vegetation cover—resulting in spatially variable risk profiles. This emphasizes that climate change functions as a risk amplifier instead of being an independent factor in disease transmission (UNDP, 2025; WHO, 2024). The synthesis reveals that even though these environmental factors are generally accepted, their influence is greatly shaped by local infrastructure and environmental management practices. This emphasizes the importance of tailored and integrated intervention strategies as opposed to standardized methods.

Policy, surveillance, and cross-sectoral gaps

The synthesis identifies integrated surveillance systems as a critical requirement for effective VBD control. Evidence across studies shows that monitoring systems combining entomological data, clinical case reporting, and climatic indicators are more effective in enabling early detection and targeted intervention (Ali and Kamraju, 2025; Rivera *et al.*, 2023). Table 3 details the critical metrics and data sources needed to operate these systems, including vector abundance indices, clinical incidence data, climatic anomalies, and measures of community engagement. The synthesis reveals that although these indicators are well established in policy frameworks, their practical implementation remains inconsistent. Many health systems are deficient in technical capacity, data integration infrastructure, and cross-sectoral coordination to convert these metrics into effective early warning systems. Further, the review points out that effective integration of meteorological and health data, especially within coordinated national frameworks, leads to more prompt outbreak detection and more precise interventions. Additionally, strengthened surveillance networks and improved data interoperability can facilitate timely risk assessment, support evidence-based decision-making, and enhance public health preparedness. However, in many low-resource and rapidly urbanizing settings, surveillance systems remain fragmented, limiting their predictive and operational value for effective disease prevention (van den Berg *et al.*, 2021; Lyimo *et al.*, 2022).

Table 2: Major vector-borne diseases, climatic drivers, and environmental risk factors (Zavaleta-Monestel *et al.,* 2025; WHO, 2024)

Vector-borne disease	Primary vector / pathogen	Main climate or environmental driver	Key impacts	Poor environmental maintenance factors
Dengue	*Aedes aegypti*, *Aedes albopictus* (virus)	Rising temperature, irregular rainfall	Increased mosquito breeding and outbreaks	Open water storage, blocked drains, poor waste disposal
Malaria	*Anopheles* mosquitoes (*Plasmodium* spp.)	Temperature rise, stagnant water, flooding	Extended transmission season, higher morbidity	Stagnant unmanaged water, poor drainage, lack of mosquito nets
Chikungunya	*Aedes* mosquitoes (virus)	Warm, humid conditions, heavy rainfall	Rapid community-level outbreaks, joint pain burden	Containers, tyres, or tanks left uncovered
Zika virus	*Aedes aegypti* (virus)	Heat and rainfall variation	Birth defects, neurological effects	Domestic water collection without lids, urban litter accumulation
Lyme disease	*Ixodes* ticks (*Borrelia burgdorferi*)	Warmer winters, vegetation growth	Spread to new highland or temperate zones	Overgrown vegetation, unmanaged animal habitats
Rickettsial diseases	*Ticks*, *mites* (bacteria)	Seasonal humidity and warmth	Skin lesions, fever, systemic infection	Poor livestock hygiene, unclean shelters, and bush overgrowth

Table 3: Core metrics and systems for policy and practice (Rivera *et al.,* 2023; Ali and Kamraju, 2025)

Metric / indicator	Source type	Policy levers	Practical use
Vector abundance indices (larval, adult)	Entomological surveys, community reports	Local vector control funding, target mapping	Prioritize locations for larval source reduction
Clinical case incidence and seasonality	Health facility records, surveillance reports	Diagnostic training, stockpiling diagnostics	Triggers focused on clinical response and case management
Climatic anomalies (temperature, rainfall)	Meteorological datasets, climate models	Early warning protocols, seasonal planning	Predicts high-risk transmission windows
Community engagement index	Qualitative studies, participatory monitoring	Capacity building, micro-grants	Guides investment in community-led interventions

Equity, infrastructure, and community capacity

The synthesis consistently shows that low-income regions, particularly in sub-Saharan Africa and South/Southeast Asia, bear the highest burden of climate-linked VBDs while contributing the least to global emissions (APMEN, 2025; Zavaleta-Monestel *et al.*, 2025). These areas encounter a twofold challenge of significant climatic exposure and restricted adaptive capacity. The spread of malaria and dengue into highland or non-traditional regions highlights the need for tailored, climate-informed, community-based approaches (de Souza and Weaver, 2024; UNDP, 2025). However, the effectiveness of such strategies is strongly influenced by underlying infrastructure conditions, including water supply systems, sanitation, and housing quality. The synthesis emphasizes that the decentralization of health services, the fortification of primary care systems, and the incorporation of climate variability into local planning processes are essential for improving resilience (Hiscox *et al.*, 2025; Rivera *et al.*, 2023). These approaches enable context-specific adaptation and improve responsiveness to emerging disease patterns. Nevertheless, enduring inequalities in resource distribution, healthcare access, and institutional assistance continue to impede the scalability and effectiveness of adaptation strategies, thus limiting their impact on the most vulnerable groups.

Research gaps and implications for scaling solutions

Cross-country expert synthesis and recent systematic reviews indicate priority areas for future research and implementation (Zavaleta-Monestel *et al.,* 2025):

- Climate-specific risk mapping: More granular, real-time climate and vector data sharing can enable precision targeting of high-risk communities and adaptive control strategies.

- Cross-sectoral coordination: There is ongoing need to break down barriers between meteorological, environmental, and health sector sharing protocols, budgets, and timelines for scalable action.
- Sustained financing: Developing and sustaining early warning systems (EWS), diagnostic facilities, and vector control infrastructure continues to pose a financial challenge for numerous vulnerable countries.
- Community empowerment: Investment in training, microgrants, and participatory monitoring significantly enhances local compliance and long-term effectiveness of vector-control.
- Equity: Explicit targeting and tracking of the most vulnerable populations is essential for achieving global health and climate justice. Children under five remain the most at-risk global demographic (APMEN, 2025).

Synthesis

The findings of this study demonstrate that multisectoral, context-specific, and equity-oriented approaches are required to effectively lessen the health threats posed by climate-driven VBD risks. As climate change accelerates, effective collaboration among science, policy, and community innovation will be essential for safeguarding public health (APMEN, 2025; WHO, 2024). No single intervention is sufficient; rather, effectiveness depends on the interaction between climatic conditions, community capacity, and institutional support.

RECOMMENDATION

1) Implementing Advanced Alert Systems: Regional authorities should develop integrated platforms that work together to synthesize climatic, entomological, and clinical data to permit rapid, localized public health responses to emerging VBD threats. Emphasis ought to be placed on interoperable systems that connect community-generated data with national surveillance frameworks. *2) Investing in Environmental Management and Community-Based Surveillance:* Sustainable control requires a shift away from temporary chemical interventions toward permanent physical modifications. This encompasses the formalization of the role of community health volunteers, along with the provision of technical training for localized vector control activities. Nonetheless, the feasibility is contingent upon ongoing funding and institutional backing, especially in informal or resource-limited environments. *3) Adaptive Health Capacity Systems:* Local health clusters must enhance frontline diagnostic capabilities in primary care settings. Capacity-building programs should focus on training providers in identifying evolving disease patterns. This approach will enable districts to dynamically adjust resource allocation, depending on the specific vector risks present within their localized environments. *4) Promoting Sustainable and Hygiene-Based Practices:* Public health strategies should prioritize their focus toward fostering long-term behavioral changes in community engagement. Promoting practices like safe water storage, effective waste management, and proper environmental sanitation can help decrease habitats conducive to vector breeding. *5) Fostering Cross-Sector Adaptive Governance:* Governance frameworks should promote coordination across health, environmental, water, and urban planning sectors. Institutional integration remains a major challenge, and requires clear accountability mechanisms, financing structures, and policy alignment. This study is constrained by its dependency on secondary data sources, limiting the inclusion of fresh empirical results or primary qualitative data exploring local adaptation in diverse socio-ecological settings (Cheong *et al.,* 2023). Certain potentially pertinent data remains unreachable because of language or publication limitations, and upcoming studies beyond 2025 may enhance comprehension further. The non-systematic nature of the search strategy may also limit completeness of evidence coverage, although efforts were made to ensure thematic

representativeness. Future research priorities include: 1) Longitudinal studies assessing community adaptation trajectories. 2) Economic analyses quantifying costs and benefits of integrated climate-health interventions. 3) Development of interoperable data platforms supporting real-time warning system. 4) Evaluation of equity-focused policies ensuring vulnerable populations are prioritized (Campbell-Lendrum *et al*., 2015; WHO, 2024). These studies will provide a foundation for responsive, effective, and fair strategies aimed at alleviating the serious public health dangers associated with climate-related VBDs.

CONCLUSION

This study offers a comprehensive qualitative synthesis of the evolving relationship between anthropogenic climate change and the global resurgence of VBDs. These results bolster the claim that climate variability has transitioned from a secondary environmental concern to a key factor influencing contemporary infectious disease patterns. Through the integration of evidence from ecological, socioeconomic, and institutional viewpoints, this research clarifies how the convergence of increasing temperatures, modified precipitation patterns, and rapid urbanization engenders precarious conditions for pathogens previously constrained by geographical and thermal limitations. This study greatly enhances our comprehension of the biological processes through which slight climatic changes trigger substantial epidemiological occurrences. The investigation demonstrates that a mere 1-2 ^{o}C increase in environmental temperature markedly shortens the extrinsic incubation period (EIP) of pathogens within their vectors, consequently elevating the incidence of transmission throughout a vector's lifespan. Furthermore, the study underscores a notable "altitude creep" and "latitude expansion" observed in species including Aedes aegypti and Phlebotomus sandflies. Urban centers situated at high altitudes, which previously enjoyed a certain level of "thermal protection," are currently experiencing prolonged transmission periods and elevated vector populations due to rising minimum temperatures that enable these species to survive and flourish in areas of highland that were once deemed unsuitable. The investigation further establishes that environmental drivers do not act in isolation; rather, they are mediated by deep-seated social and infrastructural vulnerabilities. This investigation reveals that the impact of climate-related illnesses is unevenly distributed, with the most vulnerable populations residing in locales characterized by substandard housing, unreliable water storage, and inadequate waste management, which collectively create conditions conducive to disease transmission. Within urban settings, the "urban heat island" phenomenon exacerbates the effects of poor sanitation, thereby prolonging the period of vector activity throughout the year and circumventing the natural seasonal patterns that typically regulate it. These observations emphasize the crucial relationship between public health resilience and the broader municipal infrastructure, specifically the urgent change from erratic water storage systems to trustworthy piped networks, in conjunction with the adoption of circular waste recovery approaches. Furthermore, this research elucidates a significant disparity at the institutional level, specifically between the processes of data acquisition and the capacity for effective, practical responses. Despite the progress achieved in digital surveillance, many systems still engage in reactive operations rather than proactive measures. The synthesis underscores the necessity of transitioning to "One Health" governance, which integrates human, animal, and environmental health sectors to identify zoonotic spillover events prior to their evolution into human epidemics. The effectiveness of integrated models, which encompass sentinel monitoring and the integration of real-time climatic data, provides a validated framework for transitioning from disjointed reporting to advanced, localized EWS.

Additionally, this study emphasizes community-led adaptation as the most enduring and economically viable approach to long-term vector control. The results demonstrate that as communities shift from passive recipients of health information to engaging actively in source reduction initiatives—such as through neighborhood committees or student-led volunteer programs—vector indices may decrease by as much as 95%. This transition requires formal institutional support, including training, micro-grants, and the integration of "citizen science" into national surveillance networks. Leveraging local knowledge and existing social structures allows health systems to monitor and manage the environment in a way that top-down approaches cannot. To summarize, establishing resilience in the face of climate and health challenges demands a comprehensive approach that relies on scientific data, is reinforced by institutional frameworks, and prioritizes community engagement. This study provides a strategic foundation for policymakers, which emphasizes that the future public health security depends on bridging the gap between global climate science and local social action. While the threat of climate-related diseases is growing, the evidence presented here suggests that combining infrastructure stability, digital integration, and community empowerment can transform high-risk areas into examples of adaptive resilience.

AUTHOR CONTRIBUTIONS

M.T. Akhtar, as the author solely conceived the study, performed the analyses, interpreted the results, and drafted and revised the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, 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

APMEN	Asia Pacific Malaria Elimination Network
CASP	Critical appraisal skills programcommunity-based adaptation
CBA	Community-based adaptation
CDCP	Center for Disease Control and Prevention
EID	Emerging infectious disease
EIP	Extrinsic incubation period
IVM	Integrated vector management
EWS	Early warning systems
GVCR	Global vector control response
spp.	species (plural)
U.S.	United States Department of Health
DHHS	and Human Services
UNDP	United Nations Development Programme
VBDs	Vector-borne diseases
WHO	World Health Organization

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ORIGINAL RESEARCH ARTICLE

Eco-friendly of chitosan effects from fish scales, shrimp shells, and black soldier fly larvae serves as a growth regulator

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ABSTRACT

BACKGROUND AND OBJECTIVES: Organic waste accumulation demands sustainable valorization strategies. Black soldier fly larvae efficiently convert waste into chitin-derived chitosan, an eco-friendly biostimulant. Nonetheless, the comparative effectiveness of insect-derived chitosan versus crustacean chitosan in the acclimatization of orchids has yet to be investigated. The objectives of this study were to evaluate effects of chitosan from fish scales, shrimp shells, and black soldier fly larvae exuviae at 0, 5, 10, and 15 milligrams per liter on growth of four epiphytic orchids (*Coelogyne asperata, Coelogyne pandurata, Dendrobium* species, *Grammatophyllum speciosum*) over 12 weeks, while characterizing structural differences using Fourier Transmission Infrared spectroscopy.

METHODS: A completely randomized factorial design with five replicates per treatment was employed. The chitosan from the exuviae of black soldier fly larvae was obtained through processes of demineralization, deproteinization, and deacetylation (with a deacetylation rate of 70 percent), whereas the chitosan derived from commercial fish and shrimp exhibited deacetylation rates of 95 and 80 percent respectively. Plantlets were cultured on Murashige and Skoog medium supplemented with chitosan treatments. Plant height, leaf, root, and shoot numbers were recorded weekly. Two-way Analysis of Varian was performed.

FINDINGS: The Fourier Transmission Infrared spectroscopy confirmed characteristic chitosan peaks across sources. Shrimp chitosan exhibited a pronounced Nitrogen-Hydrogen bending vibration at 685.45 centimeters to the power of minus one, while black soldier fly larvae exuviae chitosan displayed a unique skeletal vibration at 660.70 centimeters to the power of minus one. The source and concentration of chitosan did not have a significant impact on plant height, root count, or shoot count across all species. Nevertheless, the number of leaves exhibited responses that were specific to each species. In *Coelogyne asperata*, shrimp chitosan at 10 miligram per liter produced 6.8 leaves versus 4.2 in controls (62 percent increase). The *Grammatophyllum speciosum* treated with shrimp chitosan at 5 miligram per liter yielded 5.5 leaves versus 3.8 in controls. The source and concentration of chitosan did not have a significant impact on plant height, root count, or shoot count across all species. Nevertheless, the number of leaves exhibited responses that were specific to each species.

CONCLUSION: The black soldier fly larvae exuviae chitosan serves as a sustainable alternative to crustacean chitosans for orchid acclimatization. Leaf proliferation can be enhanced in a species- and source-dependent manner, supporting circular economy principles and guiding tailored biostimulant formulations for orchid conservation.

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47	6	1

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INTRODUCTION

The escalating generation of organic waste presents a pressing environmental challenge, yet this biological resource can be effectively repurposed through circular economy principles. The larvae of the black soldier fly (*Hermetia illucens*) have emerged as exceptional agents for bioconversion, efficiently transforming diverse organic byproducts into valuable biomass (Santoso *et al*., 2023). Apart from their contribution to waste valorization, these insects serve as a sustainable source of chitin, which can be converted into the adaptable biopolymer chitosan. Research has demonstrated that black soldier fly larvae (BSFL) cultivation from food waste achieves a high sustainability index, particularly excelling in economic viability while maintaining strong environmental and social dimensions (Kullan *et al*., 2026). The chitosan derived from insects demonstrates exceptional bioactive characteristics, serving as a natural biostimulant for plants that promotes growth and improves stress resilience. This study therefore explores the potential of chitosan from black soldier fly larvae exuviae (BSFLE), alongside conventional sources, as an ecofriendly growth promoter in the acclimatization of vulnerable orchid species. Orchids, which belong to the family Orchidaceae, represent one of the most diverse and ecologically significant groups of flowering plants globally, with over 25,000 species distributed across diverse habitats (Awasthi *et al*., 2023; Awasthi *et al*., 2024; Hu *et al*., 2022; Wei *et al*., 2025). These plants are distinguished not only by their exceptional morphological diversity and sophisticated pollination strategies but also by their ecological contributions and economic relevance in the horticulture and floriculture (Zhang *et al*., 2024). Southeast Asia harbours numerous endemic orchid species, including *Coelogyne asperata, Coelogyne pandurata, Dendrobium* species (sp)., and *Grammatophyllum speciosum*, which are known for their unique floral structures and cultural significance. However, orchids are facing several threats from habitat loss, climate change, and overcollection, necessitating effective conservation strategies that integrate propagation and sustainable cultivation techniques. Improving the growth and acclimatization of orchids outside of their natural environment remains a vital challenge for conservation and commercial production, underscoring the demand for innovative biostimulants that can encourage vigorous development and resilience to stress (Syafitri *et al*., 2024; Turnip, 2023). Four representative orchid species were selected to encompass different growth habits, conservation statuses and commercial relevance: two threatened epiphytes (*Coelogyne asperata, Coelogyne pandurata*), a flagship giant orchid with high public profile (*Grammatophyllum speciosum*) and a widely cultivated genus (*Dendrobium* spp.) that serves as a model for cut flower production. This combination provides a cautious assessment of chitosan's effectiveness across various species, while recognizing that responses specific to species and genotype, which are well-documented for chitosan (Stasińska-Jakubas and Hawrylak-Nowak, 2022). The significance of examining the impact of chitosan from various sources and concentrations on orchid development is rooted in the potential of this biopolymer as a natural growth stimulant and plant defence activator. Chitosan, a deacetylated form of chitin, is highly regarded for its biocompatibility, biodegradability, and diverse bioactivities, such as antimicrobial, antioxidant, and elicitor properties that support plant growth and improve stress resilience (El-Araby *et al*., 2022; El-Araby *et al*., 2024). Chitosan is conventionally derived from crustacean shells, including those of prawns (Vázquez-Aldana *et al*., 2025) and fish scales (Yasmin *et al*., 2025); however, alternative sources like BSFLE have surfaced as sustainable and underexploited biomass with significant bioactive potential. Examining the unique effects of chitosan derived

from fish, prawns, and BSFLE at varied concentrations with 0, 5, 10, and 15 milligrams per liter (mg/L) on four orchid species yields valuable information for optimizing biostimulant utilisation in orchid propagation and conservation. Recent advancements in chitosan research have elucidated its influence on the modification of plant physiological responses and growth metrics. A prior study demonstrated that the application of chitosan to the leaves significantly enhanced both shoot length and biomass in orchids by modulating phytohormone levels and improving water retention (Bhattacharyya *et al*., 2021; Masjedi *et al*., 2017). Similarly, Wang *et al*. (2021) reported that chitosan treatment increases secondary metabolite accumulation and growth in orchids, highlighting its potential to improve plant vigor under stressful conditions (Pujari *et al*., 2021). Furthermore, the bioactivity of chitosan derived from various sources, along with its molecular weight and degree of deacetylation, has a substantial impact on its efficacy in promoting plant growth (Suwanchaikasem *et al*., 2024). These studies collectively emphasize the importance of specific chitosan characteristics in affecting the efficacy of biostimulants. Furthermore, it has been shown that the effects of chitosan are concentration- and species-specific (Poznanski *et al*., 2023; Stasińska-Jakubas and Hawrylak-Nowak, 2022). Moderate chitosan concentrations optimize growth promotion, whereas higher doses may induce phytotoxicity Ningsih and Sari, 2023; Suwanchaikasem *et al*. (2024) emphasized that differential orchid responses to chitosan elicitation are influenced by species physiology and receptor affinity, necessitating tailored application protocols. Additionally, Escobar Rodríguez *et al*. (2025); Lagat *et al*. (2021b) demonstrated the valorisation of BSFLE in the production of chitosan, endorsing insect-derived chitosan as a sustainable environmental choice that is in harmony with circular economy ideals. These data together guide the investigation of BSFLE chitosan as an innovative biostimulant for orchids. Notwithstanding these advancements, a study void remains concerning the comparative effectiveness of chitosan sourced from BSFLE against standard crustacean origins in promoting orchid development. Although numerous studies on chitosan from different sources have been conducted, no prior research has concurrently compared chitosan derived from fish, shrimp, and BSFLE across four epiphytic orchid species during the acclimatization process. This study examines the structural variations in chitosan derived from fish, prawns, and BSFLE by Fourier-transform infrared spectroscopy (FTIR) and assesses their impact at various concentrations on the growth characteristics of four orchid species. The primary aim of this study is to comprehensively assess how the chitosan source (fish, shrimp, or BSFLE) and the concentrations influenced the growth of four orchid species, namely *Coelogyne asperata, Coelogyne pandurata, Dendrobium* spp., and *Grammatophyllum speciosum*, during the acclimatization phase. Specific objectives include characterizing the physicochemical properties of chitosan derived from these sources, as well as the quantification of growth responses, including plantlet height and the number of leaves, roots, and shoots. This study was conducted at the Faculty of Mathematics and Natural Sciences, Mulawarman University, Samarinda, East Kalimantan, Indonesia in 2025.

MATERIALS AND METHODS

Materials used

Four orchid species were used in this study: *Coelogyne asperata, Coelogyne pandurata, Dendrobium* sp., and *Grammatophyllum speciosum*. The orchid plantlets were obtained from an in vitro culture laboratory at the Faculty of Mathematics and Natural Sciences, Mulawarman University, Samarinda, East Kalimantan, Indonesia. All chemicals utilized in the extraction and purification of chitosan, such as sodium hydroxide (NaOH), hydrochloric acid (HCl),

and acetic acid (CH_3COOH), were of analytical grade. Distilled water was used throughout the experiment.

Chitosan sources

Chitosan from shrimp shells, Himeda, GRM93358, degree of deacetylation 80 percent (%) and fish scales (Phy Edumedia, SCRF/CH/05-24, degree of deacetylation 95%) were obtained from a commercial market. Chitosan from BSFLE was prepared based on a previously described method (Lagat *et al*., 2021). BSFLE samples were sourced from a local rearing facility post-molting stage, carefully cleaned, subjected to oven drying at 60°C, and ground into a fine powder. Demineralization was achieved using 1 molar (M) HCl for 2 hours (h) followed by deproteinization with 1 M NaOH at 90 degree Celsius (°C) for 3 h. The resulting insect chitin was deacetylated using 50% NaOH at 100°C for 3 h. The chitosan derived from BSFL was subjected to filtration, washing, drying, and subsequently stored in a dry environment until it was needed for further applications. This method resulted in a deacetylation degree of 70%.

Fourier transform Infrared spectroscopy

The analysis using FTIR spectroscopy was performed to verify the identity and functional groups of chitosan from the three biogenic sources. The chitosan samples were formulated into potassium bromide (KBr) pellets and analyzed with a PerkinElmer Spectrum Two FTIR spectrometer in the wavenumber range of 4000–400 per centimeter inverse (/cm). Key absorption peaks corresponding to functional groups, such as amine ($-NH_2$), hydroxyl (-OH), carbonyl (C=O), and carbon–oxygen single bond (C–O) stretching, were used to validate the molecular structure of each chitosan sample.

Experimental design and chitosan treatments

The experiment was conducted using a completely randomized factorial design involving three factors: chitosan source (shrimp, fish, and BSFLE), chitosan concentration (0, 5, 10, and 15 mg/L), and orchid species (*Coelogyne asperata, Coelogyne pandurata, Den*drobium spp and *Grammatophyllum speciosum*). Each treatment combination was replicated five times, utilizing one plantlet per replicate, thereby enhancing statistical strength and decreasing variability between the experimental units. Growth evaluations were conducted weekly throughout the 12-week experimental timeframe.

Culture media preparation

The culture media were created by initially adding 600 milliliters (mL) of sterile distilled water into a beaker positioned on a magnetic stirrer hotplate. Subsequently, 30 gram (g) of granulated sugar were incorporated and mixed with a magnetic stir bar until completely dissolved. Once the dissolution was complete, 4.43 g of Murashige and Skoog (MS) was added, along with chitosan derived from BSFLE, shrimp, or fish, according to the designated treatment concentrations of 5, 10, and 15 mg/L. These concentrations were based on preliminary range finding tests that showed no measurable effect below 2.5 mg/L and signs of phytotoxicity (leaf chlorosis, reduced root initiation) at 20 mg/L or above; the range therefore covers the subtoxic, potentially bioactive window. Sterile distilled water was subsequently incorporated to modify the final volume to 1000 mL. The potential of hydrogen (pH) of the solution was measured and adjusted to 5.8, as needed, using NaOH to raise the pH if below 5.8 or HCl to lower it above this value. After reaching the desired pH, 8 g of agar powder was incorporated into the solution. The mixture was boiled, and the hot medium was immediately dispensed into culture bottles, which were sealed using heat-resistant plastic secured with rubber bands. The sealed bottles underwent autoclaving at a temperature of 121°C and a pressure of 17.5 pounds per square inch (psi) for a duration of 15 minutes to guarantee thorough sterilization. After autoclaving, the culture bottles were allowed to cool and were subsequently arranged on sterilized

racks within a laminar flow culture room for further use.

Planting process

At this point, every variety of orchid plantlet was meticulously prepared and subsequently placed into a sterile bottle filled with subculture media, ensuring that all procedures were conducted under aseptic conditions and in compliance with the guidelines of a Laminar Air Flow Cabinet (LAFC). The bottles were labelled according to the treatment and planting date. Light intensity was measured at 45 ± 5 µmol/m²/s (photoperiod 16 h/8 h light/dark). Relative humidity in the culture room was maintained at 65 ± 5% using a humidifier. These conditions were recorded daily with a thermo hygrometer (Lutron HT- 3007) and light meter (Li 250A). The culture room was maintained in a sterile condition through daily applications of 70% alcohol.

Growth parameter measurement

Plant height was measured weekly for 12 weeks after planting (WAP), using a ruler from the base to the apex of the main stem. The leaf number was recorded by counting all fully developed leaves on each plant at weekly intervals throughout the 12-week period. Root development was measured by recording the overall number of visible roots that appeared weekly during the same observation timeframe. Shoot number was determined by recording the number of new shoots emerging on each plant every week for 12-weeks after planting.

Data compilation and analysis

All data collected during the 12-week period were compiled into structured spreadsheets, categorizing each plant by species, chitosan source, chitosan concentration, and observation week. The datasets constituted the basis for the statistical analyses described in the data analysis section. Statistical investigations were carried out to evaluate the influence of the chitosan source (Fish, Shrimp, BSFLE) and concentration (0, 5, 10, and 15 mg/L) on the growth performance of four orchid varieties. Initially, the main growth parameters were assessed for normality and homogeneity. A three-way analysis of variance (ANOVA) was first performed to test main effects and interactions among source, concentration and species. When significant three-way interactions were found ($p < 0.05$), separate two-way ANOVAs (source × concentration) were run for each species. Post-hoc comparisons used Tukey's Honestly Significant Difference (HSD). All assumptions were validated (Shapiro-Wilk, Levene). This approach facilitated the recognition of treatment combinations that significantly influenced each growth metric independently. All ANOVA assumptions, including normality, were validated by Shapiro–Wilk and Levene's tests. All statistical analyses were performed using GraphPad Prism (version 10) and Excel (Microsoft Office, Inc., United State of America), with significant criteria established at *P* is less than zero point zero five ($p < 0.05$). A post-hoc power analysis (GPower 3.1) was performed based on the observed effect sizes for leaf number ($\eta^2 = 0.32$). With alpha (α) = 0.05, sample size (n) = 5 per treatment gave a power of 0.82 for detecting a significant effect on leaf number, which is acceptable. For other parameters (height, root, shoot) the achieved power was lower (0.45–0.60), indicating that non-significant results should be interpreted cautiously and larger sample sizes may be needed in future studies.

RESULTS AND DISCUSSION

The FTIR determination

Chitosan, a derivative of chitin that has undergone deacetylation, serves as a biopolymer with numerous applications in the fields of biomedicine, agriculture, and environmental remediation, owing to its biocompatibility, biodegradability, and antimicrobial properties (El-Araby *et al.*, 2024). The physicochemical properties of chitosan vary depending on its source and extraction method, and can be characterized using FTIR spectroscopy (Sofyan,

2024; Vilar Junior *et al.*, 2016). This study analyzed chitosan derived from fish (A), shrimp (B), and BSFLE (C) to identify the key functional groups and structural differences among these sources. The FTIR analysis of chitosan derived from three sources (fish, shrimp, and BSFLE) revealed distinct spectral patterns, indicating variations in their chemical structures (Fig. 1). The FTIR spectra of chitosan from fish (A), shrimp (B), and BSFLE (C) exhibited characteristic absorption bands corresponding to functional groups, such as oxugen hydrogen single bond (O-H), nitrogen-hydrogen single bond (N-H), and carbon-hydrogen single bond (C-H) stretching vibrations, as well as amide and carbonyl groups. The spectra were analyzed in the range 4000–500/cm, with prominent peaks identified for each source. Respectively, the FTIR spectrum of fish-derived chitosan shows prominent peaks at 3826.16/cm (O-H stretching), 3579.42/cm (N-H stretching), and 3213.87/cm (O-H/N-H combined stretching). The amide I band appears at 1589.63/cm, while the amide II band was observed at 1419.28/cm. The C-H stretching vibrations are noted at 2881.47/cm and 2832.97/cm. The peak bserved at 1026.83/cm is associated with the stretching of a carbon-oxygen-carbon single bond (C-O-C), which signifies the presence of the glycosidic linkage in chitosan. The presence of these peaks confirmed the deacetylation process and the typical polysaccharide structure of chitosan. These peaks also corresponded with the bands indicated in the statement, including 3826.16/cm (O-H stretching), 3579.42/cm (N-H stretching), and 1589.63/cm (amide I). However, the precise wavenumbers may fluctuate based on the extraction techniques methods or instrumentation. In shrimp-derived chitosan displays peaks are observed at 3827.74/cm (O-H stretching), 3712.39/cm (N-H stretching), and 3164.84/cm (O-H/N-H combined stretching). The amide I band was observed at 1586.94/cm and the amide II band at 1420.11/cm. C-H stretching vibrations were noted at 3050.40 /cm and 2335.99/cm. The peak at 1018.47/cm corresponds to C-O-C stretching. The spectrum additionally displays a distinct at 685.45/cm, which is attributed to the out-of-plane bending vibrations of the N-H groups and is less prominent in the other sources. Martínez-Robinson *et al.* (2022) conducted FTIR analysis on chitosan from *Farfantepenaeus californiensis* exoskeleton, identifying characteristic bands for O-H, N-H, and amide groups, consistent with the statement's peaks at 3827.74/cm (O-H stretching), 1586.94/cm (amide I), and 685.45/cm (N-H out-of-plane bending). In a similar manner, Sjamsiah *et al.* (2024) conducted an analysis of oligochitosan derived from shrimp shells, which confirmed structural alterations following hydrolysis, as evidenced by FTIR peaks within the 700–3000/cm range, thereby supporting the finding of a significant N-H bending vibration. The chitosan from BSFLE exhibited peaks at 3607.73/cm (O-H stretching), 3578.30/cm (N-H stretching), and 3139.99/cm (O-H/N-H combined stretching). The amide I band appears at 1589.63/cm, and the amide II band at 1419.28/cm. The C-H stretching vibrations are observed at 2881.47/cm and 2832.97/cm. The peak at 1026.83/cm corresponds to C-O-C stretching. Significantly, the spectrum exhibits a peak at 660.70/cm, which can be ascribed to the skeletal vibrations of the pyranose ring, a characteristic that is less pronounced in other sources. Lagat *et al.* (2021) reported FTIR bands for BSFLE chitosan at 1650/cm and 1587/cm, closely resembling commercial shrimp chitosan, while peaks at 1655/cm (amide I) and 1590/cm (NH_2 bending), supporting the statement's claim of a unique peak at 660.70/cm for skeletal vibrations. Comparative analysis of the three sources of chitosan using FTIR spectra revealed similarities and differences (Table 1). All the spectra exhibited characteristic peaks for O-H, N-H, and C-H stretching, confirming the presence of the primary functional groups of chitosan.

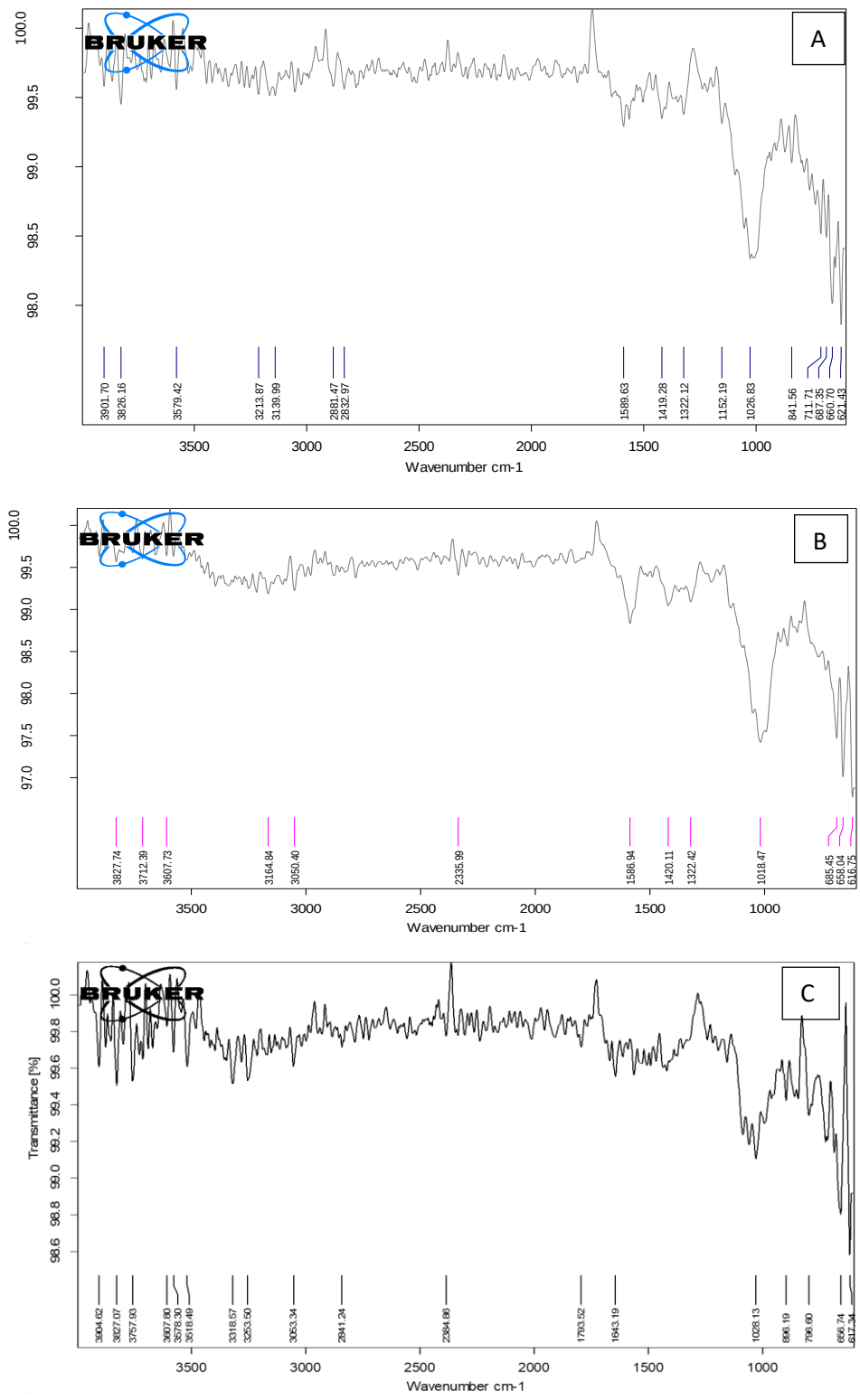

Fig. 1: The FTIR of three sources: A. fish; B. shrimp; black soldier fly larvae exuviae of chitosan

Table 1: The FTIR peak assignments across chitosan sources (/cm)

Source	O-H stretching	N-H stretching	Amide I	Amide II	C-O-C stretching	Unique peaks
Fish scales	3700–3000	3700–3000	1640	1545	1026	564 (NH bending)
Shrimp shells	3827.74	3712.39	1586.94	1420.11	1018.47	685.45 (N-H bending)
BSF larvae exuviae	3607.73	3578.30	1589.63	1419.28	1026.83	660.70 (skeletal)

Nevertheless, chitosan obtained from shrimp exhibited a more significant N-H bending vibration at 685.45/cm. In contrast, chitosan derived from black soldier fly larvae exuviae revealed a distinct peak at 660.70/cm. On the other hand, fish-derived chitosan shows a broader O-H/N-H combined stretching band, which may reflect variations in the hydrogen bonding patterns. Furthermore, amide I and II bands were consistent across all sources, confirming the presence of acetylated residues. However, the relative intensities of these bands differed, with chitosan derived from shrimp exhibiting the most significant intensity for the amide I band, implying a greater residual acetyl content. The C-O-C stretching vibrations (1026–1018/cm) were consistent across all the spectra, confirming the integrity of the glycosidic linkages. Degree of deacetylation (DD) varied across sources (fish 95%, shrimp 80%, BSFLE 70%) and is known to modulate chitosan's bioactivity (Mukarram *et al*., 2023). However, the species specific leaf promotion (BSFLE best for *C. pandurata* and shrimp best for *C. asperata*) cannot be explained solely by DD, as the highest DD (fish) was not always most effective. Differences in molecular weight, acetylation pattern and remaining protein/lipid components are likely contributing factors, as emphasized by Elouali *et al*. (2024).

Plant height

This study examined the effects of chitosan derived from three different sources, namely fish, shrimp, and BSFLE, and four concentrations (0, 5, 10, and 15 mg/L) on the plant height of four orchid species over a 12-week acclimatization period. Figs. 2 and 3 illustrate the plant height trends for each orchid species in these treatments. Notwithstanding the noticeable differences in growth patterns, the statistical evaluation conducted at week 12 indicated that there were no significant variations ($P > 0.05$) in plant height among all chitosan sources and concentrations within each orchid species. Specifically, for *C. asperata* and *C. pandurata*, plant height measurements under the three sources of chitosan showed overlapping growth trajectories regardless of the concentration applied, as indicated by the uniformity of the symbols representing 0, 5, 10, and 15 mg/L concentrations. Similarly, *Dendrobium* sp. and *G. speciosum* exhibited comparable growth responses across all chitosan treatments, with no statistically significant differences discernible among sources or concentrations. The lack of considerable differences indicates that neither the source of chitosan nor its concentration within the examined range had a significant effect on the height growth of these orchid species during the 12-week period. Moreover, the source of chitosan in fish, shrimp, or BSFLE did not have a differential impact on plant height, which is consistent with the results of Román-Doval *et al*. (2023) and Stasińska-Jakubas and Hawrylak-Nowak (2022), who noted similar bioactivity of chitosan from various sources when purified to equivalent levels of deacetylation and molecular weight. This suggests that the physicochemical properties

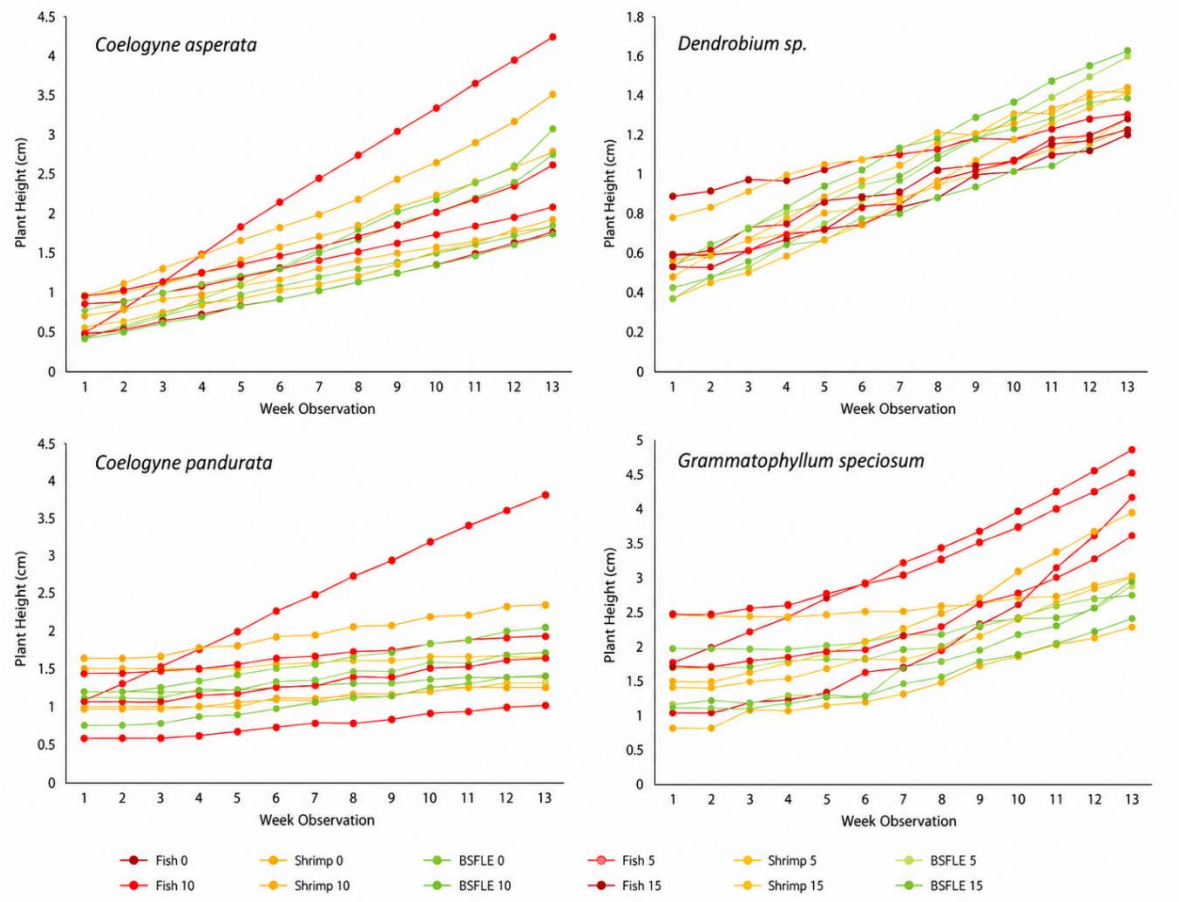

Fig. 2: Plant height of the several orchid acclimatized using various sources and concentration of chitosan during 12 weeks of observation. At week 12, the statistical analysis indicated no significantly different (*P > 0.05)* for all sources and various concentration of chitosan in each types of orchid. Notes: Chitosan from fish indicated with red line; shrimp, orange line; Black soldier fly larvae exuviae/BSFLE, green line. The concentration level (mg/L) of chitosan indicated by: circle for 0; triangle for 5; Square for 10; and diamond for 15 mg/L.

of chitosan rather than its biological source predominantly determine its biostimulant efficacy. It is also critical to consider that plant height is a single morphological parameter and may not fully capture the spectrum of the effects of chitosan across different developmental growth stages.Alternative growth metrics, including root development, biomass accumulation, flowering time, and biochemical indicators, may uncover more subtle responses under diverse environmental and physiological conditions influencing overall plant performance and adaptive capacity. (Lopez-Moya *et al.*, 2017; Suwanchaikasem *et al.*, 2024).

Leaf number

The present study also demonstrated distinct and variable interspecific physiological responses among four orchid species (Coelogyne asperata, Coelogyne pandurata, Dendrobium sp., and Grammatophyllum speciosum) to chitosan treatments varying by source (fish, shrimp, and BSFLE) and concentrations (0, 5, 10, and 15 mg/L). The number of leaves, evaluated after a period of 12 weeks, demonstrated statistically significant variations, as denoted by the different letters (a, b) positioned above the bars, which illustrate the varying effectiveness of chitosan treatments (Fig. 4). Practically, an 62 % increase

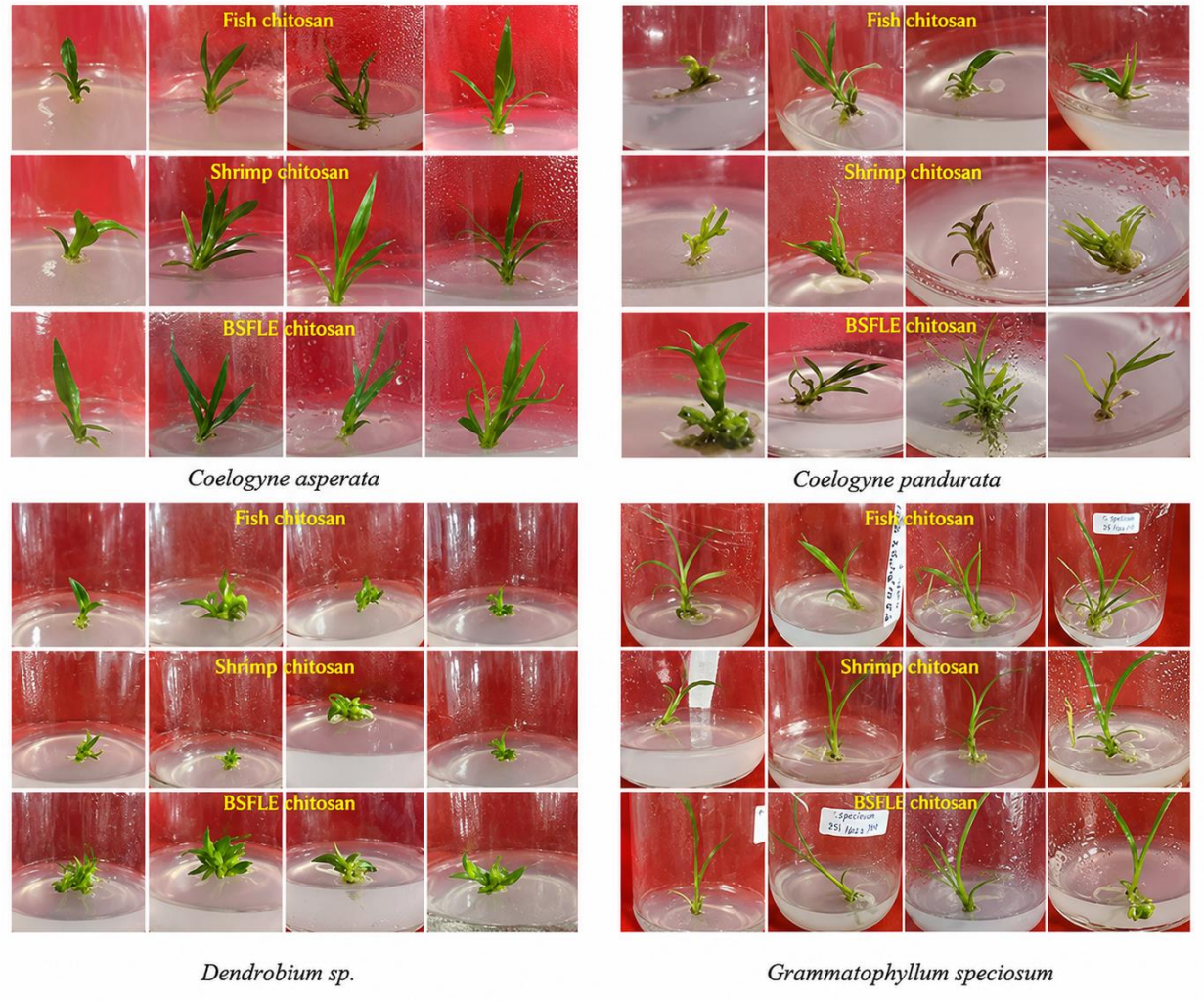

Fig. 3: Planlets of four types of orchid acclimatized with various sources (Fish, Shrimp, and Black soldier Fly Larvae Exuviae/BSFLE) and different concentration (from left to right at each type of chitosan: 0, 5, 10, 15 mg/L) of chitosan at week 12

in leaf number (*Coelogyne asperata*, shrimp chitosan 10 mg/L) translates into an estimated gain of 3–4 weeks in acclimatisation time, because plants with 6–7 leaves were ready for potting 25 days earlier than control plants with 4 leaves. These enhancements hold considerable economic importance for commercial orchid nurseries and expedite the reintroduction of rare species. Chitosan acts as a defence elicitor that triggers a cascade of signalling events: it increases cellular Ca^{2+} and reactive oxygen species (ROS), which activate mitogen activated protein kinases (MAPKs) and transcription factors. In turn, this upregulates antioxidant enzymes (superoxide dismutase, catalase, peroxidase) and modulates phytohormone homeostasis (Mukarram *et al.*, 2023). The net effect can be either growth promotion or defence, depending on dose and species. The current leaf promotion is probably a consequence of a mild, chronic stimulation that activates auxin/cytokinin signaling without initiating a complete defense response (*Suarez-Fernandez et. al.*, 2020). Interaction with endogenous hormones is well documented.

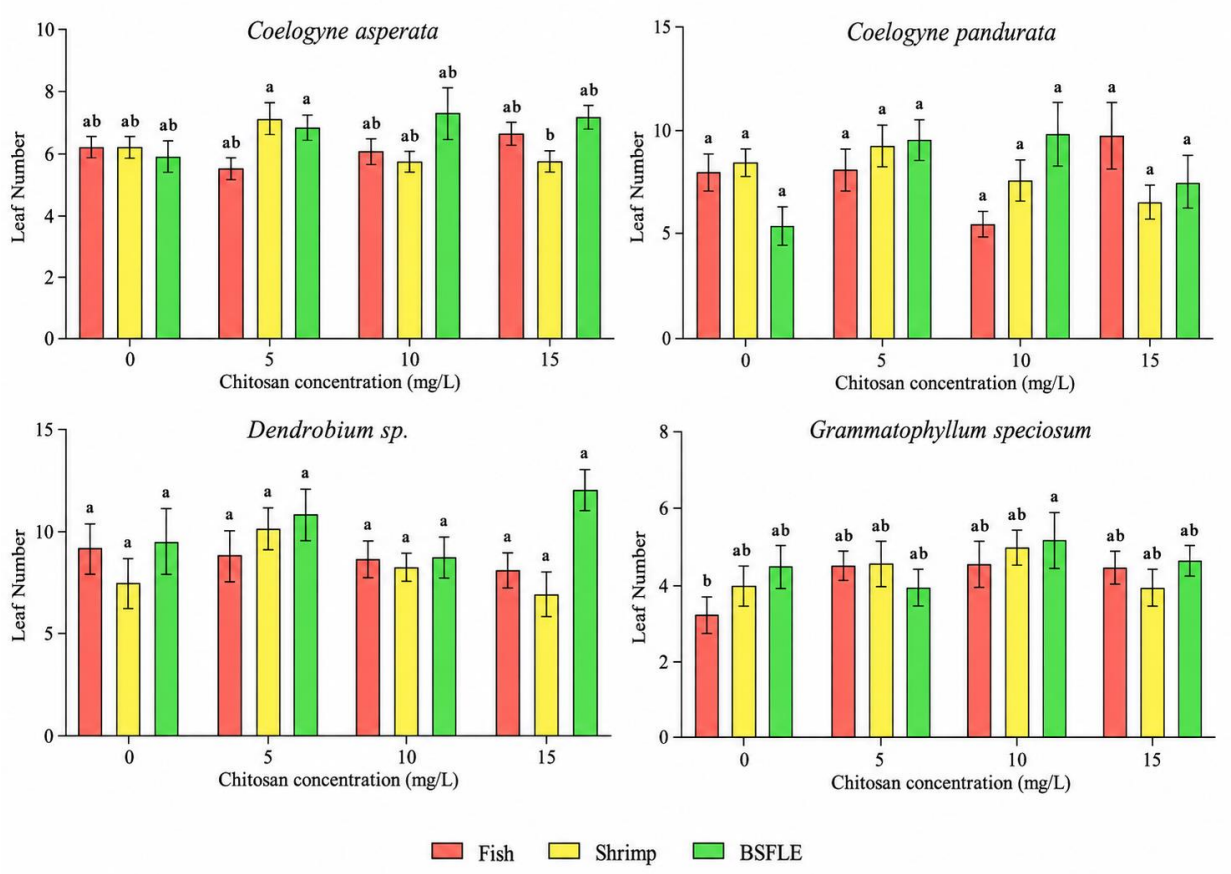

Fig. 4: Leaf number (mean ± SE, n = 5) of four orchid species after 12 weeks of acclimatisation with chitosan from fish, shrimp or BSFLE at 0, 5, 10, 15 mg/L. Different letters (a,b) above bars within the same species indicate significant differences ($p < 0.05$). Absence of letters indicates no significant difference

In wheat, chitosan increased IAA, GA and CK concentrations (El Amerany *et al.*, 2022). In tomato, chitosan microparticles initially activated the reporter genes for auxin and cytokinin (Suarez-Fernandez *et. al.*, 2020). Moreover, chitosan can repress gibberellin signalling in barley embryos (Lopez Moya *et al.*, 2017). In this study, the increase in species-specific leaf responses may be a reflection of the different ways in which the three chitosan sources modulate these hormone pathways. These differential hormonal interactions may further influence leaf initiation, expansion, and overall vegetative development among the studied species. Subsequent studies have delivered thorough insights into how chitosan acts as a growth enhancer for plants and a trigger for defense responses, thereby explaining the observed increases in leaf number. Chitosan bioactivity is influenced by several factors, such as its molecular weight and degree of deacetylation, which are influenced by the source material (Mukarram *et al.*, 2023; Román-Doval *et al.*, 2023). This observation is consistent with the species-specific responses identified in this study between shrimp-derived chitosan and that derived from BSFLE. The superior performance of shrimp-derived chitosan at intermediate concentrations for *C. asperata* and *G. speciosum* aligns with Abou El-Enin *et al.* (2023); El Amerany *et al.* (2022) found that chitosan enhances plant growth parameters,

including leaf proliferation, through the modulation of nutrient uptake and hormonal signalling. Moderate chitosan doses optimize leaf development. The distinct optimal response of *C. pandurata* to BSFLE-derived chitosan at 5 mg/L may vary in bioactivity, depending on the source-specific molecular structure. The unique oligomeric profile of BSFLE chitosan could more effectively interact with receptors in *C. pandurata*, stimulating growth at lower concentrations (Fuhrmann *et al.*, 2022; Lee *et al.*, 2022; Schäfer *et al.*, 2025). Moreover, the increase in leaf number of *Dendrobium sp*. in a dose-dependent manner with fish-derived chitosan at 15 mg/L was corroborated by earlier studies which highlighted that elevated chitosan concentrations can promote growth in specific monocots by stimulating defense-related enzymes and improving stress tolerance (Ji *et al.*, 2022; Sathiyabama and Manikandan, 2021). These results are also in line with previous findings revealing that chitosan's dual role in promoting growth and eliciting oxidative stress responses may explain why *Dendrobium sp.* tolerates and benefits from higher chitosan levels, whereas other species favour lower doses (Pujari *et al.*, 2021). Responses that are specific to each species can be attributed to the differences in the perception of chitosan oligosaccharides at the floral and root levels. Every orchid species contains a unique array of chitin/chitosan binding receptors, whose affinities fluctuate according to the chitosan DD and MW (Suwanchaikasem et al., 2024). A key limitation is the unequal DD across sources (fish 95%, shrimp 80%, BSFLE 70%). The DD affects solubility, charge and receptor affinity (Mukarram *et al*., 2023; Carera *et al*., 2023). Therefore, the observed source-specific leaf promotion cannot be attributed solely to biological origin; DD differences may have contributed. The assertion that BSFLE chitosan serves as a feasible alternative continues to hold true; however, subsequent studies ought to evaluate sources with corresponding DD to distinguish source-specific effects.

Root number

The evaluation of root number in four orchid species, *Coelogyne asperata, Coelogyne pandurata, Dendrobium* spp., and *Grammatophyllum speciosum*, subjected to chitosan treatments of fish, shrimp, and BSFLE at concentrations of 0, 5, 10, and 15 mg/L over a 12-week acclimatization period revealed no statistically significant differences among all treatment groups ($p > 0.05$) (Fig. 5). Notwithstanding the evident numerical trends, including a marginal increase in root numbers associated with shrimp-derived chitosan treatments at a concentration of 10 mg/L, these findings did not achieve statistical significance when analyzed across different sources, concentrations, or species. This uniformity in root number response indicates that within the tested parameters, the chitosan source and concentration did not exert a discernible effect on root proliferation in the studied orchids. These findings are consistent with prior research demonstrating that the influence of chitosan on root development can be variable and often species- and context-dependent. Numerous studies have indicated that chitosan promotes root growth mainly by modulation of phytohormones and activation of antioxidant defense mechanisms; however, these effects may be subtle or obscured under specific experimental conditions (El Hadrami *et al.*, 2010). The absence of significant differences in root number may reflect the complex interplay of chitosan's molecular characteristics, such as degree of

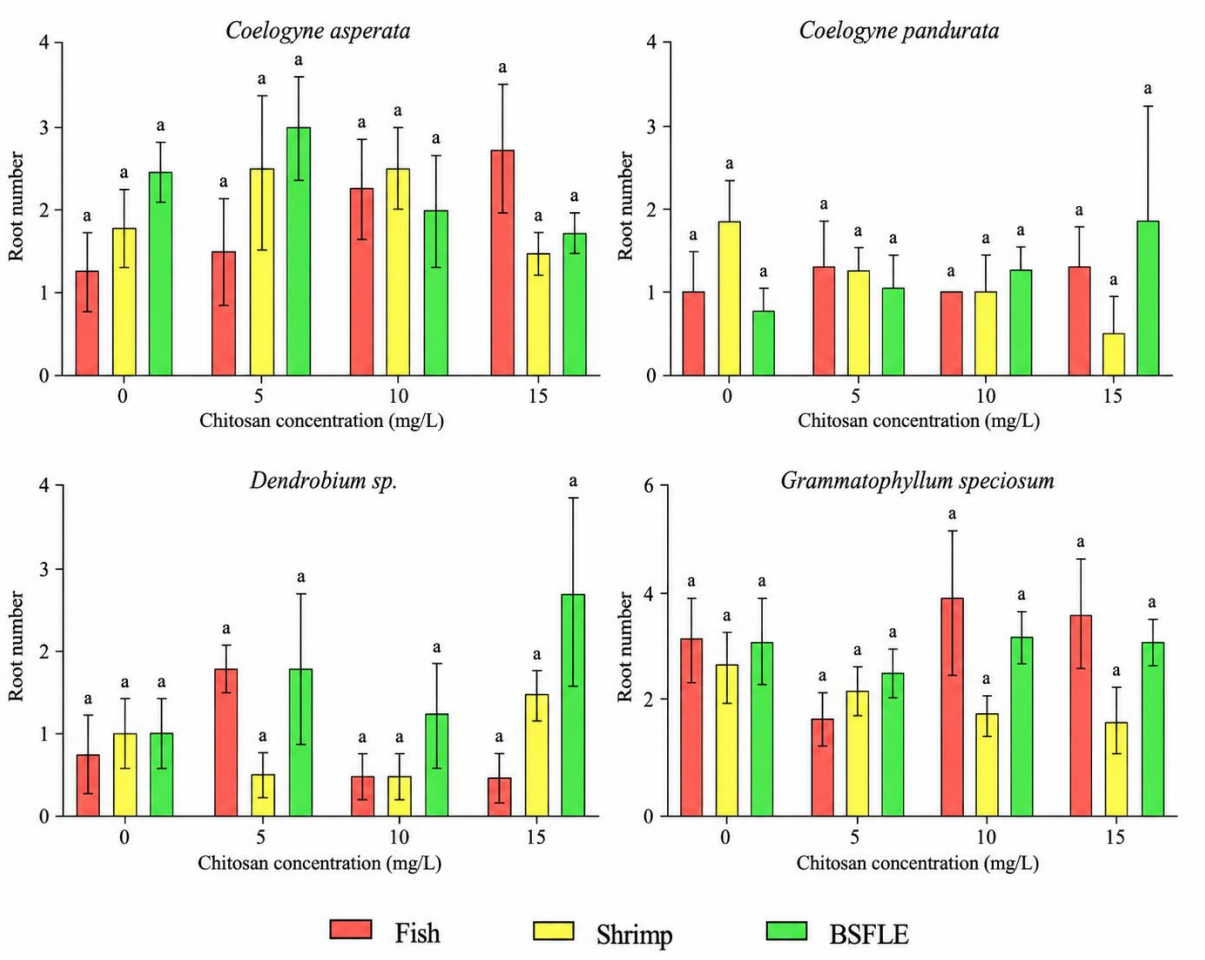

Fig. 5: Root number of the several orchid acclimatized using various concentration of chitosan. Different alphabet (a,b) above the bars at the same orchid indicate significantly different at $P < 0.05$. The data observation was obtained at the week 12 of acclimatization

deacetylation, molecular weight, and purity, which vary by source but do not necessarily translate into uniform biological effects (Kumar, 2000). The chitosan obtained from shrimp demonstrated a greater deacetylation rate (80%) than that of BSFLE chitosan (70%). Nevertheless, this did not lead to statistically superior root proliferation, aligning with findings that molecular differences alone do not guarantee enhanced root induction (Kumari *et al.*, 2017). The deficiency of a remarkable reaction in various orchid species may be linked to fundamental physiological attributes and growth phases that impact root formation, possibly taking precedence over external agents such chitosan (Suwanchaikasem *et al.*, 2024). The subdued root reaction in *G. speciosum*, recognized for its unique root structure, further corroborates species-specific sensitivity to biostimulants (Quitadamo *et al.*, 2021). The chitosan concentrations tested, between 5 and 15 mg/L, likely neither enhance nor suppress root growth, aligning with studies suggesting moderate chitosan levels optimize growth, while elevated concentrations may cause stress or phytotoxicity under prolonged exposure and varying environmental conditions (Soostani *et al.*, 2025).

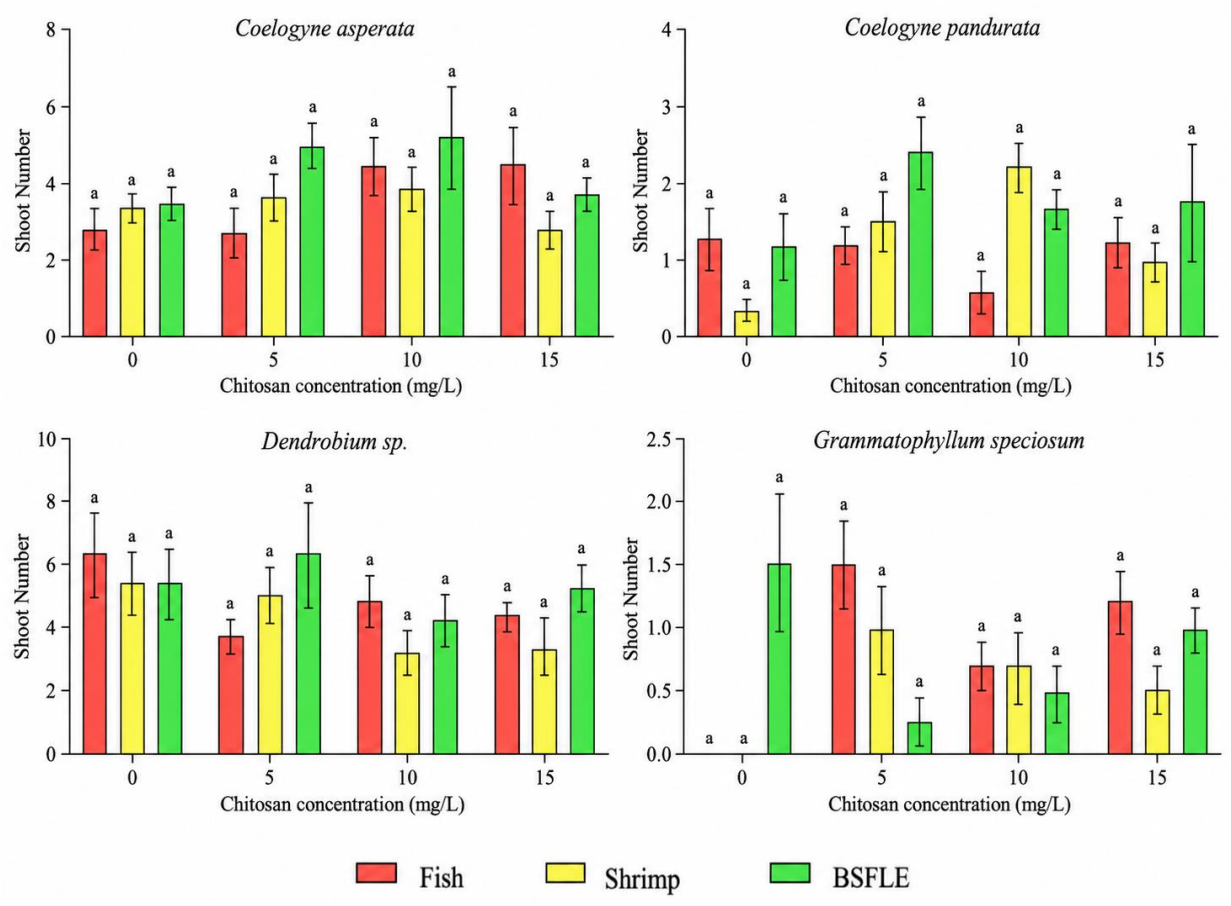

Fig. 6: Shoot number of the several orchid acclimatized using various concentration of chitosan. Different alphabet (a,b) above the bars at the same orchid indicate significantly different at $P < 0.05$. The data observation was obtained at the week 12 of acclimatization

The outcomes further underscore the likely effects of environmental and methodological variables during acclimatization, including nutrient availability and humidity, which may influence root growth and potentially conceal subtle treatment effects (Riseh *et al.*, 2023). The remaining proteins and lipids present in chitosan derived from insects may affect its bioactivity, potentially explaining the intermediate and statistically insignificant root responses observed with BSFLE chitosan under varying experimental conditions and species-specific physiological responses during early developmental growth stages (Mei *et al.*, 2024).

Shoot number

The study investigated the effects of the chitosan derived from fish, shrimp, and black soldier fly larvae exuviae (BSFLE) at concentrations of 0, 5, 10, and 15 mg/L on the number of shoots on four different types of orchids. It found that there were some trends in shoot growth, but the trend were not statistically significant across all species (Fig. 6). Specifically, although shrimp-derived chitosan at 10 mg/L appeared to promote the highest shoot numbers in *C. asperata* and *C. pandurata*, these increases were not statistically significant across all treatments and species. For *Dendrobium* spp. and *G. speciosum*, chitosan treatments from all

sources and concentrations, including shrimp at 10 mg/L, did not produce statistically significant differences in shoot count when compared to the controls ($p > 0.05$). In *G. speciosum*, shoot number responses were particularly muted, with no significant variation detected among any of the chitosan treatments. The overall absence of a substantial impact on shoot quantity among the four orchid species is consistent with the wider observation that the impact of chitosan on morphological traits can be specific to the species and dependent on concentration, often demonstrating minor or non-significant effects on particular growth characteristics (Shah *et al.*, 2021). Chitosan's physicochemical properties, such as its molecular weight and degree of deacetylation, which can differ by source, may affect bioactivity, yet chitosan generally do not lead to significant amounts of shoot growth under the conditions tested (Wang and Roman, 2023). Furthermore, lack of significant variations suggests that chitosan's role as a shoot growth promoter is limited or overshadowed by the natural growth patterns of the species and the factors that help orchids adapt to their environment (El Amerany *et al.*, 2022). Comparative studies have indicated analogous results, wherein chitosan treatments improved specific growth parameters such as root development or leaf count, while shoot number either remained unchanged or exhibited only slight enhancements. This may be due to the complex regulation of shoot meristem activity, which involves multiple hormonal and genetic controls that chitosan alone cannot sufficiently modulate (Suwanchaikasem *et al.*, 2024).

CONCLUSION

This study has illustrated that chitosan sourced from the exuviae of black soldier fly larvae acts as a feasible and eco-friendly alternative to standard crustacean-derived chitosan for the acclimatization of orchids. The black soldier fly larvae exuviae chitosan can enhance leaf number in a species-specific manner (*C. pandurat*a) but does not improve height, root or shoot growth. For orchid species that respond positively, BSFLE chitosan may serve as a sustainable alternative to crustacean chitosans, but its efficacy is not universal. The results further validated that all three chitosan sources (fish scales, shrimp shells, and BSFL exuviae) demonstrated distinct polysaccharide structures as observed through FTIR spectroscopy, with shrimp-derived chitosan showing a pronounced N-H bending vibration at 685.45/cm and BSFL exuviae chitosan revealed a distinctive skeletal vibration at 660.70/cm. These structural variations indicated source-specific physicochemical properties that may influence bioactivity. The only significant growth parameter affected was leaf number, which reacted in a manner dependent on both species and source. Plant height, root number and shoot number were unchanged. *Coelogyne asperata* treated with shrimp chitosan at 10 mg/L produced 6.8 leaves compared to 4.2 in controls, representing a 62 percent increase. *Grammatophyllum speciosum* responded optimally to shrimp chitosan at 5 mg/L with 5.5 leaves versus 3.8 in controls. *Coelogyne pandurata* showed optimal response to BSFLE chitosan at 5 mg/L, while *Dendrobium* species exhibited dose-dependent leaf increase with fish chitosan at 15 mg/L. These findings validated that the effectiveness of chitosan as a biostimulant depends on the specific orchid species as well as the unique molecular properties of the biopolymer from its source. Several limitations of current study, only four orchid species were tested, limiting generalizability across the diverse Orchidaceae family. Furthermore, the species-specific nature of chitosan's effects suggests that even among the Orchidaceae family, various

genera or hybrids might exhibit different responses to identical sources and concentrations of chitosan. Thus further screening of rare, threatened and commercially important orchids, such as *Paphiopedilum*, *Cattleya* and *Phalaenopsis hybrids*, is needed before general recommendations can be made. Chitosan concentrations were restricted to 5, 10, and 15 mg/L based on preliminary trials, leaving higher or lower doses unexplored. The degree of deacetylation varied across sources (95% for fish, 80% for shrimp, 70% for BSFLE), potentially confounding source-specific effects with deacetylation differences. Moreover, the molecular mechanisms responsible for the unique leaf responses observed in different species were not explored, encompassing variations in phytohormone levels, gene expression patterns, or changes in cell wall structure. The practical benefits of this study are substantial for orchid conservation and sustainable horticulture. The BSFLE chitosan offers an environmentally friendly alternative that reduces dependence on marine crustacean waste, which is often contaminated with heavy metals or requires energy-intensive processing. Insect farming for chitosan production aligns with circular economy principles by valorizing organic waste streams into high-value bioproducts. Customized chitosan formulations can promote leaf growth during the essential acclimatization stage for orchid nurseries and conservation initiatives, which may lead to higher survival rates and lower production expenses. Future research should prioritize elucidation of the molecular pathways through which source-specific chitosan structures influence leaf meristem activity. In particular, the present 12 week experiment captured only initial vegetative responses; longer term studies (≥12 months) are needed to assess effects on flowering, seed production, stress tolerance and biomass partitioning, as has been called for in other chitosan studies. Transcriptomic or proteomic studies that compare the responses of orchids to various chitosan sources would help in identifying potential receptors and signaling cascades. Long-term field studies extending beyond 12 months are needed to assess persistent effects on flowering, seed production, and stress tolerance. Refining the techniques for extracting BSFLE chitosan to reach elevated levels of deacetylation similar to those found in commercial products may boost bioactivity. Finally, economic feasibility studies comparing BSFLE-based chitosan production with crustacean sources would inform industrial adoption for agricultural biostimulant manufacturing.

AUTHOR CONTRIBUTIONS

S. Samsurianto conceptualized the study idea, designed the study, supervised the project, analytical measurements, and preparing the manuscript draft. R. Kusuma conducted the investigation, performed the literature review, curated the data, and drafted the manuscript. E.S.D. Rahmadhani managed data collection, performed statistical analysis, and contributed to data interpretation. M.K.B. Butar conducted the Fourier-transform infrared spectroscopy analysis and interpreted the results. R.A. Nugroho provided critical insights into insect-derived biopolymer applications, contributed to the refinement of the discussion and conclusions, and assisted in manuscript revision.

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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, 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

°C	Degree Celsius
%	Percent
±	Plus minus
ANOVA	Analysis of Variance
BSFLE	Black soldier fly larvae exuviae
BSFL	Black soldier fly larvae
cm	Centimeter
/cm	Reciprocal centimeter (wavenumber)
DMRT	Duncan Multiple Range Test
Fig	Figure
FTIR	Fourier-transform infrared spectroscopy
g	Gram
h	Hour
H_2	Hydrogen
HCl	Hydrogen chloride (hydrochloric acid)
HNO_3	Nitric acid
K	Potassium
KBr	Potassium bromide
kg	Kilogram
L	Liter
LAFC	*Laminar air flow cabinet*
Ltd	Limited
M	Molar
m	Meter
mg	Milligram
Mg	Magnesium
mg/L	Milligram per liter
mL	Milliliter (10^{-3} liter)
mL/g	Mililiter per gram
mL/min	Milliliter per minute
mm	Milimeter
MMT	Million metric ton
MPa	Megapascals
MS	Murashige and Skoog

Mt	Metric ton
MUFA	Mono-unsaturated fatty acid
N_2	Nitrogen
Na	Sodium
NaOH	Sodium hydroxide
P	Phosphorous
rpm	Revolutions per minute
SE	Standard error
spp	Species pluralis
WAP	Weeks after planting

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CASE STUDY

Spatiotemporal dynamics of land use applied to sustainability in the Andes mountain range

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ABSTRACT

BACKGROUND AND OBJECTIVES: Land use and land cover changes are a major driver of environmental transformation in mountain regions, where steep environmental gradients amplify impacts on water regulation, biodiversity, and agricultural systems. The upper Chicamocha River basin, located in the Colombian Andes, is a strategic socio-ecological system that sustains regional food security and water supply. Over the last several decades, this basin has seen a swift reconfiguration of its territory, influenced by the intensification of agriculture, the growth of infrastructure, and reforms in land governance that occurred after conflicts. The study objectives were to evaluate spatiotemporal land-use changes in the Chicamocha River basin between 1986 and 2023 and examines their implications for territorial sustainability and water management.
METHODS: Multi-temporal Landsat imagery (30 meters resolution; <30 percent cloud cover) from 1986, 2000, 2016, 2021, and 2023 was processed using an object-based image analysis approach in software CATALYST professional. Segmented objects were categorized into 12 land-cover classifications in accordance with the scheme established by the Institute of Hydrology, Meteorology and Environmental Studies scheme, achieving overall accuracies and Kappa coefficients above 0.80. Change detection and transition matrices were generated in ArcGIS Pro, and dominant trajectories were quantified through gains, losses, persistence, and annual change rates. The resulting indicators were incorporated into a strengths, weaknesses, opportunities, and threats – Threats, opportunities, weaknesses, strengths strategic framework to formulate evidence-based land-use planning recommendations.
FINDINGS: The findings indicate a shift in territory marked by the simultaneous presence of ecological recovery and increased productivity. Agricultural land declined by 16.8 percent over the study period, while forests and semi-natural areas increased from 26.6 to 30.9 percent of the basin. Artificialised areas exhibited the highest cumulative growth (>200 percent), with urban land expanding by approximately 65 percent and mining increasing from 0.05 to 0.44 percent. Subsequent to 2016, there was a notable intensification of conservation and regeneration efforts, particularly in high-altitude ecosystems, which coincided with the reinforcement of environmental governance.
CONCLUSION: These findings indicate that sustainability in Andean basins depends on differentiated territorial zoning: consolidating forest recovery in upper catchments while strictly regulating urban expansion, extractive activities, and water-intensive agriculture in valley bottoms. The integrated remote sensing and transition-based methodology outlined in this document offers a replicable framework to facilitate land-use planning and multi-tiered water governance within intricate mountain socio-ecological systems.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
73	8	8

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INTRODUCTION

Land use and land cover (LULC) changes are among the most evident manifestations of contemporary socio-ecological dynamics and are primarily driven by anthropogenic activities such as deforestation, agricultural expansion, urbanisation, mining, and infrastructure development (Francos *et al.,* 2024; Mengist *et al.,* 2021). These changes not only demonstrate the interplay between society and the environment but also impact ecosystem functioning, biodiversity patterns, and the availability of natural resources. At multiple spatial scales, LULC changes modify surface energy balances, disrupt hydrological cycles, intensify climate extremes, and affect the stability of ecosystem services such as carbon sequestration, flood regulation, and water provision (Akanga *et al.,* 2022). In elevated terrains, these influences are commonly heightened owing to pronounced environmental gradients, complex landforms, and considerable climate fluctuations (Chan *et al.,* 2024). The Andes Mountain Range, the longest continuous continental mountain system in the world, extending over 8000 km across seven South American countries, Argentina, Chile, Bolivia, Peru, Ecuador, Colombia, and Venezuela, constitutes a particularly sensitive socio-ecological system (Arias *et al.,* 2021). Pronounced altitudinal gradients, outstanding biodiversity, and heterogeneous ecosystems play a crucial role in the regulation of regional climate, water availability, and carbon storage in Andean landscapes (Comer *et al.,* 2022). Recent studies demonstrate that Andean forests act as globally significant carbon sinks and that land-use changes in these environments can intensify temperature increases and alter precipitation regimes, especially under the influence of large-scale climatic phenomena such as La Niña (Duque *et al.,* 2021; Manciu *et al.,* 2023). Furthermore, the alterations in land use patterns in Andean watersheds, alongside climatic factors, have significant consequences for soil erosion, sediment movement, and river shape (Carrillo and Mao, 2020; Rivera-Fernández *et al.,* 2025). The rise in agricultural intensification, deforestation, and urban expansion has been associated with elevated erosion rates, loss of nutrients, and changes in drainage systems, especially during severe rainfall occurrences (Gebremariam *et al.,* 2025; Areu-Rangel *et al.,* 2024). These geomorphological responses, combined with heterogeneous precipitation patterns, shape the hydrosedimentary dynamics of Andean basins and condition their vulnerability to floods, landslides, and water scarcity (Maragaño-Carmona *et al.,* 2023). LULC change also represents a critical driver of biodiversity loss in the Andes (Ríos-Touma *et al.,* 2023). This area contains an unusually high number of endemic species relative to its small size on Earth's surface (Yánez-Muñoz *et al.,* 2024). Habitat conversion associated with agriculture, grazing, mining, and infrastructure development reduces habitat connectivity and threatens species persistence, particularly for taxa with narrow thermal tolerances such as amphibians and forest-dependent birds (Palacio *et al.,* 2020). These ecological pressures have a direct impact on ecosystem services such as pollination, water regulation, and carbon sequestration, and the deterioration of these services threatens both environmental resilience and human well-being in mountain areas (Ioan *et al.,* 2025). Given these dynamics, multi-temporal monitoring of LULC using remote sensing and geographic information systems (GIS) has become a strategic approach for detecting, quantifying, and interpreting territorial transformations (Sahle and Yeshitela, 2018; Yesuph and Dagnew, 2019). Numerous studies worldwide demonstrate that multi-scale and multi-temporal analyses provide robust technical inputs for land-use planning, environmental management, and sustainability-oriented public policies. Applications range from dynamic environmental zoning in Brazilian watersheds (Yadav *et al.,* 2024) to integrated land–water

assessments in African basins (Desta *et al.,* 2017; Rajaei *et al.,* 2021) and spatial optimisation of land use in arid and mountainous environments (Masoudi *et al.,* 2021). Nonetheless, the applicability of these methods necessitates meticulous contextualization, especially in areas where socio-political factors significantly influence biophysical processes. In Colombia, the Eastern Cordillera is a strategic Andean socio-ecological system due to its role in regulating water, supporting agricultural production, and conserving biodiversity (Rodríguez *et al.,* 2023). Moorland ecosystems supply primary water sources such as the Chicamocha River and Lake Tota, supporting human consumption, irrigation, and productive activities (Suárez Parra *et al.,* 2023). The presence of high-altitude ecosystems, inter-Andean valleys, and nascent agricultural frontiers forms a complicated mosaic of land-use practices, often in situations of ecological delicacy (Fontanilla-Díaz *et al.,* 2021). In Andean regions, traditional agricultural practices and community-based water management systems have historically shaped landscape configuration; however, increasing market integration and institutional transformations have altered these dynamics in recent decades. Within this context lies the upper Chicamocha River basin (CARCh, acronym in Spanish). This bioregion sustains food security and livelihoods for more than 20 municipalities in central-eastern Colombia (Suárez Parra *et al.,* 2023). Despite its ecological richness and high levels of endemism (Vallejos-Garrido *et al.,* 2023), the basin has experienced increasing pressures over the past decades, including agricultural expansion, urbanisation, diffuse pollution, and mining-related conflicts. These processes have led to a decline in water quality, diminished base flows, and placed pressure on water governance frameworks (Poveda-Sotelo *et al.,* 2022; Ríos-Touma *et al.,* 2023; Zárate-Rueda *et al.,* 2022). Additionally, the post-2016 Peace Agreement between the Colombian government and the FARC-EP (acronym in Spanish) has reconfigured rural land-use dynamics by enabling new economic activities and accelerating land-use change in Andean and Andean–Amazonian transition zones (Ángel-Osorio *et al.,* 2020; Lopez Barrera *et al.,* 2022). Despite the strategic relevance of the CARCh, existing studies have addressed LULC change in a fragmented manner, often focusing on water provision, ecosystem conservation, or socio-environmental conflicts separately. Despite the availability of important local diagnoses and sectoral analyses, there remains a deficiency in a comprehensive, long-term evaluation that merges multi-temporal LULC analysis with the spatial identification of human-induced pressures and their territorial consequences. This limitation constrains the ability to characterise dominant transformation trajectories, understand how productive and natural areas are being reconfigured over time, and generate technical evidence directly applicable to land-use planning and water management under increasing environmental and social pressures. Within this framework, this study explores the subsequent research questions: i) What spatiotemporal patterns and trajectories of LULC change have occurred in the CARCh between 1986 and 2023? Moreover, ii) How do these land-use transitions spatially overlap with strategic ecosystems, agricultural areas, and artificialised territories, and what implications do these dynamics have for territorial sustainability and water resource management in an Andean mountain context? This study aims to evaluate land-use changes in the CARCh between 1986 and 2023 using Landsat satellite imagery, remote sensing techniques, and GIS to identify patterns of territorial transformation and their implications for ecosystems and agricultural production. In this sense, this study constitutes a technical input to guide territorial planning, water management strategies and regional sustainability policies, providing solid evidence for decision-making in complex socio-environmental contexts. This study was conducted in Chicamocha, Colombia, in 2024.

MATERIALS AND METHODS

Study area

The upper Chicamocha River basin is located in the eastern Andes of Colombia (Fig. 1). This basin covers an area of 2147.7 square kilometres (km^2), distributed across 24 municipalities in the department of Boyacá (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2025). The altitudinal range of the basin varies between 2650 and 2800 meters (m) above sea level (Quevedo *et al.,* 2020a). The basin is composed of a fluvio-lacustrine plain of halohydrothermal origin, surrounded by mountain ranges of sedimentary rocks interspersed with volcanic formations, featuring a landscape characterized mainly by gentle slopes (Castro-Ricaurte and Cardenas, 2023; Garavito and Caro, 2018). The area is influenced by high climatic variability and experiences phenomena such as recurrent frosts in high mountain areas (Fajardo Rojas, 2019; Martínez *et al.,* 2017), forest fires during dry seasons, mass movements on steep slopes, and flooding in low areas (Ochoa-Sánchez *et al.,* 2025). These multi-scalar events modify the natural dynamics of the territory, condition land-use patterns (Castro-Ricaurte and Cardenas, 2023), affect agricultural productivity, and increase the vulnerability of communities settled in the region (Valencia Ortiz and Martínez-Graña, 2023). The average annual temperature is 13.1 degrees Celsius (°C), with March and November being the warmest months (Quevedo *et al.,* 2020b). The climate can be described astropical mountain, with alternating periods of high and low rainfall, influenced by the intertropical convergence zone (ITCZ). Rainfall patterns display a bimodal distribution, occurring from south to north during April and May and from north to south between September and November, with atypical variations between May and August (Garavito and Caro, 2018). The CARCh is regarded as a crucial area for food security in Colombia and serves as a significant provider of agricultural products. To ensure productivity and reduce vulnerability to climate variability, reservoirs and irrigation districts have been developed to regulate water supply and mitigate the risk of flooding during periods of intense rainfall (Quevedo *et al.,* 2021). The analysis of spatiotemporal LULC dynamics in the CARCh, between 1986 and 2023, was structured into four sequential and complementary phases: i) data preparation, ii) object-based land-use classification, iii) multitemporal change analysis, and (iv) strategic territorial assessment (Fig. 2). This comprehensive framework integrates remote sensing, GIS, and expert-driven strategic analysis to produce reliable and replicable technical inputs for sustainable land-use planning in Andean mountain environments.

Phase 1: Data preparation and temporal framework

Multi-temporal satellite imagery from the Landsat missions (Landsat 5, 7, 8, and 9) was used to characterise land-use dynamics for the years 1986, 2000, 2016, 2021, and 2023 (Table 1). These dates were determined according on two complementary criteria: i) the availability of cloud-free approximately <30 percent (%) and radiometrically consistent imagery ensured comparability across the entire time series (Zhang *et al.,* 2024), and ii) the selected years correspond to significant socio-environmental and political milestones in the region, encompassing both pre- and post-infrastructure expansion phases, agricultural intensification processes, and the timeframe following the 2016 Peace Agreement in Colombia, which notably transformed land governance and rural land-use dynamics in Andean basins (Murillo-Sandoval *et al.,* 2021). All images were downloaded from the USGS EarthExplorer platform (Path 7, Row 56) and clipped using the official CARCh shapefile to delineate the area of interest (AOI) (USGS, 2025). The uniform spatial resolution of 30 meters facilitated the long-term observation of land-use patterns and minimized uncertainty related to scale in change detection assessments.

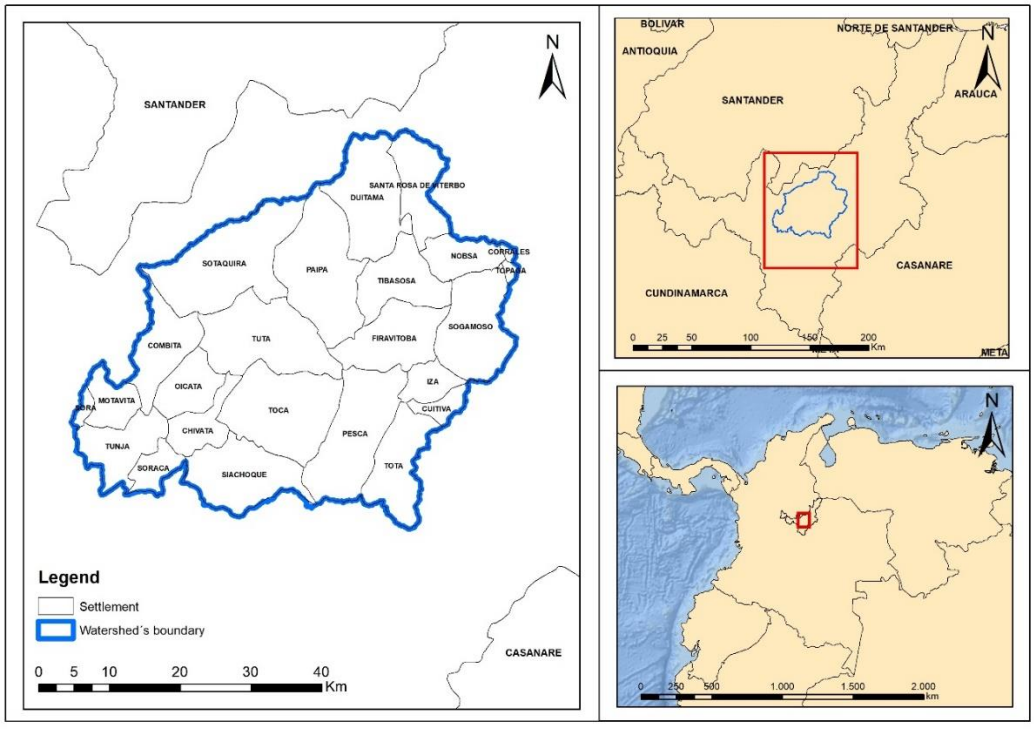


Fig. 1: Geographic location of the study area in the upper Chicamocha River basin in Colombia

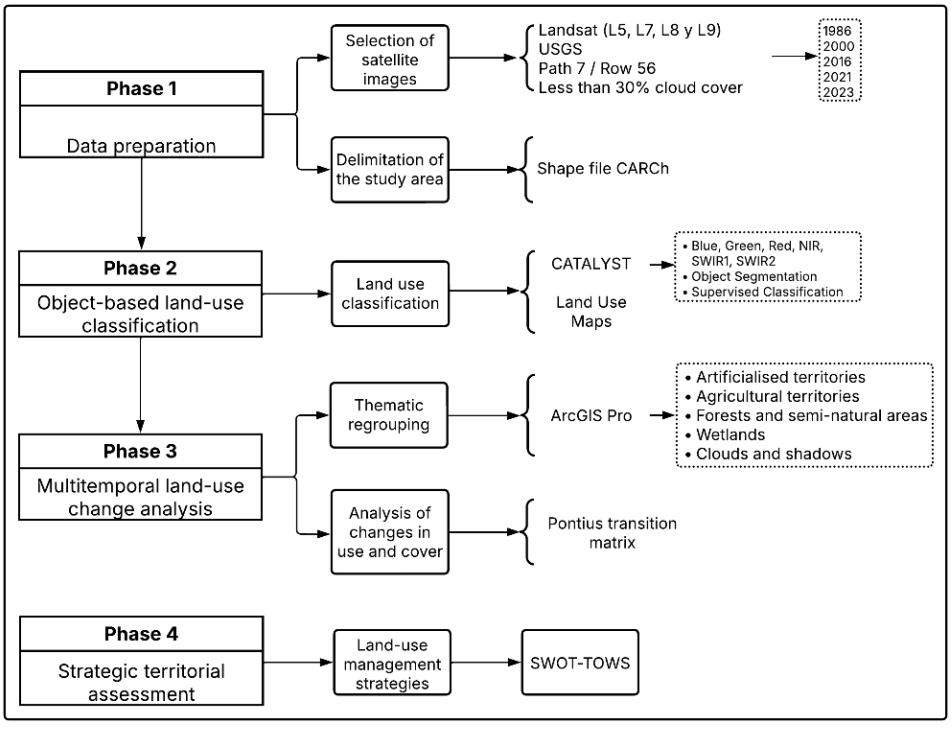


Fig. 2: Flowchart of the methodological approach

Table 1: General characteristics of Landsat images

Satellite mission	Landsat sensor	Image acquisition	Pixel size
L5	Landsat 4-5 Traffic Message Channel (TMC2L1)	13/01/1986	
L7	Landsat 7 Enhanced Thematic Mapper Plus (ETM+) C2L1	13/12/2000	
L8	Landsat 8-9 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) C2L1	16/01/2016	30 m
	Landsat 8-9 OLI/TIRS C2L1	13/11/2021	
L9	Landsat 8-9 OLI/TIRS C2L1	27/11/2023	

Phase 2: Object-based land-use classification

Land-use classification was conducted using CATALYST Professional software, applying an object-based image analysis (OBIA) approach (Mohammadi and Sedaghat, 2024; Nguyen *et al.,* 2025). OBIA was selected for its established effectiveness in alleviating spectral confusion in heterogeneous mountain landscapes, especially concerning crops, pastures, urban areas, clouds, and greenhouses (Darren How *et al.,* 2020). Image segmentation was performed using a multiresolution algorithm with scale = 25, shape = 0.5, and compactness = 0.5. These values were determined through iterative validation tests combining visual assessment and object coherence analysis, ensuring that segmented objects accurately represented meaningful landscape features such as agricultural parcels, forest patches, and urban blocks, while avoiding over- or under-segmentation (Nguyen *et al.,* 2024). For each segment, spectral attributes, including minimum, maximum, mean, standard deviation, and geometric attributes, including circularity, elongation, and rectangularity, were computed to enhance class separability (Cechim Junior *et al.,* 2023). Training samples were outlined by employing a blend of high-resolution satellite imagery, existing land-cover maps, and expert visual interpretation. A defined and balanced number of training polygons was determined for each class to ensure statistical robustness (Phinzi *et al.,* 2023). Supervised classification was subsequently utilized to produce 12 land-cover categories in accordance with the classification framework suggested by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, acronym in Spanish) (Table 2) (Instituto de Hidrología, 2012; Fagua *et al.,* 2023). Clouds and shadows were initially classified as independent categories to prevent spectral contamination (Dash *et al.,* 2023). In the course of post-processing, these classes were concealed and omitted from change analysis, thereby guaranteeing that transitions were computed solely for valid land-cover data (Velastegui-Montoya *et al.,* 2019; Velastegui-Montoya *et al.,* 2020). Classification accuracy was assessed using confusion matrices and the Kappa coefficient (Arthur *et al.,* 2025; Bagwan and Gavali, 2021). Validation points were selected using stratified random sampling. A total of 600 validation points were generated using stratified random sampling, with at least 50 points per class to ensure statistical representativeness. Overall accuracy (OA) and Kappa values (K) for each year exceeded 0.80, confirming the reliability of the land-use maps.

Phase 3: Multitemporal land-use change analysis

The classified maps were analysed in ArcGIS Pro to quantify land-use transitions for the periods 1986–2000, 2000–2016, 2016–2021, and 2021–2023 (Zhai *et al.,* 2024). Pixel-based change detection was performed using the Combine and Tabulate Area tools, enabling the construction of transition matrices that describe gains, losses, persistence, and conversions among land-use categories (Pacheco *et al.,* 2024). To enhance clarity and conform to territorial planning objectives, the original 12 land-cover classes were restructured into five hierarchical categories, as depicted in Table 3 (Instituto de Hidrología, 2012; Fagua *et al.,* 2023). This regrouping reflects functional similarities in land-use impacts on hydrological regulation, ecosystem services, and landscape fragmentation. In this context, roads,

Table 2: Parameters for image segmentation

Sl.No.	Classes	Details
1	Urban	Concentrates population, cities, and road infrastructure
2	Industrial	Productive infrastructure such as factories, power plants, refineries, and port areas
3	Mining	Mining extraction zones
4	Agriculture	Agricultural production
5	Confined cultivation	Agricultural areas such as greenhouses, nurseries, or crops
6	Open-field agriculture	Land prepared for agriculture
7	Pasture	Areas covered by natural or introduced pastures
8	Sparse vegetation	Scattered or sparse vegetation cover is present in moorland areas
9	Forest	Natural forest formations
10	Water	Bodies of water such as rivers, lakes, reservoirs, or lagoons
11	Clouds	Temporal coverage recorded in satellite images
12	Shade	Areas with no reflectance in satellite images

Table 3: Hierarchical levels for the reclassification matrix

Sl.No.	Territories - Level 1	LULC Classes - Level 2
1	Agricultural	Cropland, confined cropland, pasture, and agricultural land
2	Artificialised	Urban, industrial, and mining areas
3	Forests and semi-natural areas	Forest and sparse vegetation
4	Wetlands	Water
5	No data	Clouds and shade

dams, and mining sites were specifically recognized through object-based classification and subsequently evaluated as artificial transitions that impact forest persistence and semi-natural landscapes. Although no landscape metrics were computed, the spatial quantification of infrastructure expansion and mining growth enables the identification of fragmentation patterns, reductions in habitat continuity, and potential impacts on ecosystem integrity. By incorporating these dynamics into the strategic evaluation phase, the study links infrastructure-driven landscape transformation with biodiversity conservation and territorial sustainability in the Andean context. To assess the detected transformations, the spatial results were exported to Microsoft Excel, where transition matrices and pivot tables were constructed (Table 4). The construction of the matrix followed the methodological approach of Pontius *et al.* (2004) and Belay *et al.* (2024), allowing the calculation of absolute and relative changes, annual growth rates, and dominant transformation trajectories (Muñoz Marcillo *et al.,* 2023). The mean annual rate of change for each land-use category was used to compute the annual growth rates over the specified time interval. This approach provides a linear estimation of yearly land-use dynamics and ensures comparability across periods of unequal temporal length. The use of a mean annual change metric is appropriate for descriptive spatiotemporal assessments that quantify net landscape transformations. These metrics establish a quantitative framework for pinpointing significant land-use dynamics, including agricultural expansion, urban growth, and forest regeneration. In this context, the following processes were defined: i) conservation and expansion of artificialised territories, urban frontier areas, infrastructure, agricultural territories and bodies of water; ii) regeneration corresponding to forests and semi-natural areas. Methodological integration not only facilitates the recognition of spatial dynamics but also delivers relevant technical insights for territorial planning, water management, and the preservation of strategic ecosystems. Fig. 3 summarises the methodological flow used in the three phases.

Table 4: Land use reclassification matrix

Territories	Land use	Artificialised			Agricultural				Forests and semi-natural areas		Wetlands
		Urban	Industrial	Mining	Agriculture	Confined cultivation	Open-field agriculture	Pasture	Sparse vegetation	Forest	Water
Artificialised	Urban Industrial Mining	Conservation of artificially developed areas			Expansion of the agricultural frontier				Regeneration of natural areas		Expansion of bodies of water
Agricultural	Agriculture Confined cultivation Open-field agriculture Pasture	Expansion of urban boundaries and infrastructure			Conservation of agricultural lands				Regeneration of natural areas		Expansion of bodies of water
Forests and semi-natural areas	Sparse vegetation Forest	Expansion of urban boundaries and infrastructure			Expansion of the agricultural frontier				Conservation of forests and semi-natural areas		Expansion of bodies of water
Wetlands	Water Shade	Expansion of urban boundaries and infrastructure			Expansion of the agricultural frontier				Regeneration of natural areas		Conservation of bodies of water

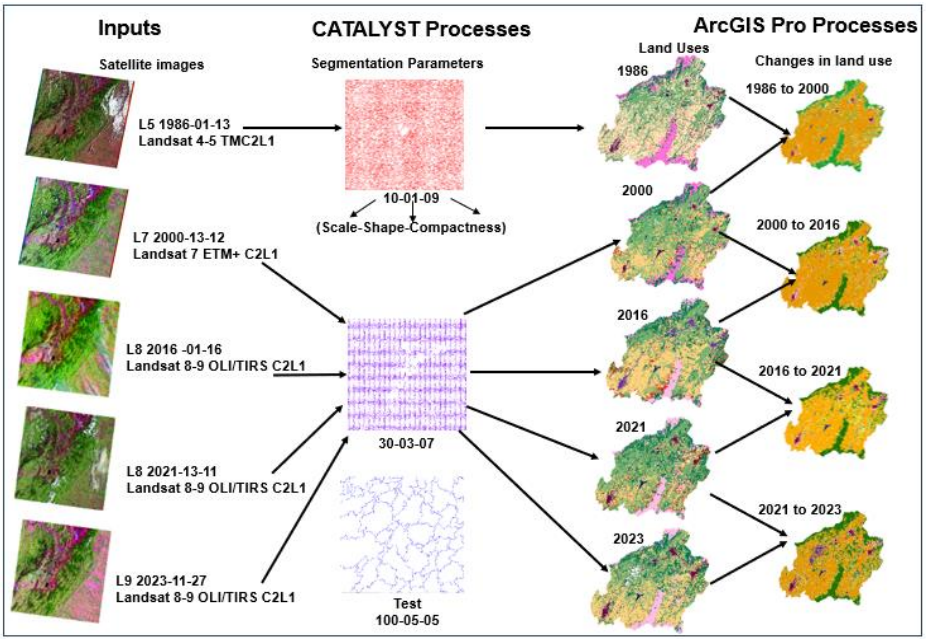


Fig. 3: Methodological summary for the multi-temporal analysis of land uses in CARCh

Phase 4: Strategic territorial assessment (SWOT–TOWS)

The quantitative results derived from the multitemporal change analysis were integrated into a strategic territorial assessment using the SWOT–TOWS (strengths, weaknesses, opportunities, and threats) framework. This tool facilitated the development of strategies aimed at attaining optimal outcomes and enhancing decision-making (Phadermrod *et al.,* 2019). Strengths and weaknesses were defined based on internal biophysical and land-use dynamics (e.g., forest persistence and agricultural expansion rates). Simultaneously, opportunities and threats

were influenced by external socio-political and institutional elements, which encompassed infrastructure development, mining pressures, and the governance frameworks related to land (Gkoltsiou and Mougiakou, 2021). The SWOT analysis was developed through a structured expert-selection process involving 10 specialists with demonstrated professional experience in land management (n = 3), environmental planning (n = 4), and water governance and hydrological management (n = 3) (Herrera-Franco *et al.,* 2022). Experts were selected based on three criteria: i) a minimum of five years of professional or academic experience in Andean territorial planning, ii) direct involvement in land-use or watershed management projects, and iii) institutional representation from academia, public environmental agencies, and regional planning authorities. The selection procedure was carried out via a two-phase participatory workshop. In the first stage, participants were individually presented with the multi-temporal outputs derived from Phases 2 and 3, including classified land-use maps, transition matrices, annual growth rates, and quantitative indicators of gains, losses, and persistence for each category (Etongo *et al.,* 2023). This strategy confirmed that all strategic assessments were firmly rooted in empirical geospatial evidence. In the second stage, a moderated plenary discussion was conducted to collectively identify and prioritise strengths, weaknesses, opportunities, and threats. Consensus was achieved through continuous dialogue and agreement, with the resulting components structured into a SWOT matrix. Subsequently, the TOWS matrix was applied, strengths are combined with opportunities and threats (S+O; S+T), while weaknesses are paired with opportunities and threats (W+O; W+T), to formulate land-use management strategies to improve territorial sustainability, regulate urban expansion, conserve strategic ecosystems, and strengthen water resource management in the CARCh. This expert consultation, characterized by its structured and evidence-based approach, enhances methodological transparency and guarantees that strategic outputs are explicitly connected to quantified spatiotemporal land-use dynamics. Although this study does not implement explicit predictive simulation models, the spatiotemporal framework developed here provides a robust empirical basis for future scenario modelling in Andean Mountain regions. Through the quantification of long-term land-use trajectories, annual transition rates, and major conversion pathways across various political and socioeconomic periods, the analysis reveals structurally enduring dynamics and regime shifts that are crucial for predictive methodologies. The integration of geospatial change metrics with institutional, infrastructural, and governance-related drivers through the SWOT–TOWS framework establishes a scenario-oriented platform that supports future modelling exercises under differentiated climate, socioeconomic, and policy conditions, thereby directly informing forward-looking sustainable land-use planning.

RESULTS AND DISCUSSION

The spatiotemporal analysis of LULC in the CARCh between 1986 and 2023 reveals a territorial reconfiguration characterised by the coexistence of agricultural contraction, expansion of artificialised areas, pasture dynamics, and the progressive recovery of forests and semi-natural ecosystems. These dynamics demonstrate the relationship between established productive traditions, recent socio-political developments, and spatially distinct conservation processes within an Andean mountain context. Fig. 4 illustrates the spatial distribution of LULC classes for 1986 (OA=82.2% and K=0.80), 2000 (OA=85.4% and K=0.83), 2016 (OA=81.9% and K=0.80), 2021 (OA=81.4% and K=0.80), and 2023 (OA=82.1% and K=0.81). Agricultural and livestock uses dominate the basin throughout the study period, confirming the CARCh's historical productive vocation. Nonetheless, a noticeable decline in the area

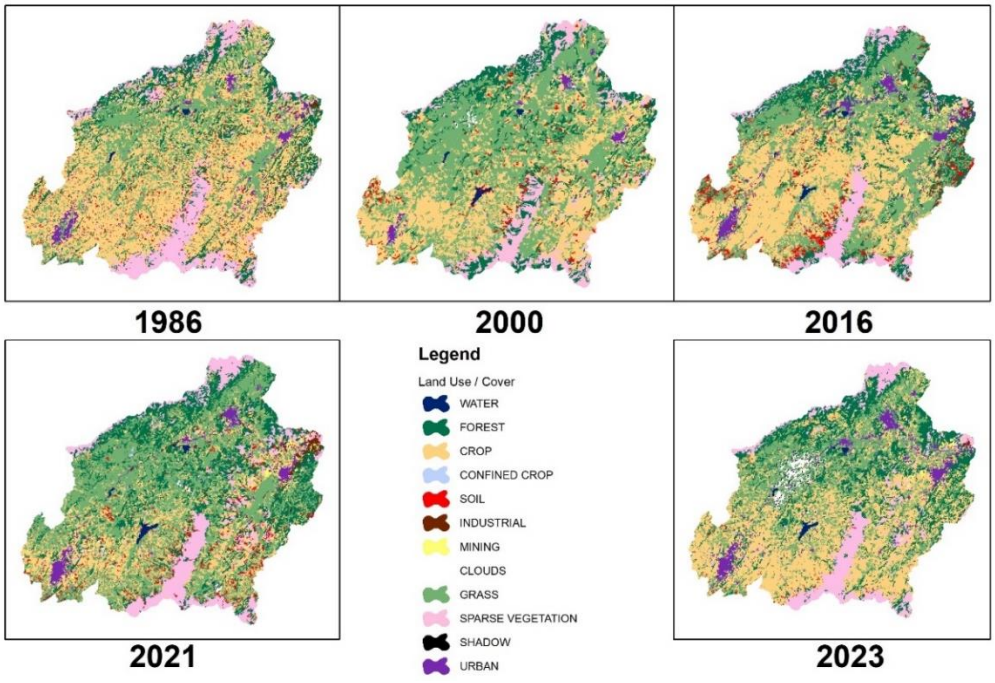


Fig. 4: Land use and land cover maps in the CARCh for 1986, 2000, 2016, 2021, and 2023 were obtained from supervised classification of Landsat images

dedicated to agriculture has been observed post-2000, especially in the mid- and lower-elevation regions, where urban, industrial, and mining activities are progressively taking over agricultural land. Forests and semi-natural areas show a contrasting trajectory. After an initial reduction between 1986 and 2000, these covers exhibit clear signals of regeneration and consolidation from 2016 onwards, especially in high-mountain and steep-slope areas. This pattern suggests the combined effects of land-use restrictions, conservation initiatives, and reduced agricultural pressure in marginal zones. Artificialised modified regions, despite their geographically restricted, are persistently expanding in proximity to urban centers and transit routes, indicative of rising population numbers, infrastructure development, and extractive activities. Water bodies increase markedly after 1991 due to the construction of the La Copa reservoir and remain a structurally stable component of the landscape thereafter. The quantitative evolution of land uses shown in Table 5 reinforces the spatial patterns observed in Fig. 4. Urban areas increased from 5,326 ha (2.5%) in 1986 to 8,821 ha (4.1%) in 2023, representing a relative growth of approximately 65%. Mining demonstrates the highest proportional growth, escalating from 0.05% to 0.44% of the basin, which confirms the consolidation of extractive operations in certain sectors. Industrial land use continues to be relatively restricted, yet it displays occasional surges associated with infrastructure development. Agricultural land undergoes pronounced fluctuations. Cropland declines sharply between 1986 and 2000, partially recovers by 2016, and stabilises thereafter, while pastures expand markedly around 2000 and subsequently contract. This behaviour indicates a reorganisation rather than a simple decline of agricultural systems. The development and ongoing expansion of confined cultivation since 2000 demonstrate a movement towards intensive production systems, affecting both water demand and soil management practices.

Table 5: Multitemporal evolution of land uses in the CARCh (1986-2023)

Land uses	1986	2000	2016	2021	2023
Urban	5326.64	5711.11	7940.27	8203.77	8820.63
Industrial	182.41	215.64	304.29	2915.78	181.17
Mining	106.38	641.50	1886.69	1995.21	947.90
Agriculture	101020.57	66267.95	81175.45	42032.72	83328.40
Confined cultivation	0	600.87	515.56	608.26	671.26
Open-field agriculture	7294.63	4484.13	9014.33	6586.28	926.36
Pasture	43276.25	84769.36	65015.36	82184.52	48408.05
Sparse vegetation	26324.06	21714.36	17327.34	24394.13	23343.23
Forest	30927.21	28845.43	30885.32	43788.03	42999.33
Water	320.13	803.43	713.66	987.84	841.66
Clouds	0	670.05	0	766.47	3432.24
Shade	0	54.45	0	315.26	878.04
Total	214778.28	214778.28	214778.28	214778.28	214778.28

Forests and semi-natural areas increased from 26.6% to 30.9% of the basin area between 1986 and 2023, indicating net recovery. Fig. 5a highlights the contrasting trajectories between agriculture and forests, while Fig. 5b emphasises the steady growth of urban areas, confined crops, and water bodies.

Fig. 6 and Table 6 synthesise the spatial and quantitative structure of LULC transitions. During the period from 1986 to 2000, there was an increase in agriculture (9.3% of the basin) that coexisted with considerable conservation efforts for forests and seminatural areas (18.9%), suggesting a landscape characterized by both production and conservation. Between 2000 and 2016, agricultural expansion persisted but at a lower intensity, while artificialised areas increased to 3.6%, reflecting accelerating urban and infrastructure development. During the period from 2016 to 2021, there was a remarkable transition, as agricultural expansion diminished while the conservation and regeneration of forests and seminatural regions saw a substantial increase. This period coincides with post–Peace Agreement land use reconfiguration and strengthened environmental governance. Between 2021 and 2023, agricultural expansion rebounds locally, but conservation (25.5%) and regeneration (5.3%) of natural areas remain dominant, suggesting increasing resilience of high-mountain ecosystems despite persistent anthropogenic pressure. In Fig. 7, long-term trends are integrated, validating agriculture as the leading land-use category, despite a decline in stability, while forests and semi-natural areas demonstrate a persistent. Artificialised areas display continuous growth, and water bodies exhibit moderate variability linked to climatic conditions and reservoir dynamics.

Fig. 8 quantifies accumulated and annual rates of change. Artificialised territories exhibit the highest cumulative increase (>200%) and an annual growth rate of approximately 5.8%, underscoring sustained urban and extractive expansion. Forests and semi-natural areas exhibit a positive accumulated rate (~30%) and an annual increase of ~1%, indicating gradual regeneration. Agriculture stands as the sole category exhibiting a negative accumulated rate of (−16.8%) and an annual decrease of −0.47%, indicative of the reduction in extensive agriculture and its gradual substitution by alternative uses. The detected revival of forests and seminatural landscapes implies an enhancement of ecological resilience in mountainous regions, probably facilitated by conservation strategies, the coverage of protected areas, and a decrease in land-use stress. However, this study does not directly measure ecological integrity; therefore, resilience is inferred from spatial persistence and regeneration patterns.

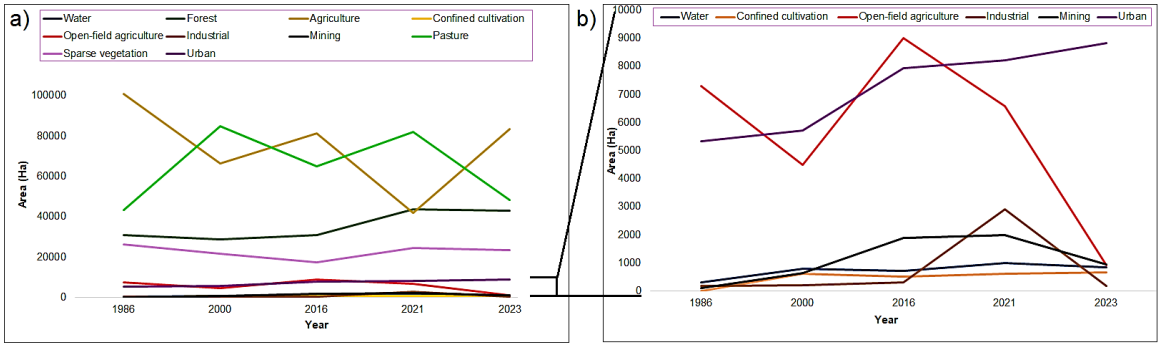


Fig. 5: Land use trends in the CARCh (1986-2023). a) Predominant land cover such as crops, pastures, and forests, b) Minor land cover such as water, urban, industrial, mining, and confined cultivation

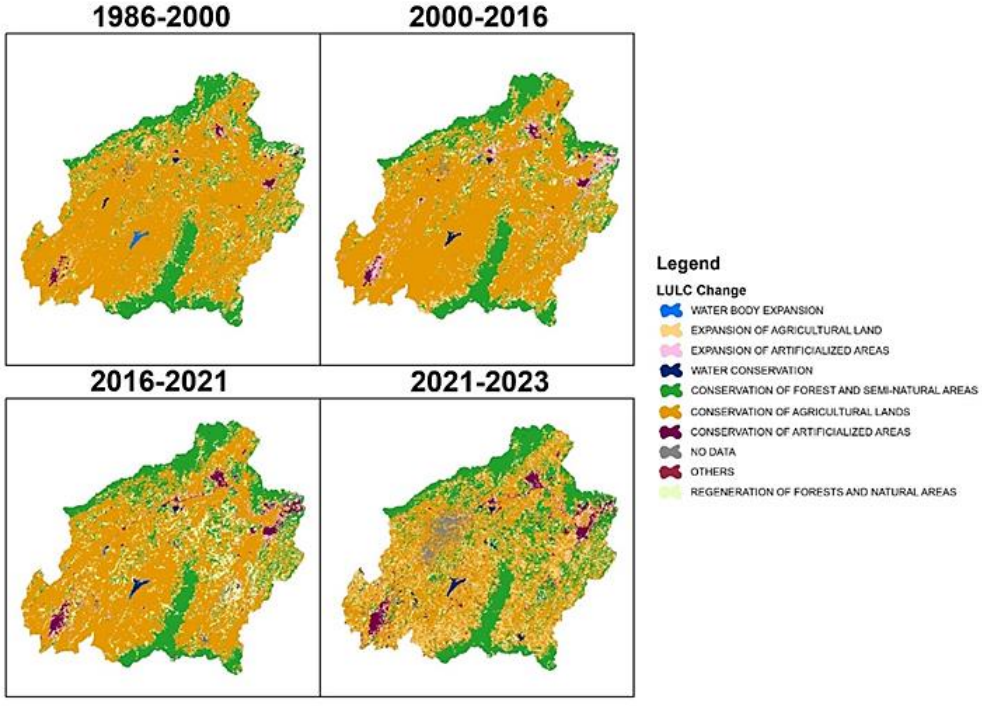


Fig. 6: Land use changes in the CARCh (1986-2023)

Table 6: Consolidation of records of changes in land use in the CARCh

Changes in land use	1986 - 2000	2000 - 2016	2016 - 2021	2021 - 2023
Expansion of water bodies	550.98	135.68	355.68	46.06
Expansion of agricultural land	20018.77	13315.28	7953.95	15548.67
Expansion of artificially developed areas	1266.69	7764.90	5211.05	3945.91
Water conservation	252.45	576.54	632.16	794.07
Conservation of natural, forested, and semi-natural areas	40510.86	37377.24	43265.17	54719.56
Conservation of agricultural lands	139503.54	141851.02	126457.83	117221.98
Conservation of artificially developed areas	1901.56	2216.68	4903.72	5809.39
No data	670.05	670.05	766.47	4167.21
Other	54.45	54.45	315.26	1186.73
Regeneration of forests and natural areas	10048.92	10816.43	24916.99	11338.71
Total	214778.28	214778.28	214778.28	214778.278

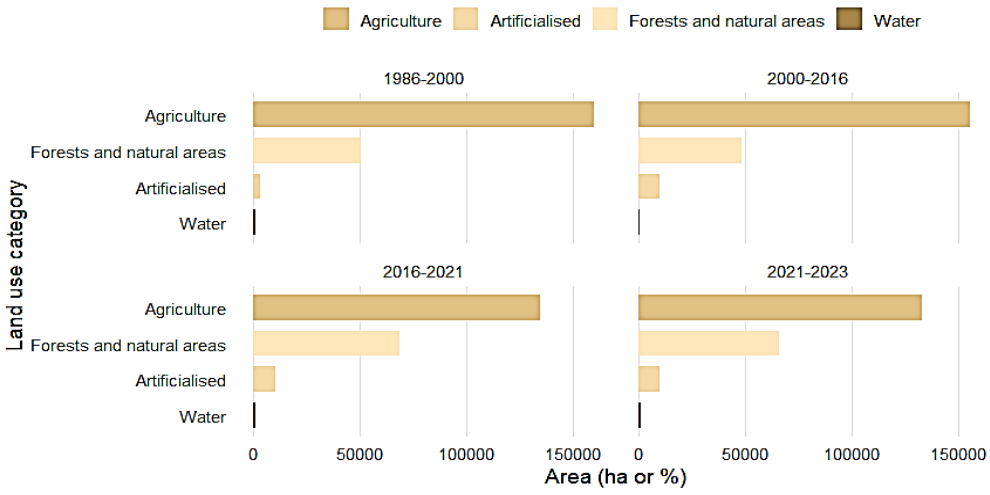
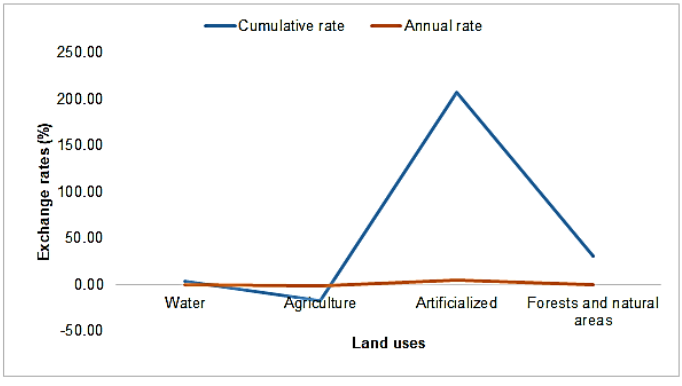


Fig. 7: Trends in land-use change in the CARCh (1986-2023)



Exchange	Water	Agriculture	Artificialized	Forests and natural areas
Cumulative rate	4.57	-16.77	207.91	30.65
Annual rate	0.13	-0.47	5.78	0.85

Fig. 8: Land use change rates in the CARCh (1986-2023)

The reduction and reconfiguration of agricultural land raises important implications for food security and subsistence farming. While Boyacá remains a key agricultural region, the contraction of extensive agriculture and the rise of confined cultivation point to increased production intensity, with potential consequences for water demand, soil fertility, and long-term sustainability (Gobernación de Boyacá, 2020). In the landscapes of the Andean mountains, production systems that are confined and based in greenhouses frequently depend on intensive irrigation, synthetic inputs, and shortened fallow periods. This reliance may hasten the depletion of soil nutrients and heighten the dependence on external agrochemicals. While such systems can improve short-term yields and economic returns, they may also heighten vulnerability to water scarcity, soil degradation, and climate variability if not supported by adaptive management practices. Consequently, the noted expansion in confined cultivation within the CARCh signifies both a chance for productive modernisation and a potential source of long-term socio-ecological risk. These patterns highlight trade-offs between productivity gains and resource pressure in Andean basins. In this context, in mountainous Andean regions, the contraction of extensive

agriculture may affect not only total production area but also crop diversity and traditional subsistence systems, which typically rely on diversified smallholder practices adapted to altitudinal gradients. Furthermore, although this study does not explicitly assess crop diversity, the identified movement towards limited, intensive cultivation might imply a higher degree of specialization and a decrease in heterogeneity in agricultural landscapes. Such transitions can enhance short-term productivity but may increase vulnerability to market fluctuations, climatic variability, and input dependency, thereby influencing long-term food security and socio-ecological resilience. The expansion of artificialised areas, although spatially limited, poses disproportionate risks to ecological connectivity and water regulation, particularly in valley bottoms and peri-urban zones. The intersection of urban expansion, mining activities, and hydrological infrastructure intensifies competition for water resources and increases exposure to hydroclimatic hazards. The outcomes of this study are in agreement with various research that have characterized land cover changes in Andean basins in Colombia and other Andean countries. However, they reveal the particularities of this socio-ecological system. Studies conducted in the Andean region of Colombia, for example, in the rural area of Quindío, found that land use has historically been dominated by pastureland and that secondary forests have suffered significant contraction due to anthropogenic pressure, with loss rates greater than recovery rates over long periods (1954–2009) (Quintero-Gallego *et al.,* 2018). this analysis (Figs. 4 to 8 and Tables 5 to 6) reveals a persistent rebound in the recovery of forests and semi-natural areas since 2016, indicating enhanced territorial regeneration processes in the CARCh, . This is likely linked to conservation policies, the effect of local protected areas and alterations in land use patterns after the 2016 Peace Agreement, a factor that has also been observed in regional analyses in Andes-Amazon, where the post-war timeframe was correlated with elevated levels of agricultural expansion and deforestation in certain regions (Murillo-Sandoval *et al.,* 2021). The Jalca region (Peru) has also documented trends of grassland loss and variations in natural cover, but with much higher reduction rates in high- and fragile-ecosystem areas, along with a strong expansion of mining and introduced plantations (Tovar *et al.,* 2013). When compared, the CARCh reveals a coexistence between natural recovery and anthropogenic influences, implying that institutional and community dynamics, together with the conservation of key ecosystems such as forests and moorlands, can alleviate the decline of natural cover in central Andean basins. Andean mountain basins show that the conversion of natural vegetation to productive uses (agriculture, livestock) significantly affects hydrological regulation and the capacity to sustain base discharges, increasing flow variability and reducing the capacity of natural regulation (Patiño *et al.,* 2021; Ochoa-Tocachi *et al.,* 2016). This analysis indicates that, despite the restoration of natural cover (Figs. 7 to 8), the persistent growth of artificialized areas and the intensification of agricultural practices may result in heightened competition for water resources, especially in contexts of climate variability, consistent with these mountain studies on land use pressure on hydrological function. Although the study does not directly quantify hydrological balances or water-extraction volumes, the observed reduction in extensive agriculture (−16.8% accumulated) combined with the expansion of confined, irrigation-dependent cultivation suggests an increasing concentration of water demand in smaller, intensively managed areas. In Andean mountain basins, such spatial concentration of irrigation systems can exacerbate local competition for water resources, particularly during dry periods associated with climate variability. Consequently, the quantitative land-use trends identified in this study provide indirect but compelling evidence of escalating water pressure and potential climate vulnerability in the

basin. Furthermore, in the Colombian Amazon, it has been shown that, after the 2016 Peace Agreement, the transformation of forests into pastures and crops increased sharply, altering connectivity, biodiversity and ecosystem services if sustainable management measures are not implemented (Agudelo-Hz *et al.,* 2023). In this sense, the CARCh reveals a segment of this post-conflict dynamic through the increase of artificial uses and agriculture in the recent timeframe. Moreover, there exists an additional dimension of forest regeneration that might be associated with local factors, including environmental policies, community engagement and the presence of regulated or protected areas. This aspect partially elucidates the disparity between the outcomes observed in this study and those noted in other Colombian or Amazonian Andes. In contrast to Andean-Amazonian regions, where post-2016 dynamics were characterised by rapid forest conversion linked to agricultural frontier expansion, land grabbing, and weak territorial control, the CARCh basin exhibits a contrasting trajectory shaped by its high-mountain biophysical constraints and stronger local governance structures. The dominance of páramo ecosystems, managed water recharge areas, and prevailing environmental conditions in municipal land-use strategies likely curtailed large-scale agricultural intrusion. Additionally, community-based water management associations and irrigation districts may have reinforced territorial stewardship, discouraging extensive deforestation while allowing more controlled productive intensification in already transformed zones. Therefore, the observed forest and semi-natural regeneration in CARCh does not necessarily contradict broader national deforestation trends but rather reflects how institutional capacity, protected ecosystem coverage, altitudinal limitations, and local governance practices can mediate post-conflict land-use pressures in specific Andean basins. Ultimately, relative to land use change scenario modeling studies conducted in the Andes (which encompass integrated water management and restoration), the data implies that the restoration of natural vegetation can play a role in mitigating runoff peaks and augmenting base flows. This presents an opportunity to strengthen water resilience which, while not explicitly measured in this study, but is inferred from the observed regeneration trends and their coincidence with sustainable management practices in other Andean basins (Mejía-Veintimilla *et al.,* 2024). Additionally, the SWOT analysis (Table 7) integrates biophysical resilience, institutional capacity, and socio-environmental pressures. Strengths, such as abundant water resources and strategic ecosystems, stand in contrast to weaknesses in urban governance and obsolete planning tools.

The TOWS strategies (Table 8) translate these findings into actionable pathways. In terms of feasibility, strategies aimed at revising land-use planning tools, enhancing environmental governance, and encouraging efficient water utilization in confined agriculture are readily implementable within the current institutional frameworks. Conversely, strategies aimed at controlling informal mining and regulating urban sprawl face significant barriers linked to enforcement capacity and socio-economic dependence. Consequently, prioritization should concentrate on governance and planning initiatives that facilitate longer-term ecosystem restoration and sustainable production. From a prioritization standpoint, immediate actions may concentrate on institutional and planning modifications that are technically achievable within current governance structures, especially the revision of municipal land-use instruments (W2W4O1O2O6) and promoting efficient irrigation technologies (W6O2O5). These initiatives directly address structural medium-term strategies that could strengthen participatory governance partnerships (S4O2O6) and restoration initiatives (S3O3O5), which necessitate ongoing coordination yet offer significant socio-ecological returns. In contrast,

Table 7: SWOT analysis of study area

Internal		External	
Strengths (S)		Opportunities (O)	
S1	Ample water resources ensure availability for irrigation, consumption, and the generation of ecosystem services.	O1	Environmental management and land-use plans.
S2	Presence of higher education institutions and environmental research centres.	O2	Availability of national institutional strengthening programs for natural resource management.
S3	Existence of strategic ecosystems such as moorlands (high-altitude Andean grasslands), Andean forests, and riparian zones.	O3	Sustainable use of renewable and non-renewable natural resources.
S4	Strong community organisation focused on the use and management of water resources, including irrigation districts and local associations.	O4	Public policies.
S5	A variety of climates and soil types that support diverse land cover.	O5	Cooperation funds focused on the restoration and conservation of strategic ecosystems.
		O6	Institutional commitment and inter-institutional coordination among environmental authorities for the sustainable management of natural resources.
Weaknesses (W)		Threats (T)	
W1	Limited capacity to control and monitor urban sprawl.	T1	Expansion of informal extractive activities and mining without environmental controls.
W2	Outdated land-use planning instruments (POT, PBOT, or POT, acronym in Spanish) are in place in several municipalities within the watershed.	T2	Increasing occupation of areas at risk from flooding, landslides, and flash floods.
W3	Persistent conflict between land use capacity and current land use, leading to loss of productivity and environmental degradation.	T3	Inadequate compliance with environmental permits and management measures in productive and infrastructure projects.
W4	Poor alignment between land-use planning instruments and the environmental factors defined for the watershed.	T4	Increased human pressures on moorlands, waterways, and recharge areas.
W5	Low level of awareness among agricultural and livestock associations regarding current environmental regulations and land-use restrictions.	T5	Land-use changes associated with the expansion of the agricultural and urban frontier affect ecological connectivity.
W6	Overexploitation of water resources in intensive irrigation systems, especially in greenhouses.		

Table 8: TWOS strategies matrix

Code number	S + O	Code number	S + T
S1S5O1O2	Strengthening land use planning and water security through strict territorial zoning that delimits urban exclusion areas, prioritising the conservation of ecologically sensitive areas and the protection of water resources.	S2S4T1T3	Strengthen environmental surveillance, control, and monitoring amid urban growth and informal extractive activities.
S2S4O4O5	Strengthen the connection between academic institutions and local communities through ecological restoration programs for watercourses.	S2S3T2T4	Develop early warning and risk management systems for occupations in flood-prone or landslide-prone areas.
S3O3O5	Promote the conservation of strategic ecosystems with applied research programs and reforestation projects funded by national and international cooperation.	S1S4T5	Promoting sustainable water management to mitigate the impacts of agricultural and urban expansion.
S4O2O6	Consolidate environmental governance by forming alliances between communities, ecological authorities and national institutions, promoting participatory management of the territory.		

Code number	W + O	Code number	W + T
W2W4O1O2O6	Updating planning instruments through technical assistance from institutional programs, integrating environmental determinants into (POT and PBOT, acronyms in Spanish).	W1W4T2T5	Establishment of urban control mechanisms and environmental sanctions to prevent occupation in risk zones and unplanned growth.
W5O4O5	Promote training processes for agricultural and livestock associations through cooperation projects that promote sustainable practices and adaptation to climate change.	W3W6T1T4	Development of productive reconversion and ecological restoration programs in areas degraded by mining or agricultural overexploitation.
W6O2O5	Implementation of technological innovation for the efficient use of water resources in greenhouses, with the collaboration of institutional strengthening programs and international cooperation agreements.	W4W5T3T5	Strengthening environmental governance through inter-institutional coordination and citizen participation for compliance with regulations.

strategies targeting informal mining control (S2S4T1T3) and urban sprawl regulation (W1W4T2T5) face significant political, economic, and enforcement barriers, including limited monitoring capacity (W1) and socio-economic dependence on extractive or peri-urban activities. Furthermore, there is a possibility of conflicts emerging between the initiatives for agricultural modernization and the objectives of water conservation goals restrictions on irrigation efficiency are not established. Consequently, adopting sequencing strategies based on governance capacity and risk exposure is essential to avoid policy fragmentation and to ensure that pressures in productive and urban zones do not undermine conservation achievements in high-mountain areas. Finally, the CARCh exhibits a dual trajectory in which ecological regeneration in high-mountain areas coexists with intensifying anthropogenic pressure in productive and urban zones. This unique response emphasizes the importance of spatially targeted policies that consolidate conservation gains while confronting emerging challenges to food security, water resources ecosystem connectivity. The integrated use of multi-temporal LULC analysis, transition matrices, and strategic assessment provides robust evidence to support sustainability-oriented land use planning in Andean mountain systems.

CONCLUSION

The CARCh has experienced a territorial shift marked by the simultaneous presence of forest and semi-natural ecosystem restoration in high-altitude regions, alongside the the persistent expansion of artificial land uses and intensive agriculture in productive and peri-urban zones. This dual dynamic reflects differentiated socio-environmental processes in which conservation gains are concentrated in ecologically sensitive areas. At the same time, urban growth, mining, and agricultural intensification continue to exert pressure on hydrological regulation, ecosystem connectivity, and land-use sustainability, including increased exposure to flood risk in valley bottoms where urban expansion overlaps with hydrological corridors. The identified patterns imply that the sustainability of land use in Andean mountain basins is contingent upon governance that varies by territory, instead of being based on uniform land-use restrictions. While existing conservation policies and protected-area frameworks appear effective in supporting forest recovery and ecological resilience in high-altitude zones, weaknesses persist in controlling urban expansion, regulating extractive activities, and aligning multi-level planning instruments with watershed-scale environmental priorities. These results highlight the necessity of enhancing multi-

level governance by improving coordination among municipal land-use plans, regional environmental authorities, and national conservation frameworks, ensuring that watershed-scale priorities guide productive development, ecological conservation, and flood risk management. In conclusion, the primary evidence from this case indicates that Andean land-use planning must evolve past generalized conservation or development methods. It is essential to implement spatially differentiated, watershed-scale governance frameworks that effectively promote the recovery of high-mountain ecosystems while rigorously controlling productive and urban intensification in hydrologically sensitive lowland regions. This study is subject to limitations related to the 30 m spatial resolution of Landsat imagery, which constrains the discrimination of small urban patches and confined cultivation systems, as well as uncertainties associated with seasonal variability and spectral confusion in heterogeneous landscapes. Future studies ought to incorpórate higher-resolution remote sensing data along with ecological and hydrological indicators to directly evaluate ecosystem integrity and water regulation. Additionally, it is essential to create scenario-based analyses that evaluate the impacts of alternative governance and climate pathways on land-use dynamics in Andean socio-ecological systems.

AUTHOR CONTRIBUTIONS

D.M. Benítez-Ramírez contributed to the conceptualisation, research, formal analysis, methodology, software, drafting of the original document, project management, and supervision. F. Alfonso Romero-Toledo contributed to the study, methodology, and drafting of the original document. A. Velastegui-Montoya contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. P. Escandón-Panchana contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision.

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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, 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
AOI	Area of interest
CARCh	The upper Chicamocha river basin
ETM+	Enhanced Thematic Mapper Plus
FARC-EP	Revolutionary Armed Forces of Colombia - People's Army
GIS	Geographic information systems
ha	Hectare
ITCZ	Intertropical convergence zone
K	Kappa coefficient
km²	Square kilometres
L5	Landsat 5 satellite
L7	Landsat 7 satellite
L8	Landsat 8 satellite
L9	Landsat 9 satellite
LULC	Land use and land cover
m	Meters
O	Opportunities
OA	Overall Accuracy
POT	Basic land use plan
PBOT	Basic Territorial Planning Plan
OBIA	Object-based image analysis
OLI	Operational Land Imager
S	Strengths
SWOT	Strengths, weaknesses, opportunities, and threats
T	Threats
TIRS	Thermal Infrared Sensor
TMC	Traffic Message Channel
TOWS	Threats, opportunities, weaknesses, strengths
USGS	United states geological survey
W	Weaknesses

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CASE STUDY

Sustainability index and matrix multiplication of broiler farming partnerships for environmental performance improvement

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ABSTRACT

BACKGROUND AND OBJECTIVES: Broiler farming partnerships are increasingly adopted to enhance production efficiency and farmer livelihoods; however, their environmental sustainability remains inadequately addressed. Prior studies have mainly highlighted performance, while the integration of environmental, technological, social, and institutional factors has been somewhat lacking. The objectives of the study were to evaluate the sustainability status of partnership-based broiler farming systems and to identify the structural causal relationships among dominant leverage variables using an integrated Rapid appraisal for fisheries – multidimensional scaling and matrix of cross-impact multiplications applied to classification framework.

METHODS: A multidimensional sustainability assessment was conducted using a structured framework comprising ecological, economic, social, technological, and partnership dimensions. A comprehensive total of 32 sustainability attributes were recognized and integrated into a survey tool. Data were obtained from 17 expert respondents selected through purposive sampling based on their experience and involvement in broiler partnership systems. Sustainability indices and leverage factors were created utilizing multidimensional scaling, subsequently employing cross-impact matrix multiplication applied in classification structural analysis to categorize dominant variables according to their their driving power and dependence.

FINDINGS: The findings reveal a moderate sustainability status, with environmental performance achieving the highest index (70.57) percent, followed by technological (62.62) percent, economic (56.52) percent, and social (52.65). In contrast, the partnership dimension exhibited a lower sustainability level (47.00) percent. Matrix of cross impact multiplications applied to classification analysis revealed that mortality causes, chicken mortality rate, sanitation practices, feeding equipment, housing type, and manure waste utilization function as critical linkage variables, indicating strong cross-dimensional interdependencies. The study demonstrates robust interrelations among different dimensions, showing that advancements in technological efficiency and management practices foster economic improvements and lower environmental repercussions. However, weak partnership arrangements and governance limitations significantly hinder overall system performance.

CONCLUSION: The study highlights that the integration of both methods demonstrates that sustainability in broiler partnerships emerges from dynamic interactions among biosecurity, housing technology, labor capability, waste valorization, and institutional trust. This systems-based framework provides a stronger basis for designing phased sustainability interventions and adaptive governance strategies in emerging poultry industries. Recent agrifood systems studies similarly emphasize causal structural mapping as an effective instrument for planning sustainability transitions.

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INTRODUCTION

The transformation of global food systems has become one of the most pressing challenges in sustainability science. The global demand for animal protein is increasing due to two main factors: the growing population and the expansion of urban areas. Additionally, it is important to recognize that individuals are altering their dietary preferences (Henchion *et al*., 2017). The modern agri-food system causes severe environmental damage which includes emitting greenhouse gases and destroying biodiversity and depleting natural resources. Sustainable food systems have developed into the main framework which aims to provide food security while protecting environmental resources and ensuring economic stability and social fairness throughout the food supply chain (Balasundram *et al*., 2023). The livestock sector plays a crucial role as it supplies essential nutrients to the worldwide population, while also aiding rural communities and safeguarding the environment. Among livestock commodities, poultry production has become the most dynamic and rapidly expanding sector of global animal agriculture (Ahmad *et al*., 2022). Poultry meat production has increased dramatically over the past decades, rising from approximately 9 million tons in 1961 to more than 133 million tons in recent years, and currently accounts for nearly 40 percent (%) of total global meat production (FAO, 2020). Recent estimates indicate that global poultry meat production exceeded 140 million metric tons in 2023, with broiler chickens contributing more than 85% of total output. The sector is also a fundamental pillar of global food security, providing cost-effective and efficient animal protein to a growing population. In 2023, global broiler meat production reached approximately 134.6 million tonnes, while per capita poultry meat consumption continued to increase worldwide (FAO, 2024). Poultry production is expected to remain the fastest-growing meat sector, accounting for more than 60% of the projected increase in global meat production by 2034 (OECD-FAO, 2024). These trends emphasize the critical role that poultry production plays in determining the future of sustainable food systems. Despite its efficiency advantages compared to other livestock systems, the rapid expansion of poultry production raises important sustainability concerns (Vaarst *et al*., 2015). Industrial poultry systems are facing growing criticism due to their environmental impact, reliance on external feed sources, difficulties in waste management, and susceptibility to disease outbreaks (Gilbert *et al*., 2017). At the same time, the sector plays a vital socio-economic role by supporting millions of smallholder farmers and rural households, particularly in developing countries where poultry farming contributes significantly to income generation and livelihood diversification (Wong *et al*., 2017). The combination of high production efficiency and intricate sustainability challenges has amplified conversations surrounding livestock sustainability and the urgent need for systemic changes in livestock production systems. One pathway increasingly discussed in sustainability science is the agroecological transition, which emphasizes the redesign of agricultural systems to enhance ecological processes, improve resource-use efficiency, and strengthen socio-economic resilience (Vikas and Ranjan, 2024). Agroecological strategies advocate for the incorporation of farming practices, lessen the reliance on outside inputs, and strengthen the relationships between ecological and socio-economic dimensions of agricultural systems (Barrios *et al*., 2020). In livestock systems, this transition requires moving beyond purely productivity-oriented approaches toward more holistic assessments that incorporate environmental performance, institutional, arrangements, technological innovation, and social welfare outcomes. The analysis of sustainability within livestock systems necessitates analytical frameworks capable of assessing sustainability through its various

interconnected aspects according to Schwarz *et al*. (2022). Multiple academic studies have created sustainability assessment frameworks which evaluate agricultural systems through their various sustainability dimensions. The study has introduced different methods which include life cycle assessment (LCA) and indicator-based sustainability assessment and multi-criteria decision analysis as research methods. The combination of multidimensional scaling (MDS) and rapid appraisal for fisheries (RAPFISH) framework system has emerged as a quick adaptable method which assesses sustainability through its environmental and financial and technological and institutional aspects (Pitcher *et al*., 2013). RAPFISH established its initial framework to assess fisheries sustainability, however, specialists have effectively applied it in the fields of agriculture and engineering and rural development research due to its ability to merge qualitative and quantitative data into one sustainability measurement system (Rohaeni *et al*., 2023; Widjaja *et al*., 2024; Allaily *et al*., 2024; Santoso *et al*., 2024; Handayani *et al*., 2025; Munarso *et al*., 2025). The use of MDS-based approaches helps to find key system elements which have strong effects on sustainability thereby enabling the development of practical solutions for policy and management methods. To further enhance the analytical precision of sustainability diagnosis, this study complements the Rapfish–MDS framework with matrix of cross-impact multiplication applied to classification (MICMAC) analysis. While, MDS proves to be highly effective in determining sustainability status and identifying dominant leverage attributes, it fails to entirely differentiate whether highly sensitive attributes function as root drivers, linkage variables, or dependent outcomes within the system structure. In complex broiler partnership systems, dominant attributes such as mortality control, sanitation, housing infrastructure, labor organization, and governance of partnerships exhibit a strong interdependence, making the consideration of causal hierarchy vital for the design of strategic interventions. The integration of MDS and MICMAC in this study goes beyond a simple methodological combination by introducing a two-stage empirical filtering process. Leverage factors derived from MDS are used as the primary input for MICMAC, ensuring that structural analysis is grounded in empirically validated variables. This approach reduces subjectivity in variable selection and strengthens the analytical linkage between system performance and structural dynamics, addressing a key gap in sustainability assessment of agrifood systems. There has been a rising trend in the recommendation of integrated structural approaches within sustainability and agri-food system studies to fortify policy prioritization and intervention sequencing (Rachman *et al*., 2022). Patel *et al*. (2022) suggest that multidimensional sustainability frameworks are not yet widely used in artnership-based broiler production systems. Recent studies into poultry farming predominantly concentrate on enhancing production efficiency, ensuring animal health, and assessing environmental consequences. In contrast, studies on the institutional and governance aspects of contract farming systems are less common (Junaidi *et al*., 2023). Most modern poultry supply chains in developing countries use partnership-based broiler production systems, which involve contracts between farmers and integrator companies (Setiadi *et al*., 2022). Smallholder farmers confront two primary issues, as these systems offer improved access to inputs and technology, but simultaneously generate unequal power dynamics, necessitating farmers to rely on external sources for their economic necessities (Ngwenya *et al*., 2025). The need for empirical research that combines economic elements with ecological components and social factors and technological aspects and partnership governance elements into one sustainability assessment framework has increased, but such studies remain infrequent (Bartzas *et al*., 2020). A multidimensional scaling was used to assess the sustainability of broiler farming operations which

function through partnership arrangements because this study needed to fill an existing research gap. This research study currently adopts a holistic analytical strategy that encompasses five dimensions of sustainability, which are economic ecological social technological and institutional partnership governance into its assessment framework. The research study identifies key leverage points which affect sustainability results to expand existing knowledge about livestock sustainability while demonstrating how institutional arrangements impact broiler production system sustainability during the ongoing shift toward sustainable food systems. The study leverages existing background knowledge to tackle two research questions which are: 1) What is the sustainability status of partnership-based broiler farming systems when evaluated across multiple sustainability dimensions? 2) Which characteristics have the most significant impact on the sustainability performance of these systems?; 3) How can these leverage factors inform strategies for improving sustainability within broiler production systems?. Accordingly, the aim of this study is to evaluate the sustainability of partnership-based broiler farming systems using a multidimensional scaling framework and to identify key attributes influencing sustainability performance. Additionally, the study endeavors to offer an integrative sustainability evaluation to aid in the development of evidence-based policies and management approaches that bolster the resilience and sustainability of livestock production systems, aligning with the overarching goals of sustainable food systems and agroecological transformation. This study has been carried out in Agriculture Faculty, Riau University in 2025.

MATERIALS AND METHODS

This study was conducted in broiler farming areas operating under partnership schemes in Riau Province, Indonesia, one of the emerging poultry production regions in Sumatra (Fig. 1). The province has witnessed swift growth in broiler farming, driven by a rising domestic demand for poultry meat and the proliferation of integrated poultry companies operating through contract farming arrangements (Sumiati *et al*., 2025)

Characteristics of the broiler partnership system

In numerous countries, broiler production systems are progressively structured through contract farming or partnership arrangements, which integrate smallholder farmers into vertically coordinated poultry supply chains (Haq *et al*., 2020). The poultry sector functions through integrated systems. Poultry companies act as integrators, supplying crucial production elements like day-old chicks (DOC), feed, veterinary care, and technical guidance. Farmers, in turn, furnish housing, labor, and daily flock management. The integrator's promise to buy the finished broilers alleviates market risks for farmers and secures a reliable supply for processing and distribution (Karaman *et al*., 2023). The global broiler market has experienced transformation toward vertical integration because large agribusiness companies now control production stage operations. The poultry industry in the United States and Brazil has embraced contract growing as its primary method of broiler production. The systems enable integrators to achieve production technology standardization and product quality control and supply chain efficiency improvements while farmers gain access to commercial poultry production with decreased market risk (OECD-FAO, 2024). The governance and structural frameworks of poultry partnership programs display considerable variations across different countries, as the operations of these programs are influenced by institutional structures, industrial development, and market frameworks. The poultry industry in developed countries uses contract farming as its primary production method because it requires comprehensive supply chain management controlled by major corporations



Fig. 1: Geographical Location of the study area in Riau Province, Indonesia

while developing economies use partnership systems to operate their small production units through partnerships with multiple smallholder farmers (Wang *et al*., 2014). The leading poultry-producing nations implement various broiler partnership systems, as illustrated in Table 1 shows through its comparative overview. The poultry industry in Indonesia employs a partnership model which operates according to a nucleus–plasma system because integrator companies serve as the primary production controllers, and farmers act as contract growers responsible for raising broiler chickens (Fig. 2). The system enables smallholder farmers to engage in commercial broiler production while minimizing their risks from changes in input costs and unpredictable market conditions (Putri and Rondhi, 2020). The execution of this partnership system adheres to a fairly standardized business process cycle. The production process begins with the integrator supplying day-old chicks, feed, vaccines, and other production inputs to partner farmers. Farmers then raise the broilers during a production cycle typically lasting between 30 and 35 days, during which technical supervisors from the integrator company monitor farm performance, provide advisory services, and ensure compliance with recommended production standards. During the production cycle, farmers are tasked with daily operational responsibilities that encompass feeding management, environmental regulation within poultry houses, disease surveillance, and the maintenance of flock health. Production performance indicators such as feed conversion ratio (FCR), mortality rate, and final body weight

Table 1: Comparative characteristics of broiler partnership systems in selected countries

Country	Dominant partnership model	Role of integrator company	Role of farmers	Market structure	Key characteristics	Sources
United States	Contract growing system	Provide DOC, feed, veterinary services, technical supervision, and guaranteed purchase contracts	Provide poultry houses, labor, utilities, and flock management	Highly vertically integrated industry dominated by large integrators such as Tyson Foods and Pilgrim's Pride	Around 90–95% of broilers produced under contract farming systems, with farmer payments often based on performance ranking systems	Beal *et al*. (2023); OECD-FAO (2023)
Brazil	Integrated poultry production	Supply chicks, feed, veterinary inputs, and coordinate processing plants and export channels	Manage production houses and daily flock management	Strong vertical integration led by companies such as BRF and JBS	One of the world's largest poultry exporters with highly coordinated production and processing networks	OECD-FAO (2023)
Thailand	Forward contract farming	Provide production inputs, technical services, and forward pricing agreements	Invest in poultry houses and manage production cycles	Dominated by agribusiness corporations such as Charoen Pokphand Foods	Approximately 80% of broiler farmers operate under contract systems, ensuring supply chain coordination	Herrero *et al*. (2013)
India	Integrator–farmer contract farming	Provide DOC, feed, vaccines, and market access through integrator networks	Provide housing facilities and manage farm operations	Rapidly expanding poultry industry with strong integrator participation	Companies such as Suguna Foods have developed contract farming systems involving thousands of farmers	Hennessey *et al*., 2023
Indonesia	Nucleus–plasma partnership model	Provide DOC, feed, medicine, technical assistance, and purchase broilers at harvest	Provide poultry houses, labor, and daily management of broiler production	Growing vertically coordinated poultry sector involving integrator companies and smallholder farmers	Widely adopted partnership model enabling small farmers to participate in commercial broiler production while reducing market risk	Putri and Rondhi, (2020)

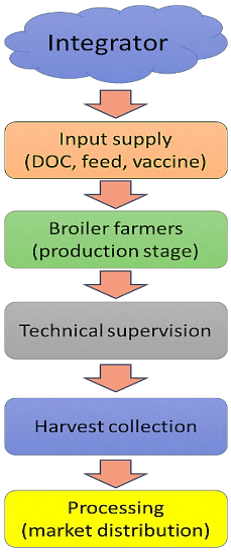

Fig. 2: Institutional and business process model of broiler partnership system

are continuously monitored, as these metrics often determine farmer compensation within partnership contracts. Upon completion of the production cycle, the integrator assembles the broilers and allocates them to slaughterhouses, processing facilities, or poultry markets. Farmer income is generally calculated based on production performance relative to contract benchmarks, which may include performance-based incentives or penalties depending on flock productivity (Setiadi *et al*., 2022; Putri and Rondhi, 2020). When contrasted with the advanced poultry industries of the United States and Brazil, Indonesia's broiler partnership systems are characterized by smaller farm operations and increased engagement from smallholder farmers. While this structure contributes to rural employment and income generation, it may also create institutional challenges related to contract transparency, farmer bargaining power, and sustainability performance within the partnership system. Comprehending the institutional traits and operational business procedures of broiler partnership systems is crucial for assessing their sustainability performance. The description of the partnership structure and production process presented in this study provides the contextual basis for applying the multidimensional sustainability assessment framework used in the subsequent analysis.

Data collection and analysis

The study utilized both primary and secondary data sources to evaluate the sustainable performance of broiler partnership farming systems in Riau Province. The study conducted field observations and semi-structured interviews and structured questionnaires to gather primary data from individuals involved in broiler partnership operations. The study consisted of partnership scheme broiler farmers and poultry integrator company representatives and livestock extension officers and local government officials from the provincial livestock service and poultry industry practitioners. The study identified these stakeholders as they were capable of supplying insights into the operational and economic and institutional components of broiler partnership systems. Prior to the survey, the study facilitated a focus group discussion (FGD) to attain a full understanding of the partnership system. The FGD required participation from farmer representatives and poultry company supervisors and agricultural extension agents and livestock service officers and academic experts in poultry production and agribusiness. The discourse highlighted significant sustainability challenges that influence broiler partnership farming, as the team established sustainability dimensions and attributes pertinent to the research context. The FGD results and the analysis of earlier sustainability assessment studies produced a set of sustainability indicators which were developed. The sustainability evaluation framework comprised five primary dimensions, which encompassed ecological and economic and social and technological and partnership components. These dimensions reflect the multidimensional nature of sustainability in livestock production systems and have been widely used in sustainability assessments employing the Rapfish approach and its derivative methods (Pitcher *et al*., 2013). A total of 32 sustainability attributes were identified across these five dimensions and subsequently incorporated into the survey questionnaire (Table 2). The selection of sustainability attributes was based on a systematic process involving literature review, expert consultation, and focus group discussions (FGD). The characteristics were adjusted from well-known sustainability assessment frameworks and fine-tuned to capture the distinct aspects of broiler partnership systems. This process ensured that each attribute is theoretically grounded, contextually relevant, and representative of key sustainability dimensions. A total of 17 expert respondents were selected using purposive sampling, based on their expertise, experience, and involvement in broiler partnership systems. The participants included poultry farmers,

Table 2: Rap-sustainability dimensions and their corresponding attributes

Ecology	Economy	Social	Technology	Partnership
1. Barn Cleaning Frequency	8. Farm Profitability	16. Productive Age	22. Feed Storage	29. Partnership Capital
2. Solid Waste Management	9. Manure Waste Utilization	17. Education Level	23. Livestock Production Inputs	30. Farmer Participation
3. Liquid Waste Management	10. Carcass Waste Utilization	18. Family Labor	24. Feeding Equipment	31. Farmer Group
4. Odor Emission	11. Non-Livestock Income	19. Local Labor	25. Drinking Equipment	32. Partnership Agreement
5. Equipment Sanitation	12. Chicken Mortality Rate	20. Community Conflict	26. Housing Type	
6. Environmental Sanitation	13. Mortality Causes	21. Farming Experience	27. Floor Type	
7. Distance to Settlements	14. Broiler Market Price		28. Technological Equipment	
	15. Farm Input Price			

technical supervisors from companies, government officials overseeing livestock, agricultural extension agents, and poultry industry analysts. Each respondent was asked to evaluate the performance of each sustainability attribute using a three-point ordinal scoring scale, where 0 indicated poor performance, 1 represented moderate performance, and 2 indicated good performance. This scoring method facilitated the conversion of qualitative evaluations from experts into quantitative data that is appropriate for multidimensional analysis. Sustainability performance is classified into four levels, based on percentage intervals of 0–25% (poor, highly unsustainable), 25.01–50% (less, moderately sustainable), 50.01–75% (quite, fairly sustainable), and 75.01–100% (good, very sustainable). These categories are detailed in Table 3. The ordination technique employs the alternating least squares approach, which is founded on the square root of Euclidean distance, referred to as the alternating least-squares scaling (ASCAL) algorithm. This approach improves ordination by minimizing the squared differences dij to the squared data(origin=oijk across three dimensions (i,j,k), referred to as S-Stress.The ordination process is determined based on Euclidean distance In n-dimensional space and is expressed, using Eq. 1 (Pitcher *et al*., 2013; Pitcher and Preikshot, 2001):

$$d = \sqrt{(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \cdots)} \quad (1)$$

The positioning of objects or points in MDS was determined by regressing the Eu clidean distance (dij) between points I and j against the reference point (oij), as expressed, using Eq. 2 (Pitcher *et al*., 2013):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The regression method applied to Eq. 2, utilized the ALSCAL algorithm. This approach optimizes the squared distance (dijk) relative to the squared data(point of origin=oijk), which, in three dimensions (i,j,k), is expressed through a formula known as S-Stress, using Eq. 3 (Pitcher *et al*., 2013):

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

where, the squared distance is Euclidian distance assigned a value, using Eq. 4 (Pitcher *et al*., 2013):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka\,(x_{ia} - x_{ja})^2} \quad (4)$$

The values of the leverage factors fall within the range of 2%-8%, indicating a moderate to good impact. If < 2%, the factor is considered not influential, while if > 8%, the factor is considered dominant (sustainable) according to Pitcher and Preikshot (2001), Table 4 presents the factors that have an impact and are dominant.

Table 3. Sustainability index categories and status for each dimension (Kavanagh and Pitcher, 2004)

No.	Index range (%)	Classification	Sustainability status
1	0–25	Poor	Unsustainable
2	25.01–50	Less	Less
3	50.01–75	Quite	Fairly
4	75.01–100	Good	Very

Table 4: Parameter values of the leverage factor

No.	Factor value (%)	Category	Description
1	<2.0	Neutral	Not influential
2	2-8	Influential	Moderate to good impact
3	>8.0	Significant l	Dominant

Monte Carlo analysis assesses uncertainty in MDS by calculating the error margin. When the difference between MDS and Monte Carlo values is minimal (<5%), that the MDS analysis offers a reliable sustainability evaluation with a 95% confidence level. To improve the accuracy of the Rapfish–MDS outcomes, the primary leverage attributes were subjected to additional analysis through MICMAC. This method was used to determine whether the most sensitive sustainability attributes act as driver, linkage, dependent, or autonomous variables within the broiler partnership system. The variables included in MICMAC were selected from the highest leverage attributes across the five sustainability dimensions, followed by validation through FGD. A total of 14 key variables were retained for structural analysis. Expert judgments were then used to build a cross-impact matrix, where the influence of one variable on another was scored on a four-level scale (0 = no influence; 1 = weak; 2 = moderate; 3 = strong). The matrix underwent processing to produce driving power and dependence values, which were subsequently categorized into four MICMAC quadrants: autonomous, dependent, linkage, and independent variables. This classification enhances the MDS findings by elucidating the causal hierarchy and interaction patterns among dominant sustainability factors. Thus, the integration of MDS and MICMAC provides a two-stage framework that improves the robustness of policy recommendations through more targeted intervention prioritization.

RESULTS AND DISCUSSION

Sustainability analysis

The findings of the MDS analysis concerning the sustainability performance of broiler farming suggest that the system is categorized as fairly sustainable, as evidenced by the sustainability index scores across multiple dimensions. The analysis shows that all dimensions achieved structured query reporter (SQR) (R^2) values above 0.90, indicating a strong goodness-of-fit of the MDS model, while stress values ranged from 0.1388 to 0.1702, suggesting an acceptable level of ordination reliability. The ecological dimension achieved the highest sustainability index score of 70.57% while the technological dimension reached 62.62% and the economic dimension attained 56.52% in their respective sustainability assessments all three showing fairly sustainable results. The social dimension exhibited a marginally reduced index of 52.65%, which is categorized as fairly sustainable. The partnership dimension achieved its lowest score of 45.00% which revealed less sustainable conditions while demonstrating existing governance and institutional difficulties that affect the broiler partnership system. The results of the sustainability standards assessment are shown in Table 5, which illustrates the findings using a radar diagram depicted in Fig. 3.

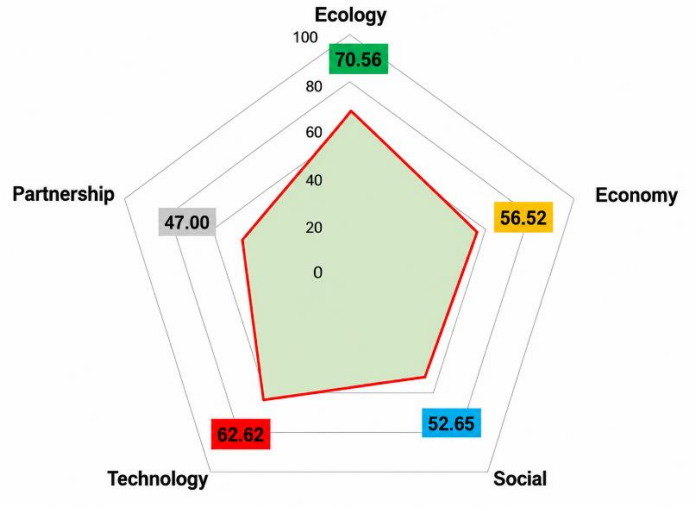

Fig. 3: Sustainability scores across five key dimensions, where 100 represents the highest sustain ability level (very good) and 0 indicates the lowest (very bad)

Table 5. Sustainability assessment scores by dimension

Dimension	Index score (%)	Stress value	SQR/R2	Sustainability status
Ecology	70.57	0.1455	0.9457	Fairly
Economy	56.52	0.1388	0.9466	Fairly
Social	52.65	0.1579	0.9363	Fairly
Technological	62.62	0.1506	0.9422	Fairly
Partnership	45.00	0.1702	0.9275	Less

Ecology dimension

The environmental sustainability index of the broiler farming partnership system reached 70.57% according to the Rapfish-MDS analysis which classified it as moderately sustainable. The leverage analysis indicates that the broiler partnership system achieves environmental sustainability via its three principal components, namely equipment sanitation (5.203), barn cleaning frequency (4.682), and environmental sanitation (4.679) which act as the core elements. The two attributes show major influence because they confirm that broiler farming operations face their main environmental issues from waste handling and emission control problems. The system illustrates efficient environmental management practices that necessitate further enhancement to reach full sustainability for production operations. The efficiency of waste management and sanitation practices, along with a farm's ability to manage externalities such as odor emissions and nutrient pollution determine environmental sustainability in emerging poultry industries. This is due to the fact that livestock systems can generate significant air, water, and soil pollution when waste management is inadequate (Akporube, 2023). The study shows moderate index results which demonstrate that environmental management practices exist in the organization but their application needs yet to achieve complete optimization throughout all operational functions which include manure management and emission control and biosecurity maintenance (Devnath *et al*., 2025). The findings of global livestock sustainability studies regarding environmental outcomes align at a common point, as improvements in farm management practices have produced beneficial environmental outcomes. However, the actual environmental performance is still constrained by persistent challenges related to waste management, sanitary infrastructure, and

pollution mitigation strategies (Zhang *et al*., 2023). The leverage analysis indicates that the frequency of equipment sanitation, barn cleaning, and environmental sanitation practices are crucial factors influencing environmental sustainability within the broiler partnership system; these aspects are essential for maintaining criticalbiosecurity and hygiene management protocols (Fig. 4). The combination of inadequate sanitation practices together with environmental contamination which results from organic waste accumulation and ammonia emissions creates a direct pathway for pathogens to spread (Leinonen *et al*., 2019). Better cleaning methods together with effective manure management practices establish an environmental advantage which results in reduced microbial contamination together with decreased odor emissions and diminished nitrogen pollution (Braga *et al*., 2025). The continuous environmental problems faced by poultry systems are mainly due to two critical waste management failures: the generation of odors and the processing of liquid waste. The transition to sustainable practices requires establishments to implement uniform sanitation standards while developing better manure management methods and enforcing stricter environmental control measures in their partnership systems for broiler production.

Economic dimension

The Rapfish-MDS analysis demonstrates that the broiler partnership system achieved an economic sustainability index of 56.52% which shows moderate sustainable development. The system provides economic stability through its contract-based operations, yet it faces exposure to production threats, and its value distribution model fosters unfairness among stakeholders. Studies show that contract farming bolsters financial security for farmers, but they remain susceptible to potential hazards (Kiprop *et al*. 2025). The analysis of leverage shows that mortality causes (6.95) and chicken mortality rate (6.36) represent the most significant factors which demonstrate that biological risk functions as the key factor determining economic sustainability. Additionally, manure waste utilization (5.25) and non-livestock income (5.13) show strong influence, indicating that income diversification and by-product valorization are critical for enhancing economic resilience (Fig 5). Analysis of leverage reveals that factors related to mortality are the most significant attributes, affirming that biological risks serve as the main determinants of economic performance, since elevated mortality negatively impacts productivity and profitability (Leinonen *et al*., 2019). Manure utilization and income diversification play important roles in strengthening economic resilience, as converting waste into valuable products and developing non-livestock income sources can increase revenue and reduce vulnerability (Beal *et al*., 2023). Enhancing economic sustainability necessitates the fortification of biosecurity, waste valorization, income diversification, and the establishment of fair contract mechanisms to bolster resilience and promote a more equitable value distribution.

Social dimension

The Rapfish–MDS analysis shows that the social sustainability index of the broiler farming partnership system reached 52.65%, indicating a moderately sustainable condition. This indicates that the system plays a role in supporting rural livelihoods and employment; however, it is still constrained regarding the human capital development. In livestock systems, social sustainability is closely linked to labor participation, community acceptance, and livelihood support, particularly in smallholder-based production systems (Birhanu *et al*., 2023). Leverage analysis identifies family labor (3.54) and local labor (3.52) are the most significant factors, underscoring the pivotal role of broiler farming in generating employment in rural areas. In contrast, productive age (2.31) and education level (1.57) show moderate influence, suggesting that demographic factors are less compared to labor participation. Meanwhile, community conflict

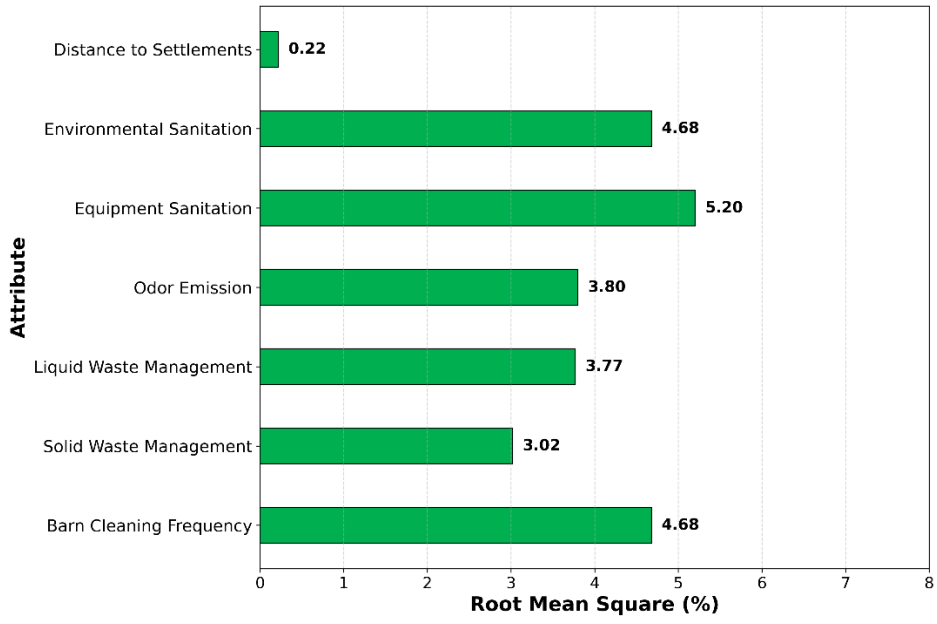

Fig. 4: Leverage values of ecology attributes

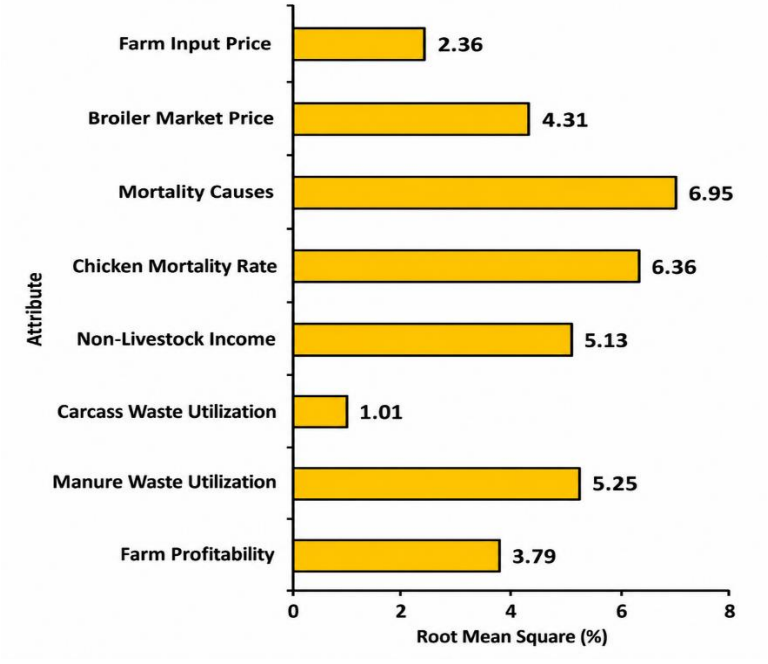

Fig. 5: Leverage values of economy attributes

(0.88) and farming experience (0.39) have minimal influence, indicating relatively low social tension and broad community acceptance of broiler farming activities (Fig. 6). The leverage analysis emphasizes that family and local labor are the most significant factors, affirming that broiler

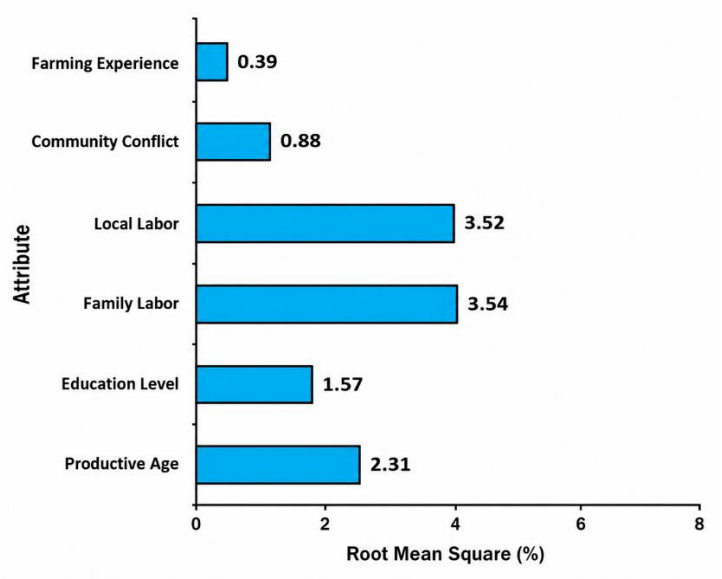

Fig. 6: Leverage values of social attributes

farming serves as a crucial generator of rural employment and bolsters local economic circulation. In contrast, factors such as education level and demographic characteristics show moderate influence, while low community conflict indicates strong social acceptance of poultry farming activities. The findings of this study align with previous research that indicated livestock systems contribute to the improvement of rural community welfare through their effective involvement of local workforce participation and their backing of community development efforts (Herrero *et al*., 2013). Social sustainability requires development efforts which should enhance human capital and develop workforce abilities while maintaining community involvement to create an equitable and strong livestock production system.

Technological dimension

The Rapfish–MDS analysis indicates that the technological sustainability index of the broiler farming partnership system reached 62.62%. This conclusion reveals that the fundamental production technologies of the system already exist. The system should adopt cutting-edge technologies together with integrated systems to ensure comprehensive implementation. The development of poultry systems in developing countries progresses at a slow pace because of limited access to capital and institutional support (Patel *et al*., 2022). The assessment of leverage reveals that feeding equipment, rated at 6.55, is the key element in the study. The second most important factor which follows this attribute has a scoring weight of 5.42. The third most important factor in the study has a scoring weight of 4.72 (Fig. 7). These results emphasize that feeding equipment, housing type, and floor systems as the most influential attributes, emphasizing that basic infrastructure and mechanization are key determinants of technological sustainability. Effective feeding systems enhance feed efficiency and minimize waste, whereas appropriate housing and ventilation systems regulate microclimate conditions, thereby boosting productivity and animal health (Liang *et al*., 2020). In contrast, more advanced technologies such as automation, sensors, and digital systems show limited influence, indicating low adoption of precision livestock technologies, which are increasingly recognized as important for improving efficiency

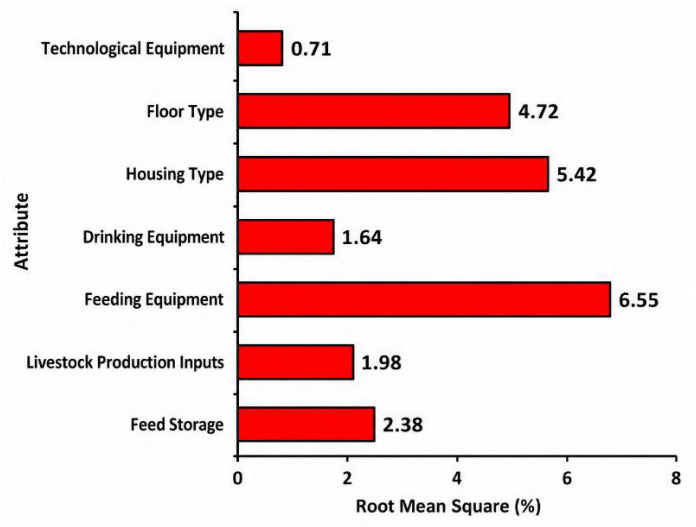

Fig. 7: Leverage values of technological attributes

and sustainability (Sumiati *et al*., 2025). Improving technological sustainability necessitates a focus on enhancing infrastructure and adopting new technologies. Investment in feeding systems and housing is crucial because of their significant influence on production performance. The use of precision livestock technologies which include sensors and automation systems leads to better operational performance and disease management and improved animal welfare. The adoption of these technologies necessitates that farmers obtain comprehensive training and extension services, which must be enhanced. The partnership systems depend on integrator companies who provide essential technology transfer and capacity building support which helps organizations achieve their production system transformation goals.

Partnership dimension

The Rapfish–MDS analysis shows that the partnership dimension reached a sustainability index of 47.00% which results in its classification as less sustainable. According to the findings of the study, the existence of contracts between farmers and integrator companies does not contribute to better governance standards and the rights of farmers. The poultry sustainability of contract systems depends on three factors which include transparency and fairness and the distribution of bargaining power between parties. The analysis shows that partnership agreement (4.69) and partnership capital (4.48) serve as critical factors which drive the importance of both financial support mechanisms and contractual clarity. The creation of explicit and enforceable contracts serves as an essential prerequisite that allows parties to outline their pricing frameworks, responsibilities and risk-sharing agreements, while inadequate contracts result in income instability and reduced trust (Ton *et al*., 2018). Farmers can access modern value chains through capital access but governance transparency issues create dependency risks (Ragasa *et al*., 2018). Farmer participation (3.53) and farmer group (2.84) show moderate influence which indicates that collective action remains underdeveloped (Fig. 8). To advance this dimension, it is essential to achieve better governance transparency, alongside enhanced finance and more robust farmer institutions. The primary strategies for achieving this objective include two actions which need to enhance contract fairness while they also need to expand financial instruments through

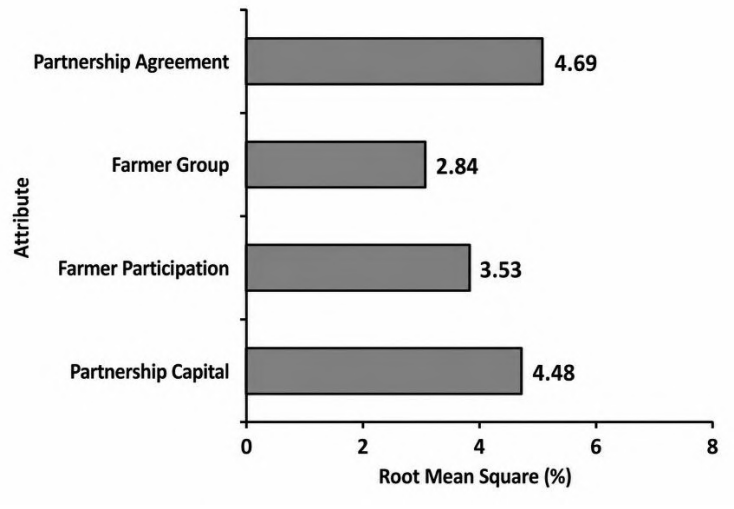

Fig. 8: Leverage values of partnership attributes

credit and insurance and strengthen farmer organizations to enhance their bargaining power through knowledge exchange. The establishment of participatory governance mechanisms serves as an essential prerequisite that allows organizations to foster trust as they pursue their objectives of establishing equitable relationships. The partnership system needs these essential measures to achieve its transformation into an institutional framework that maintains fairness and resilience.

Cross-dimensional synthesis and policy implications

The multidimensional assessment using Rapfish–MDS demonstrates that the sustainability of broiler farming partnerships requires analytical approaches which examine all operational dimensions to understand their relationship between environmental, economic, social, technological, and institutional dimensions. This study promotes a systemic viewpoint, highlighting that sustainability results are influenced by both reinforcing and constraining interactions across these dimensions rather than by enhancements in individual factors. The integrated framework here matches current sustainability research because it shows how economic and social and environmental systems need their relationships analyzed through an entire system view in agri-food environments (Arora-Jonsson *et al*., 2023). The results reveal several critical interdependencies. The economic outcomes of the business operations depend on technological features of feeding systems and lighting systems and housing infrastructure because these features enhance feed efficiency and animal health and productivity. The progress in technology results in environmental advantages as it facilitates improved housing and management systems to cut down emissions and waste externalities (Sakata and Siqueira, 2024). Environmental management practices which include manure handling and pollution control create positive economic sustainability impacts because they decrease operational waste and enhance resource utilization according to circular production standards. The social aspects of labor participation, skill development, and farmers' knowledge are essential for both adopting new technologies and managing farms effectively. According to the study by Akter *et al*. (2023), inadequate knowledge and limited availability of crucial inputs and training programs considerably hinder the efficiency and sustainability of broiler production. The institutional dimension of

partnerships functions as the primary coordinating framework, overseeing input distribution, market equilibrium, and knowledge dissemination. Setiadi *et al*. (2002) suggests that contract-based broiler farming systems can enhance farmer earnings and foster rural community development; however, their efficacy is contingent upon robust governance practices and inclusive decision-making processes. Conversely, Queenan *et al*. (2021) reveal that the confluence of weak institutional systems and fragmented governance structures engenders systemic limitations, thereby hindering the achievement of sustainability across various system components. Furthermore, the analysis highlights the importance of meticulously handling substantial trade-offs. Advances in technology frequently yield greater productivity, subsequently leading to economic benefits. However, if not managed properly, these advancements can also cause various environmental problems. These problems can affect how land is used, how much is emitted, and how resources are consumed. The systems designed to improve efficiency result in diminished labor demands, which in turn have detrimental impacts on social inclusion and employment prospects in rural communities. The production of broilers occurs within a multifaceted system that encompasses essential trade-offs influencing the the three sustainability dimensions. The research identifies multiple systemic leverage points which can be used for intervention based on the existing interconnections. The first cross-cutting factors that influence both financial and ecological outcomes encompass biosecurity and health management and the control of mortality rates, based on the research outcomes of Akter *et al*. (2023). The second research focus area includes feeding systems and housing and environmental control technologies.

MICMAC-based structural analysis of key sustainability leverage factors

The dominant leverage attributes identified through Rapfish–MDS were subsequently examined using MICMAC structural analysis to reveal their causal architecture within the broiler partnership sustainability system. This supplementary layer of analysis categorizes variables based on their driving strength and interdependence, facilitating a shift from dimensional scoring toward systemic interpretation. The resulting direct influence graph and influence–dependence map (Figs. 9-10) show that sustainability performance is not shaped by isolated attributes, but by a tightly connected network of environmental hygiene, biological risk, production technology, labor structure, and partnership governance. The integration of MDS and MICMAC therefore enhances the scientific value of this research by transforming key attributes into a strategic sustainability transition map, a methodological approach that has gained increasing attention in contemporary agrifood systems and sustainable supply-chain studies (Sharma *et al*., 2022). The structural configuration suggests a highly interconnected and feedback-sensitive system, with most variables concentrated in the high influence–high dependence area. This pattern implies that the broiler partnership system functions as a linkage-dominant socio-technical structure, where operational modifications in one variable swiftly disseminate across other sustainability dimensions. The strongest causal cluster is formed by mortality causes, chicken mortality rate, equipment sanitation, environmental sanitation practices, manure waste utilization, and feeding equipment. These variables jointly connect the environmental, technological, and economic dimensions through a biological-risk pathway. In practical terms, weak sanitation standards increase pathogen pressure,

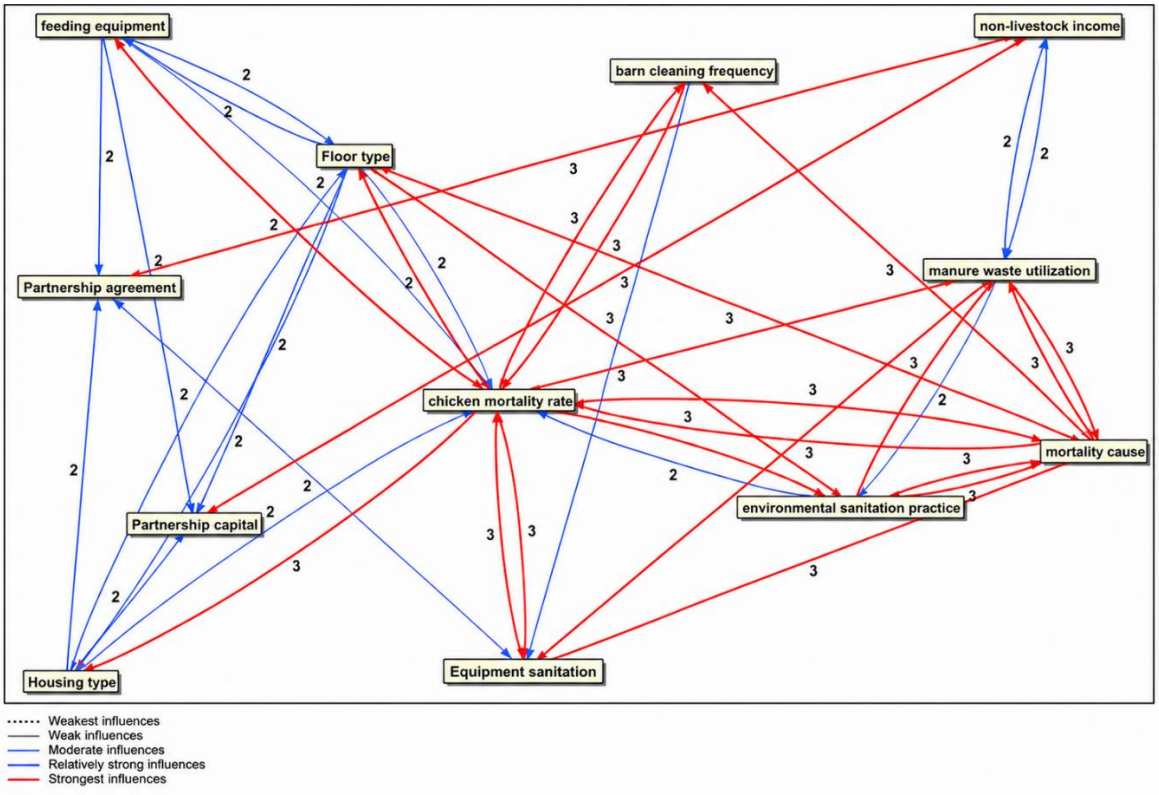

Fig. 9: MICMAC direct influence graph of dominant sustainability leverage variables in broiler farming partnerships

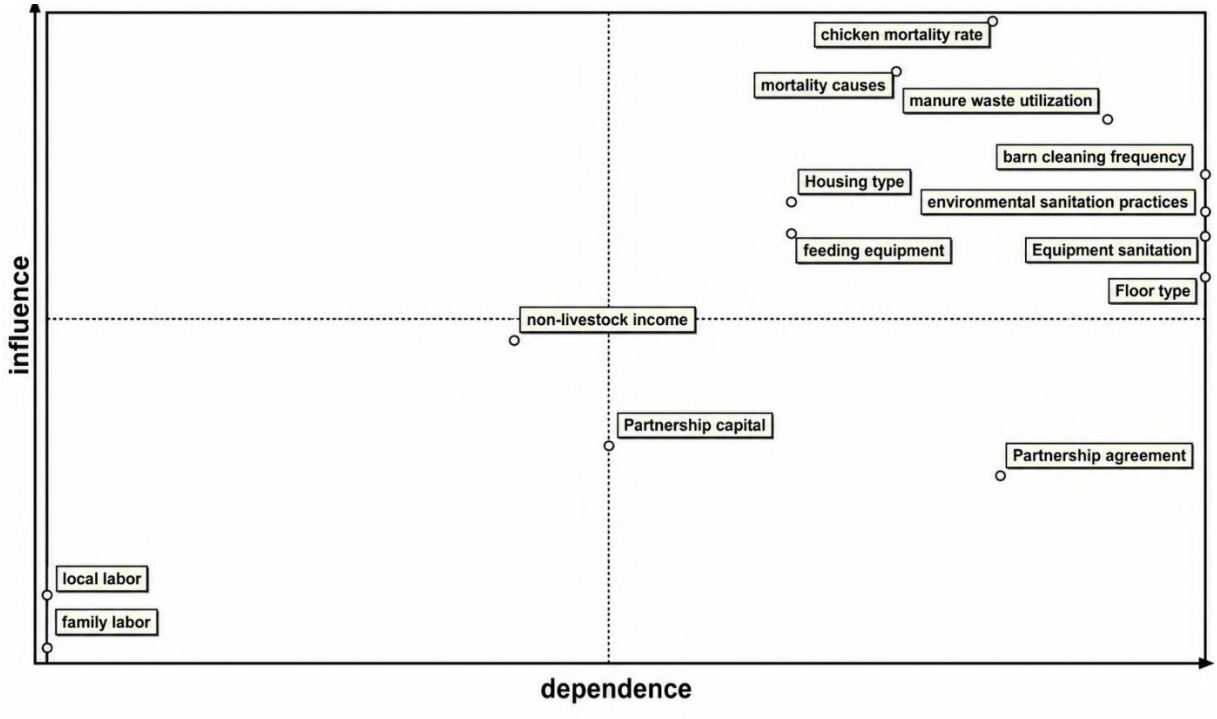

Fig. 10: MICMAC direct influence–dependence map showing the structural classification of key sustainability variables

which raises mortality, lowers production efficiency, reduces manure valorization potential, and eventually weakens farm income. Recent poultry sustainability studies likewise verifies that hygiene management, waste utilization, and mortality control represent some of the most crucial control points in sustainable broiler systems, particularly when confronted with climate and disease pressures (Attia *et al*., 2024). A more in-depth quadrant assessment illustrates that the chicken mortality rate and the factors contributing to mortality function as the primary linkage variables, combining significant driving effects with a similarly high level of dependence. These variables are the most sensitive nodes in the system because they both influence and are influenced by housing type, floor type, feeding equipment, sanitation discipline, and manure management. This position implies strong domino-effect potential: even a small decline in cleaning frequency or housing hygiene could initiate an increase in mortality which subsequently leads to economic losses, contract strain, and diminished capacity for reinvestment. In contrast, family labor and local labor are located near the autonomous–driver boundary with lower dependence, suggesting that they operate as upstream enabling variables. Their function is not direct, yet it holds significant strategic importance, as labor discipline influences the consistent implementation of feeding precision, barn sanitation, and daily flock monitoring are implemented consistently. The institutional variables present another crucial systemic perspective. Partnership agreement and partnership capital display relatively high dependence, indicating that governance quality and financial continuity are strongly shaped by upstream technical and biological performance. This suggests that institutional sustainability in broiler partnerships is not solely a contractual concern, but rather a developing outcome of operational reliability and risk control. When mortality and sanitation risks are well managed, trust between farmers and integrators improves, contract compliance strengthens, and capital recycling becomes more stable. Similar structural behavior indicating that governance variables tend to be influenced by production stability and collaborative trust mechanisms (Sharma *et al*., 2022). The strategic implication is a clear hierarchy of intervention priorities. The first control layer should target the linkage variables particularly mortality causes, mortality rate, sanitation routines, and manure waste utilization because these nodes produce the largest systemic ripple effects. The second layer should reinforce labor capability through technical training and biosecurity discipline, ensuring the reliability of routine farm operations. The third layer should adapt partnership contracts and capital support systems to ensure that institutional frameworks develop in accordance with enhanced technical performance. This sequence is critical because poorly managed linkage variables may destabilize the entire sustainability architecture, whereas well-managed linkage nodes can accelerate cross-dimensional improvements.

CONCLUSION

This study applied an integrated Rapfish–MDS and MICMAC framework to evaluate the sustainability of partnership-based broiler farming systems across environmental, economic, social, technological, and institutional dimensions. The findings suggest that the system demonstrates a moderate level of sustainability in general, with the environmental and technological aspects exhibiting comparatively better performance, whereas the partnership aspect continues to be the primary institutional vulnerability. This imbalance confirms that the sustainability of broiler farming partnerships is not constrained primarily by operational capacity, but by governance quality, contractual transparency, and farmer empowerment. The comprehensive evaluation revealed multiple key leverage factors, such as mortality management, sanitation

methods, feeding apparatus, type of housing, labor involvement, partnership contracts, and capital access. These attributes demonstrate that sustainability outcomes emerge from strong interactions among biosecurity management, technological efficiency, socio-economic participation, and institutional arrangements. Enhancements in sanitation and mortality management can concurrently alleviate environmental impact, enhance production efficiency, and bolster farm profitability, while better housing and feeding systems support both technical and welfare performance. The additional MICMAC structural analysis strengthens these findings by clarifying the causal hierarchy among dominant leverage factors. The results show that sanitation, mortality-related variables, feeding systems, and housing infrastructure serve as the main drivers and linking variables, which means they influence subsequent outcomes in economic resilience, labor stability, and partnership performance. Conversely, institutional variables such as partnership agreement and capital are often more contingent upon the reliability of upstream technical systems and the processes that foster trust. This confirms that sustainability interventions should prioritize high-driving variables first, as improvements in these nodes can trigger positive cross-dimensional effects throughout the system. Ultimately, the study reveals that for sustainable broiler partnership systems to thrive, an integrated transition pathway is essential, incorporating elements such as technical modernization, environmental management, farmer inclusion, and governance reform. The combined MDS–MICMAC framework offers a more robust foundation for evidence-based policy, as it not only pinpoints essential leverage points but also assesses their structural priority within the sustainability system. This systemic perspective offers a practical roadmap for improving the resilience and environmental performance of broiler farming partnerships in emerging poultry economies.

AUTHOR CONTRIBUTIONS

Cepriadi, the corresponding author, has contributed in supervising the second author and preparing the manuscript. Novian has contributed in analyzing data. A.D. Santoso prepared all the maps and figures and interpretation of the results. M. Herlon participated in the interpretation of the MDS results and manuscript preparation. H. Daulay prepared manuscript and analyzed data.

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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
ASCAL	Alternating least-squares scaling
d	Euclidian distance
dij	Euclidian distance from point i to point j
DOC	Day-old chicks
FAO	Food and agriculture organization
FCR	Feed Conversion Ratio
FGD	Focus group discussion
ijk	Dimension
LCA	Life cycle assessment
MDS	Multidimensional scaling
MICMAC	Matrix of Cross-Impact Multiplications Applied to Classification
OECD	Organisation for economic co-operation and Development
oijk	point of origin
RAPFISH	Rapid appraisal for fisheries
R^2	SQR
RMS	Root mean square
oijk	point of origin

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CASE STUDY

Logarithmic morphometric–evaporative modeling of hydro-ecological functions of small and medium lakes

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ABSTRACT

BACKGROUND AND OBJECTIVES: Small and medium-sized lakes are numerically dominant in arid and semi-arid landscapes, yet their contributions to regional water balance and evaporation remain poorly constrained due to limited depth observations. The study objectives were to establish a regionally calibrated morphometric and hydrological framework that connects lake surface area with depth utilizing a logarithmic relationship derived for steppe environments in northern Kazakhstan. The framework enhances current methodologies by allowing for the concurrent estimation of lake depth, water volume, evaporation losses, and hydrological vulnerability in areas with limited data.

METHODS: The model was calibrated using morphometric data from 119 lakes in the Karaganda Region and applied to 268 lakes with surface areas of 10 square kilometers or less in the Akmola Region. The study incorporates the distribution of lake sizes, estimates of depth, and models of evaporation, while also presenting a Morphometric Evaporative Vulnerability Index that merges lake area, estimated depth, and regional evaporation intensity.

FINDINGS: Lakes that measure between 1 and 10 square kilometers constitute about 80 percent of total lake surface area and approximately 79 to 80 percent of the estimated water volume within the studied lake population. In contrast, lakes that are smaller than 1 square kilometer account for approximately 8 percent of surface area and contribute less than 5 percent of the total volume. More than 80 percent of lakes have average depths below 2 meters, with about 41 percent concentrated between 1 and 1.5 meters. The analyzed lakes collectively store about 0.97 cubic kilometers of water, whereas the larger lakes contain around 1.24 cubic kilometers. Annual evaporation losses total about 567 million cubic meters, of which medium-sized lakes contribute about 450 million cubic meters, while small and large lakes contribute about 46 and 71 million cubic meters, respectively.

CONCLUSION: The results show that shallow and medium-sized lakes are predominant in evaporation fluxes and hydrological sensitivity, attributed to their extensive surface exposure and restricted depth. In contrast, larger lakes mainly serve as long-term reservoirs for water storage. The dominance of shallow lakes, comprising more than 80 percent of the total number, highlights their role as early indicators of hydrological stress. The recommended framework delivers a scalable and data-efficient instrument for evaluating regional lakes, determining their vulnerability rankings, and integrating these findings into water resource management and climate adaptation strategies that utilize geographic information systems.

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INTRODUCTION

Freshwater lakes are critical components of the global hydrosphere, functioning as regulators of water storage, biodiversity, and regional climate interactions. Nonetheless, lakes across the globe are progressively experiencing shrinkage, salinization, and ecological decline due to climate change, alterations in land use, and water extraction. Their vulnerability has been highlighted in international discussions, including the United Nations Water Conference-2023, which emphasized the need to better quantify and protect lake systems as essential elements of water security (United Nations, 2023). Despite their recognized importance, the distribution of scientific attention remains uneven. Large lakes and reservoirs are well studied due to their substantial storage capacity, whereas small and medium-sized lakes remain underrepresented, even though they are numerically dominant and play a critical role in regional hydrological processes. The frequently cited claim that lakes store over 80 percent of surface freshwater (Musie and Gonfa, 2023) remains context-dependent and requires careful interpretation, particularly when distinguishing between large and small lake contributions. In arid and semi-arid regions, small and medium-sized lakes form dense and frequently interconnected systems that significantly affect the regional water balance, evaporation dynamics, and ecosystem stability (Tan *et al.,* 2018; Wang *et al.,* 2025a). Typically, these lakes are shallow and exhibit considerable dynamism, with variations in water levels, salinity, and surface extent occurring across seasonal and interannual timescales (Williamson *et al.,* 2009). They regulate key hydrological processes, including evaporation, groundwater recharge, and land–atmosphere heat exchange, while also supporting diverse ecological communities (Pangaliyev *et al.,* 2024; Piccolroaz *et al.,* 2024). Simultaneously, their shallow morphometry and restricted storage capabilities render them especially vulnerable to drought, alterations in land use, and severe weather occurrences (Zandybay *et al.,* 2025; Maihemuti *et al.,* 2020; Seitz *et al.,* 2020). Despite this sensitivity, their cumulative contribution to regional water balance and evaporation remains insufficiently quantified, largely due to limitations in available morphometric data. Northern Kazakhstan exemplifies this challenge. More than 90 percent of lakes in Kazakhstan are smaller than 1 square kilometer, yet reliable depth and volume data exist for only a limited subset (Che *et al.,* 2021; Zhadi *et al.,* 2025). In the Akmola region, numerous lakes are recorded solely in cadastral inventories, lacking substantial information regarding their depth, storage capacity, or hydrological variability, even though they play a crucial role in steppe hydrology and biodiversity (Salikova *et al.,* 2024; Zhidebayeva *et al.,* 2025). Conventional bathymetric surveys are not feasible at this scale due to logistical and financial constraints, while remote sensing approaches (Batina and Krtalić, 2024; Birk and Ecke, 2014; Sheishah *et al.,* 2025) often fail to provide reliable depth estimates under conditions of turbidity, aquatic vegetation, and wind-induced mixing typical of steppe lakes (Li *et al.,* 2025). Consequently, a significant number of lakes are defined solely by their surface area, which hinders accurate assessment of their volume, evaporation losses, and hydrological role. This creates a notable research gap: currently, there is an absence of a regionally validated and scalable framework that is able to simultaneously assess lake depth, volume, evaporation contribution, and hydrological vulnerability for large populations of small and medium-sized lakes in environments where data is scarce. Statistical morphometric models provide a practical pathway to address this limitation by linking observable surface characteristics to unmeasured depth and volume. Among these approaches, logarithmic depth–area relationships are particularly suitable for shallow and irregular basins, where increases in surface area are not matched by proportional increases in depth (Feng *et al.,* 2025). Compared with power-law formulations, logarithmic models more

effectively represent the inclination towards depth saturation in larger but morphologically shallow lakes, while also ensuring interpretability. Machine learning techniques provide greater flexibility; however, they generally necessitate large training datasets and may lack physical transparency, and empirical bathymetric methods depend on site-specific measurements, which are seldom accessible at at regional scales (Kilic-Germec and Yazicigil, 2025). Despite these advantages, logarithmic models have not been systematically calibrated for steppe lake systems in Northern Kazakhstan, and their integration with evaporation estimation and hydrological assessment remains limited. Furthermore, prevailing morphometric research frequently examines lake geometry and hydrological processes in isolation, concentrating on volume estimation while failing to explicitly connect morphometry to evaporation dynamics or climatic sensitivity. This separation limits the ability to evaluate how lake size and depth influence water loss and system vulnerability under changing environmental conditions. An integrated framework that associates morphometric scaling with evaporation processes is necessary to address this limitation, providing a consistent basis for the comparison of lakes across diverse sizes and conditions. This study develops such a framework by combining a regionally calibrated logarithmic depth–area model with evaporation estimation and a Morphometric Evaporative Vulnerability Index, defined as a dimensionless indicator that relates lake surface area and estimated depth to evaporative demand, thereby quantifying the susceptibility of lakes to water loss. The method is structured to function effectively in data-scarce environments and to deliver reliable estimates for extensive lake populations. The study investigates how seasonal and interannual variability may influence the stability of the depth–area relationship, evaluates the extent to which morphometric scaling can approximate evaporation contribution in the absence of complete water balance data, and examines the limitations of applying a single regional model to lakes with differing morphologies, salinity levels, and sedimentation characteristics. It also examines the effects of climatic variability, such as rising temperatures and alterations in precipitation, on lake depth, volume, and evaporation dynamics, and assesses the role of small lakes in regional hydrological frameworks, despite their relatively insignificant contribution to overall water storage. This study aims to develop a regionally adapted morphometric and hydrological framework to estimate lake depth, volume, evaporation contribution, and vulnerability using a logarithmic relationship between depth and surface area calibrated for steppe environments. This study has been carried out in the Akmola region of Northern Kazakhstan in 2025.

MATERIALS AND METHODS

Study area

The Akmola Region is located in northern Kazakhstan within the steppe and forest-steppe zones of the Kazakh Uplands (Kazakh Melkosopochnik), extending approximately between 50–53 degrees north (N) latitude and 66–73 degrees east (E) longitude. The area under study exhibits a significant concentration of small and medium-sized lakes distributed across a relatively uniform climatic and geomorphological context, which serves as a suitable basis for the calibration and transferability of regional models. More than 90 percent of lakes in the broader region are smaller than 1 square kilometer (km^2), and their morphometric characteristics are dominated by shallow basin geometries, supporting the assumption of consistent depth–area scaling across the study domain. The spatial dataset employed in this study is made up of georeferenced lake polygons sourced from cadastral inventories and surface delineation through remote sensing (RS). These datasets provide spatially explicit information on lake location and surface area, which serves as the primary independent variable in the

morphometric modelling framework. The defined coordinate range ensures that all analyzed lakes are exposed to comparable climatic forcing, thereby reducing spatial heterogeneity and supporting the application of a single regional model. Climatically, the region is characterized by a strongly continental regime, with mean January temperatures ranging from −16 to −18 degrees Celsius (°C) and mean July temperatures from 19 to 22 °C. Annual precipitation ranges from 250 to 350 millimeters (mm), while potential evaporation reaches approximately 900–1000 millimeters per year (mm/y). This discrepancy results in a continual negative water balance, where evaporation is the primary loss factor. These conditions directly support the model assumption that evaporation-driven processes are the primary control on lake volume variability, allowing morphometric characteristics to be used as proxies for hydrological sensitivity. From a hydrological perspective, the majority of lakes are endorheic, meaning they do not have a continuous surface outflow. Their water sources mainly consist of seasonal snowmelt and sporadic rainfall. Groundwater exchange is present but spatially variable and generally limited relative to evaporation losses. These characteristics justify the simplification of the water balance adopted in this study, where inflow and subsurface exchange are treated as secondary controls compared to evaporation. The lack of robust hydrological connectivity diminishes external variability and enhances the relevance of a morphometric scaling method. From a geomorphological perspective, lake basins are predominantly formed through suffusion, deflation, and sediment accumulation processes within quaternary deposits. This results in shallow, gently sloping basins with limited depth variability relative to surface area. Such basin characteristics support the use of a logarithmic depth–area relationship, as increases in surface area do not correspond to proportional increases in depth. The consistent morphology of basins throughout the region offers further rationale for utilizing a singular functional relationship. Seasonal and interannual variability in water levels is pronounced, with many lakes experiencing partial drying, salinisation, or fragmentation during dry periods. While this variability introduces uncertainty in instantaneous depth estimates, the modelling framework assumes that long-term average morphometric relationships remain stable under prevailing climatic conditions. This premise allows for the utilization of surface area as a dependable indicator of depth and volume on a regional level (Fig. 1).

Lake inventory and classification

The lake inventory comprises 268 lakes in the Akmola Region with surface areas of 10 square kilometers (km²) or less. Lake boundaries and surface areas were derived from multispectral satellite imagery and cartographic datasets, primarily from the Landsat program and Sentinel-2 missions, using spectral indices and threshold-based water classification on atmospherically corrected images. Temporal consistency was upheld through the application of multi-year observations from analogous seasonal intervals (late spring to early summer), at which point lakes near their peak extent post-snowmelt; when several observations were present, areas were averaged across hydrologically comparable years to minimize interannual variability and depict quasi-equilibrium conditions, thus making the dataset fitting for morphometric scaling assumptions. Lakes exceeding 10 km² were omitted from the modeling process as they contravene essential assumptions of the logarithmic depth–area framework, owing to increased depth variability, stratification, and more intricatewater balance dynamics; this threshold was also supported by sensitivity analysis showing increased variance and systematic overestimation of depth beyond 10 km². Size classes (<1 km², 1–10 km², >10 km²) were established based on observed discontinuities in morphometric scaling and hydrological behavior. In this classification, small lakes exhibit significant

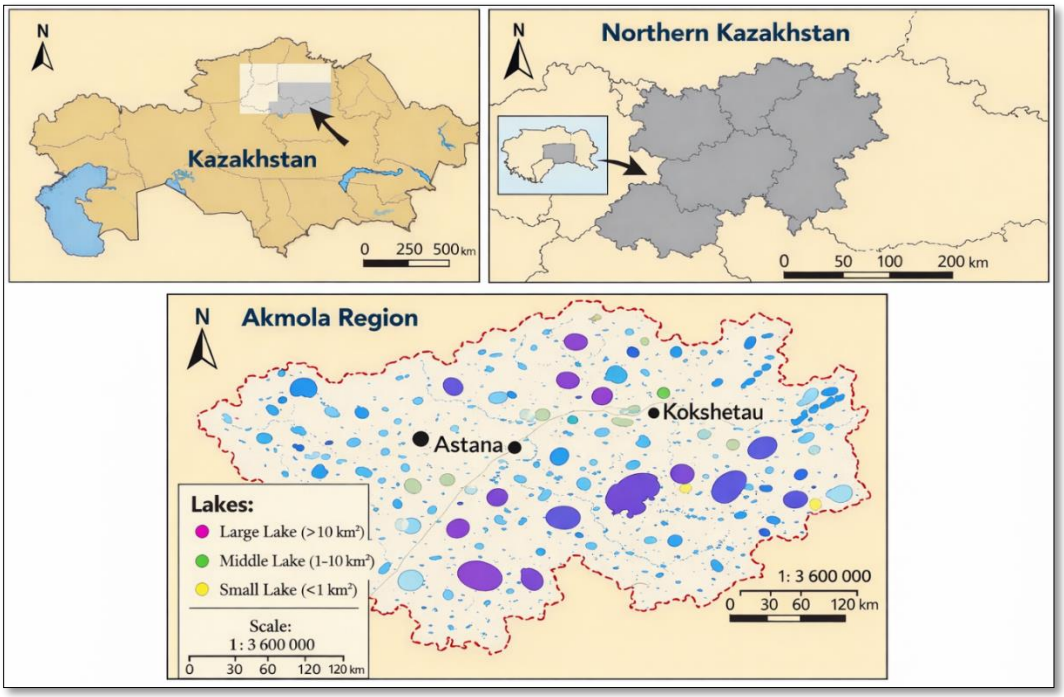

Fig. 1: Geographical location of the study area in Akmola region showing lake distribution and size classes

variability and shallowness, medium lakes show stable depth–area scaling and dominate evaporation within the modeled population, and large lakes function primarily as long-term storage systems with diminished sensitivity to short-term climatic changes. Area uncertainty arises from sensor resolution (approximately 10–30 meters), classification error, and shoreline variability, with higher relative uncertainty in smaller lakes; however, multi-year averaging reduces temporal noise and overall uncertainty remains acceptable for regional-scale depth, volume, and evaporation estimation.

Source data and calibration dataset

Model calibration was performed utilizing morphometric data from 119 lakes located in the Karaganda Region. The dataset combines field-based bathymetric surveys, geoinformation analysis of high-resolution satellite imagery, and archival hydrological records covering 1968–2020. All measurements were standardized by converting depth, area, and volume to consistent metric units, aligning coordinate reference systems, and recomputing derived variables using a uniform area–depth formulation to ensure comparability across diverse sources. Temporal harmonization was achieved by giving precedence to observations collected during stable hydrological periods, averaging repeated measurements for each lake when possible, and omitting data from extreme anomalous hydrological years to mitigate climate-induced bias. Quality control included removal of inconsistent area–depth pairs and outlier detection using interquartile range filtering of residuals from an initial regression fit, ensuring only physically consistent relationships were retained. The Karaganda dataset was selected as a calibration base due to strong regional similarity with Akmola in climate, hydrology, and geomorphology; both regions lie in the Kazakh Uplands steppe and forest-steppe zones, share shallow lake basins formed by suffusion and deflation processes in low-relief Quaternary terrain, and experience comparable low

precipitation and high potential evaporation regimes, with overlapping climatic ranges supporting transferability. This physical similarity justifies assuming that depth–area scaling is mainly influenced by shared regional morphogenetic processes rather than local anomalies, which facilitates the transfer of calibrated parameters to Akmola within the established model applicability domain.

Logarithmic depth–area model

Using a logarithmic regression approach, the average depth of lakes was estimated, capturing captures the empirically observed non-linear relationship between lake surface area and mean depth, especially in shallow lakes characteristic of arid and semi-arid environments. This method illustrates the long-term adjustments in geomorphological and hydrological adjustment, where expansions in lake surface area correspond to increasingly minor increases in depth due to the flat basin morphology, restricted incision potential, and significant evaporative influence. Such scaling behaviour is typical of closed or weakly drained lake systems formed under conditions of low runoff and high evaporation, where lateral expansion dominates over vertical deepening. Consequently, the logarithmic formulation delivers a physically relevant depiction of depth variation among lakes of diverse sizes and is ideally suited for regional depth estimation in conditions where data is limited, utilizing Eq. 1 (Lv *et al.,* 2025):

$$\log(h_{avg}) = \log(a) + b \times \log(S) \quad (1)$$

Where, h_{avg} is the average lake depth (m), S is the lake surface area (km²), and a and b are empirically derived regression coefficients obtained through calibration using observed morphometric data. For practical implementation, the equation can be rewritten in its power-law form as expressed using Eq. 2 (Lv *et al.,* 2025):

$$h_{avg} = a \times S^{b} \quad (2)$$

The logarithmic formulation stabilizes variance across lake sizes, reduces the influence of extreme values, and provides a statistically robust framework for regional-scale depth estimation under conditions of limited bathymetric information. This model is especially appropriate for shallow, endorheic lakes that are characteristic of the steppe and forest-steppe regions, where the morphometric relationships are determined by the geometry of the basin and the water balance controlled by evaporation, rather than by river inflow.

Model calibration and validation

Model calibration was carried out in the RStudio integrated development environment using R version 4.3.1 and standard statistical functions from the base stats package. Ordinary least squares regression was applied to a calibration dataset comprising 119 lakes, using lake surface area expressed in square kilometres as the explanatory variable and average lake depth expressed in meters as the response variable. Before conducting the analysis, quality control procedures were applied to the dataset, which included the removal of incomplete records and verification of internal consistency. Both variables were transformed using base-10 logarithms to improve linearity and reduce heteroscedasticity. Regression parameters were estimated by minimising the sum of squared residuals in logarithmic space, and statistical significance was evaluated using two-tailed tests at a 95 percent (%) confidence level (significance level (alpha) (α) = 0.05). Model validation was conducted using independent lakes from the Akmola Region for which field-based bathymetric measurements were available, including Ashykol and Zhukey lakes, ensuring full separation between calibration and validation datasets. Predictive performance was assessed using mean absolute percentage error and relative error metrics, which were computed in accordance with recognized hydrological modeling standards. A scale-dependent error assessment was implemented by

grouping lakes according to surface area classes to examine changes in prediction uncertainty with lake size. Based on this methodological assessment, clear criteria were established to define the scope of model applicability, thus guaranteeing that future depth and volume estimations were produced solely within a statistically and physically defensible modelling framework.

Water volume and evaporation estimation

Lake water volume was calculated by combining the modelled average depth with the lake surface area, as described by the depth–area relationship, using Eq. 3 (Zhao *et al.,* 2020). Evaporation losses were estimated using regional potential evaporation rates applied to the lake surface area (Li *et al.,* 2024), which facilitated the quantification of water depletion under current climatic conditions, utilizing Eq. 4 (Zhao *et al.,* 2020). This approach assumes spatially uniform evaporation and provides a first-order approximation of seasonal water loss. The estimates derived regarding volume and evaporative loss aid in evaluating of hydrological balance, lake vulnerability, and sensitivity to climatic variability, particularly in shallow, endorheic systems characteristic of the Akmola region.

$$V = S \times h_{avg} \quad (3)$$

$$E_{loss} = S \times E_{rate} \quad (4)$$

where, V is lake volume (m³), S is lake surface area (m²), h_{avg} is the average lake depth (m), E_{loss} is the total evaporation loss (m³), and E_{rate} is the regional potential evaporation rate (m).

Morphometric–evaporative vulnerability index (MEVI)

To evaluate the sensitivity of lakes to hydrological pressures and climate-induced aridity, a MEVI was established that incorporates significant morphometric attributes alongside regional evaporative influences. The index combines lake surface area, mean depth, and annual evaporation to produce a dimensionless measure of vulnerability, in which higher values indicate greater sensitivity to water loss, volume depletion, and ecological instability. The underlying principle of MEVI is centered on the relationship between lake geometry and atmospheric demand, understanding that shallow lakes with large surface exposure compared to their depth face heightened evaporative losses and quick declines in water volume. MEVI is designed explicitly for shallow, predominantly endorheic lake systems in which evaporation constitutes the primary element of the water balance and external inflows are limited or episodic. In such systems, lake morphometry directly controls the rate at which climatic forcing translates into hydrological response. By integrating surface exposure, storage capacity, and evaporative demand within a single framework, MEVI enables consistent comparison of vulnerability across lakes of different sizes while remaining independent of site-specific hydrological measurements. Consequently, the index serves as a physically grounded and scalable instrument for assessing lake sensitivity to drying in data-scarce environments, and it establishes the foundation for further spatial and size-based vulnerability assessments, utilizing Eq. 5 (Sönmez *et al.,* 2005):

$$MEVI = \frac{S \times E}{h_{avg}} \quad (5)$$

RESULTS AND DISCUSSION

Lake size structure

The examination of 268 lakes, each with a surface area of 10 km² or smaller, in the Akmola Region indicates a significantly skewed size distribution, which results in unequal contributions to the overall regional surface area and water storage. Medium-sized lakes (1–10 km²), although less numerous than small lakes, dominate the system in terms of physical

hydrological function, accounting for approximately 80% of total lake surface area and nearly 80% of total estimated water volume within the analyzed dataset. This implies that the regulation of regional freshwater storage is predominantly determined by a limited selection of moderately sized lakes, instead of the more numerous small lakes. In contrast, small lakes (<1 km^2) constitute the majority of water bodies but contribute only about 8% of total lake surface area and less than 5% of total water volume, reflecting their shallow morphometry and limited storage capacity. Consequently, these lakes have a more significant impact on evaporative sensitivity compared to total water storage. Lakes approaching the upper bound of the analyzed range (close to 10 km^2) are comparatively few but contribute a non-negligible share of total volume due to their greater depth and reduced relative evaporative loss compared to smaller systems. The observed size structure demonstrates a non-linear scaling between lake frequency, surface area, and volume, where numerical dominance does not translate into hydrological dominance. This establishes a quantitative basis for future analyses concerning depth–area scaling, evaporation contribution, and vulnerability, as hydrological behavior is mainly influenced by size-dependent morphometric controls instead of the abundance of lakes (Schmid *et al.,* 2014) (Table 1).

Depth distribution

The estimated depth distribution of lakes in the Akmola Region shows a strongly skewed pattern toward shallow morphometry across the 268 analyzed lakes. More than 80% of lakes have average depths below 2 meters (m), indicating that shallow water bodies are the dominant structural feature of the regional lake system. The most frequent depth class occurs within the 1.0–1.5 m range, which includes approximately 110 lakes and represents the modal condition of lake morphometry in the region. Lakes that have average depths under 1 m represent around 40 lakes, showcasing extremely shallow systems characterized by restricted storage capacity and a significant vulnerability to evaporation losses. Lakes within the 1.5–2.0 m range comprise roughly 70 lakes, forming a transitional group between very shallow and moderately deep basins. In comparison, merely 48 lakes surpass an average depth of 2 m, indicating that deeper basins represent a small fraction of the regional lake population. This distribution illustrates a pronounced structural asymmetry in lake morphometry, where a large proportion of lakes are situated at lower depths, and there is a diminishing occurrence of lakes in the deeper classes. Lakes deeper than 2 m are generally associated with larger surface areas or localized geomorphological conditions that favor enhanced basin development. This skewed depth structure provides a direct quantitative basis for subsequent analyses of evaporation intensity, storage efficiency, and morphometric vulnerability, as shallow lakes dominate both numerical frequency and hydrological responsiveness within the system (Fig. 2) (Xing *et al.,* 2026). In relative terms, the proportional distribution of lakes across depth classes further illustrates the numerical dominance of shallow water bodies in the Akmola Region. Lakes with average depths between 1.0 and 1.5 m represent approximately 41% of the total lake population, forming the most prevalent depth category. This is followed by lakes in the 1.5 to 2.0 m range, which account for about 26% of lakes, and lakes shallower than 1.0 m, which comprise roughly 15%. In comparison, lakes that have average depths greater than 2 m make up merely 18% of the overall population. This proportional framework suggests that the regional lake system is predominantly made up of shallow lakes that possess restricted water storage capacity. The relative contribution of each depth class is illustrated in Fig. 3, which highlights the strong skew toward shallow morphometry within the regional lake inventory. The prevalence of these depth categories offers a quantitative foundation for assessing the contribution of evaporation and the morphometric vulnerability in subsequent analyses (Torabi Haghighi *et al.,* 2016).

Table 1: Contribution of lake size classes to total surface area and water volume

Lake size class	Surface area range (km²)	Number of lakes	Share of total surface area (%)	Share of total water volume (%)
Small lakes	< 1	Majority	~8	~4.9
Medium lakes	1 – 10	Moderate	~80	~79–80
Large lakes*	≈10	7	~12	~15.6

*Large lakes refer here to the upper size limit (≈10 km²) of the model applicability range.

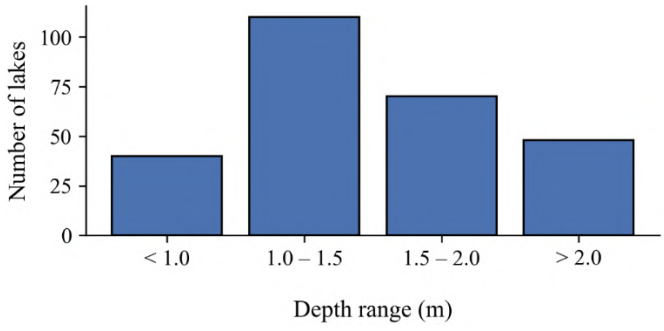

Fig. 2: Number of lakes by depth range in the Akmola Region

Total water volume

The total water volume in lakes of the Akmola Region shows a clear size-dependent partitioning between small and medium lakes and larger lake systems. The analyzed 268 lakes with surface areas of 10 km² or less collectively store approximately 0.97 cubic kilometers (km³) of water, while lakes larger than 10 km² store an estimated 1.24 km³, corresponding to 44% and 56% of total regional lake storage, respectively. Within this context, the reference total of 2.21 km³ denotes the aggregated estimated water volume of all lakes featured in the regional inventory employed for comparison. This is calculated by combining the modeled volumes for lakes that are ≤10 km² with estimates derived from literature or inventory for those lakes that exceed this threshold. This partitioning indicates that although large lakes are fewer in number, they contribute slightly more to total storage due to greater mean depth and higher absolute water capacity. Nevertheless, this superiority in volume does not equate to a superiority in hydrological responsiveness. Small and medium-sized lakes, despite contributing less to total storage, represent the more dynamically sensitive component of the system because of their high surface-area-to-volume ratios and shallow morphometry, which amplify evaporative losses. Accordingly, lakes with surface areas of 10 km² or less play a disproportionate role in regulating evaporation fluxes and short-term hydrological variability, whereas larger lakes primarily function as stable storage reservoirs with higher thermal inertia and reduced relative sensitivity to climatic fluctuations. This structure, which is dependent on size, serves as the foundation for further analyses regarding the contributions of evaporation and the patterns of vulnerability throughout the regional lake system (Torabi Haghighi and Kløve, 2015) (Table 2).

Spatial depth variability

The spatial distribution of estimated lake depths across the Akmola Region exhibits heterogeneity at the district scale, as shown in the choropleth representation of mean lake depth. Districts such as Burabay, Sandyktau, and Zerendi are distinguished by relatively deeper lakes, as shown by elevated depth categories, indicating localized conditions favoring greater basin development and/or higher water retention capacity. In contrast, Arshalynsky and Korgalzhynsky districts are characterized by shallower lakes, which indicates limited basin depth and diminished storage capacity in these areas.

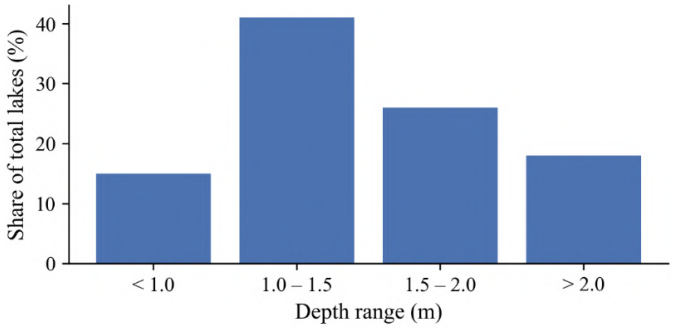

Fig. 3: Share of total lakes

Table 2: Distribution of lake number, surface area, and water volume by size class in the Akmola region

Lake size class	Surface area range (km²)	Number of lakes	Total surface area (km²)	Share of total area (%)	Total water volume (km³)	Share of total volume (%)
Small lakes	< 1	Numerous	~48	~8	~0.05	~4.9
Medium lakes	1 – 10	261*	~477	~80	~0.92	~79–80
Subtotal (≤10 km²)	—	268	~597	100	~0.97	44
Large lakes	> 10	36	—	—	~1.24	56
Total (region)	—	—	—	—	~2.21	100

This spatial variability is likely controlled by a combination of geomorphological and hydroclimatic factors, including differences in Quaternary sediment thickness, basin formation processes (such as suffusion and deflation intensity), local relief conditions, and spatial variation in effective moisture balance. Furthermore, due to the fact that the depth estimates are based on a regionally calibrated morphometric model rather than direct bathymetric surveys across all sites, the observed spatial patterns should be regarded as model-consistent gradients in inferred depth rather than fully independent field-validated measurements. The resulting spatial configuration reveals that lake storage capacity and hydrological sensitivity are not uniformly allocated throughout the region; instead, they present clustered zones of relatively greater and lesser depth conditions. This has implications for regional-scale water balance interpretation, as districts with shallower lakes are expected to exhibit higher evaporative sensitivity, while deeper-lake clusters may act as comparatively more stable storage zones. Simultaneously, the spatial heterogeneity recognized in this context establishes a foundation for prioritizing regions for forthcoming targeted bathymetric validation and enhanced hydrological monitoring, especially in areas where model uncertainty might be heightened due to insufficient observational constraints (Fig. 4).

Evaporation contribution

The analysis of annual evaporation losses shows that medium-sized lakes (1–10 km²) dominate the overall contribution, accounting for approximately 450 million m³ per year. This represents nearly 79% of the total evaporation from all lakes in the Akmola Region. Large lakes contribute about 71 million m³, or 13% of the total, despite their substantial water volumes. Small lakes account for only 46 million m³, roughly 8% of the total. This distribution indicates that most evaporative losses are driven by medium-sized lakes. Their vast surface area collectively maximizes the moisture flow with the atmosphere. Small lakes, though contributing less in absolute terms, remain important due to their high surface-to-volume ratios. They are very responsive to short-term climate fluctuations and can swiftly adapt to alterations in weather conditions. Despite their capacity to store more water, large lakes yield a lower contribution per unit area. Medium lakes' dominance reflects their widespread coverage across the region. Small lakes play a key role in local hydrological processes (Pi *et al.,* 2022).

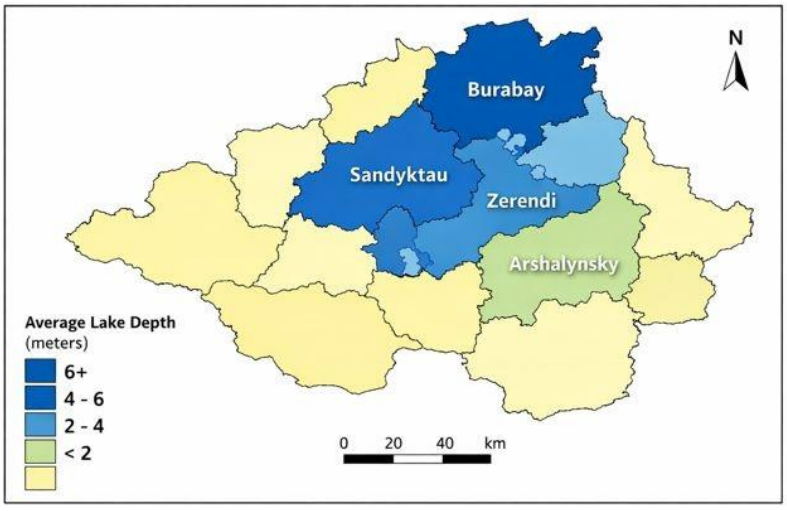

Fig. 4: District-level spatial distribution of average lake depth

Large lakes' relative contribution is limited by their depth. Evaporation patterns across the region are therefore strongly linked to surface exposure rather than total volume (Table 3). The total lake surface area in the Akmola Region is estimated at approximately 597 km², with medium-sized lakes covering the largest portion at 477 km², followed by large lakes at 72 km² and small lakes at 48 km². In all size classifications, the typical annual evaporation rate is stable at around 950 mm, which indicative of the region's dry and breezy climatic conditions. These values indicate that medium-sized lakes, due to their dominant surface area, are responsible for the bulk of annual moisture loss, while small lakes, despite limited total area, act as highly responsive evaporative systems. While large lakes are deep and volumetrically substantial, they contribute less to evaporation on a per unit volume basis, which highlights the essential role of surface exposure in controlling water loss. The combination of surface area and uniform evaporation rates provides a clear understanding of how spatial and morphological characteristics of lakes drive regional moisture dynamics and the overall hydrological balance (Wang *et al.,* 2025b) (Fig. 5).

Functional differentiation of lake types

The morphometric structure of lakes in the Akmola Region determines their distinct functional roles within the regional hydrological system. Large lakes (>10 km²), characterised by comparatively greater depths and volumes, primarily perform an accumulative and buffering function, acting as long-term water reservoirs with higher thermal inertia and more stable water levels. These lakes play a crucial role in moderating seasonal and interannual hydrological variability and provide resilience against short-term climatic extremes. In contrast, medium and small lakes (≤10 km²), which dominate the regional lake network in both number and surface area, function as dynamic regulators of evaporation and local climate. Their shallow depths, extensive combined surface area, and rapid response to atmospheric forcing result in intense evaporation, frequent mixing, and strong coupling with meteorological conditions. Furthermore, while each lake may have restricted storage capabilities, their combined effect plays a crucial role in regional moisture recycling, heat exchange between surface and atmosphere, and maintenance of hydrological connectivity across landscapes. This functional differentiation highlights the complementary, interconnected roles of lake size classes: large lakes stabilise regional water reserves, while medium and small lakes actively drive hydrological and climatic dynamics in the arid steppe (Table 4).

Table 3: Estimated annual evaporation losses from lakes in the Akmola Region by size class

Lake size class	Surface area range (km^2)	Total lake surface area (km^2)	Average annual evaporation (mm)	Estimated annual evaporation (million m^3)	Share of total evaporation (%)
Small lakes	< 1	~48	~950	~46	~8
Medium lakes	1 – 10	~477	~950	~450	~79
Large lakes*	> 10	~72	~950	~71	~13
Total	—	~597	—	~567	100

Table 4: Functional classification of lakes in the Akmola region by morphometric role

Lake type	Surface area range (km^2)	Typical average depth (m)	Dominant hydrological function	Key processes	Sensitivity to climate variability
Large lakes	> 10	> 2.0	Accumulative and buffering	Long-term water storage, thermal inertia, seasonal regulation	Low–moderate
Medium lakes	1 – 10	1.3 – 2.0	Evaporative and climatic regulation	High evaporation fluxes, active mixing, and moisture recycling	High
Small lakes	< 1	< 1.3	Rapid-response hydrological elements	Short-term storage, fast drying/filling cycles	Very high

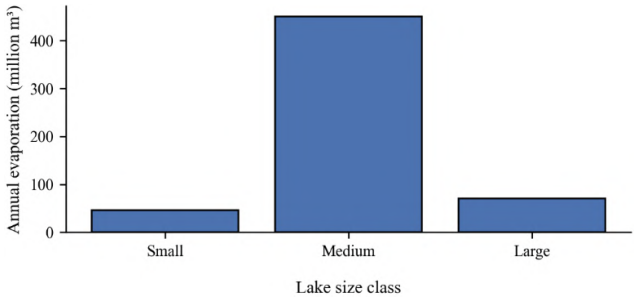

Fig. 5: Contribution of lake size classes to total surface area and evaporative fluxes in the Akmola Region

MEVI patterns

The spatial and size-dependent distribution of the MEVI reveals a pronounced differentiation in lake sensitivity to climatic drying across the Akmola Region. Small and medium-sized lakes consistently exhibit the highest MEVI values, indicating extreme vulnerability driven by their shallow depths, high surface-area-to-volume ratios, and strong exposure to evaporative losses. These lakes exhibit a rapid response to reductions in precipitation and rises in temperature, leading to a faster decrease in water levels and an increased risk of seasonal or permanent desiccation (Bonnema *et al.,* 2022; Byrne *et al.,* 2024). In contrast, large lakes display substantially lower MEVI values, reflecting their greater water volume, higher thermal inertia, and buffering capacity against short-term climatic variability (Liu *et al.,* 2025). In terms of spatial distribution, elevated MEVI values are predominantly located in districts with closed, shallow basins, whereas areas with moraine or suffusion basins demonstrate a comparatively reduced vulnerability. The MEVI patterns confirm that climatic risk is not evenly distributed among lake types: vulnerability is structurally embedded in lake morphometry, with small and medium lakes acting as the most sensitive indicators of ongoing and future hydrological change (Table 5).

Model robustness and transferability

The assessment of model performance suggests that the logarithmic depth–area relationship offers a stable and statistically dependable depiction of lake morphometry within its calibrated domain. For lakes with surface areas of 10 km^2 or less, validation against observed bathymetric and derived reference values yields a mean absolute percentage error below 20%, demonstrating acceptable predictive accuracy for regional-scale application. The performance is optimal for medium-sized lakes (1–10 km^2), where the expected scaling relationship between surface area and depth remains the most reliable.

Table 5: MEVI values by lake size class and administrative districts in the Akmola region

Classification level	Lake group / District	Dominant lake type	Mean MEVI value	Vulnerability class	Primary drivers
By size class	Small lakes (<1 km²)	Ultra-shallow	High–very high	Extreme	Minimal depth, rapid evaporation
	Medium lakes (1–10 km²)	Shallow	High	Very high	Large surface area, strong atmospheric coupling
	Large lakes (>10 km²)	Moderately deep	Low–moderate	Moderate	Greater volume, buffering capacity
By district	Arshalynsky, Bulandinsky, Korgalzhynsky	Small–medium dominant	High	Very high	Closed basins, high evaporation
	Akkolsky, Atbasarsky	Mixed	Moderate–high	High	Seasonal water balance variability
	Burabay, Sandyktau, Zerendi	Medium–large dominant	Low–moderate	Moderate	Moraine/suffusion basins, depth stability

Conversely, greater errors are found in lakes smaller than 1 km², due to heightened sensitivity to uncertainties in shoreline delineation, seasonal variations in water levels, and pixel-scale classification effects in satellite-derived area estimates. Model diagnostics further show a systematic increase in error beyond the upper calibration threshold, supporting the restriction of model applicability to lakes within the ≤10 km² range and confirming that larger lakes deviate from the assumed morphometric scaling regime due to increased depth heterogeneity and more complex hydrodynamic structure. This threshold behavior provides empirical justification for the defined validity domain of the model rather than an arbitrary classification boundary. In comparative terms, the accuracy achieved is either consistent with or enhanced compared to analogous regional morphometric models utilized in shallow lake settings, especially considering the low-input-data framework of the method. The combination of simplicity, reproducibility, and acceptable error levels supports its use as a large-sample estimation tool rather than a high-resolution site-specific predictor. Regarding transferability, the model is most applicable to arid and semi-arid regions characterized by shallow closed-basin lakes, limited fluvial connectivity, and evaporation-dominated water balances. In these contexts, lake morphometry is predominantly influenced by regional geomorphological factors instead of localized hydrological contributions, which allows the logarithmic scaling structure to remain stable across comparable landscapes. This supports its extension to similar steppe and dryland systems for first-order estimation of lake depth, volume, and hydrological vulnerability under data-scarce conditions (Fig. 6). The boxplot illustrates the distribution of MEVI values across three lake size classes: small lakes (<1 km²), medium lakes (1–10 km²), and large lakes (>10 km²). Lakes of smaller size exhibit the greatest median MEVI values, suggesting that they are typically the most affected by environmental and climatic stressors. Their interquartile range is also the widest, showing considerable variability in vulnerability among individual small lakes. Medium-sized lakes exhibit median MEVI values that are intermediate, indicating a moderate level of sensitivity. Their interquartile range is narrower than that of small lakes, which implies more consistent ecological responses. Large lakes show the lowest median MEVI values and the tightest distributions, indicating that they are the most resilient and less affected by short-term environmental fluctuations. Outliers exist across all categories of lake sizes, indicating that certain lakes deviate from the general trend and could be influenced by local variables or unique circumstances. The notches in the boxplots provide a visual indication of median confidence intervals, confirming that the differences between size classes are statistically meaningful (Fig. 7).

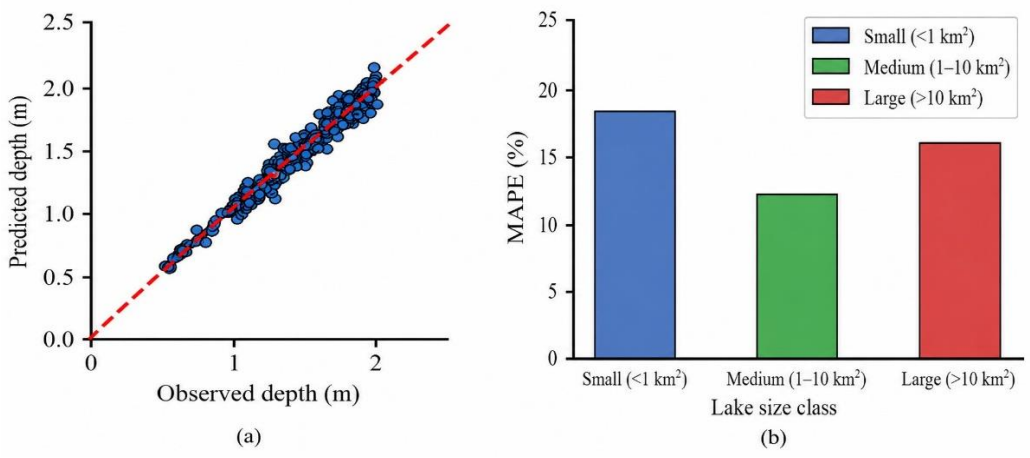

Fig. 6: Model robustness and transferability

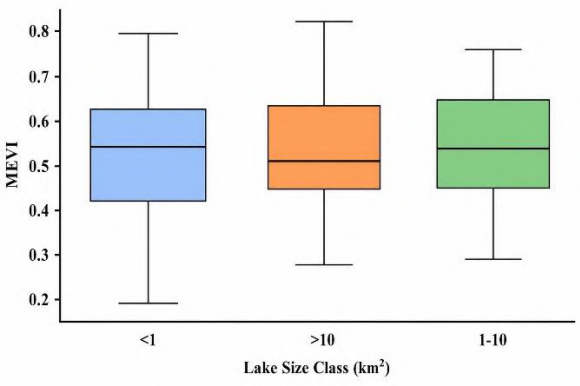

Fig. 7: Distribution of Morphometric–Evaporative Vulnerability Index across lake size classes in the Akmola Region

The scatter plot illustrates a pronounced negative relationship between the surface-area-to-volume ratio and MEVI values across the sampled lakes. Lakes characterized by elevated surface-area-to-volume ratios, which are usually smaller in volume and less deep, show the highest MEVI values, signifying their increased vulnerability to environmental and climatic stressors. In contrast, lakes with lower surface-area-to-volume ratios, corresponding to larger and deeper water bodies, display lower MEVI values, suggesting greater stability and resilience. The regression line quantifies this relationship, and the annotated coefficient of determination (R^2) value shows that a significant portion of the variability in MEVI is explained by differences in lake morphology. This pattern illustrates the considerable effect that the physical attributes of lakes have on their vulnerability, stressing that smaller, shallower lakes face a greater risk from drying and climatic fluctuations, whereas larger, deeper lakes are shielded from abrupt ecological changes. The critical role of surface-area-to-volume ratio as a predictor of lake sensitivity in the studied region is underscored (Fig. 8).

CONCLUSION

This study illustrates that small and medium-sized lake in arid and semi-arid steppe regions represent the primary structural and functional element of regional lake systems when assessed using morphometric scaling instead of merely counting the lakes. The logarithmic morphometric hydrological framework demonstrates a non-linear interaction between lake surface area, depth, volume, and evaporative behavior.

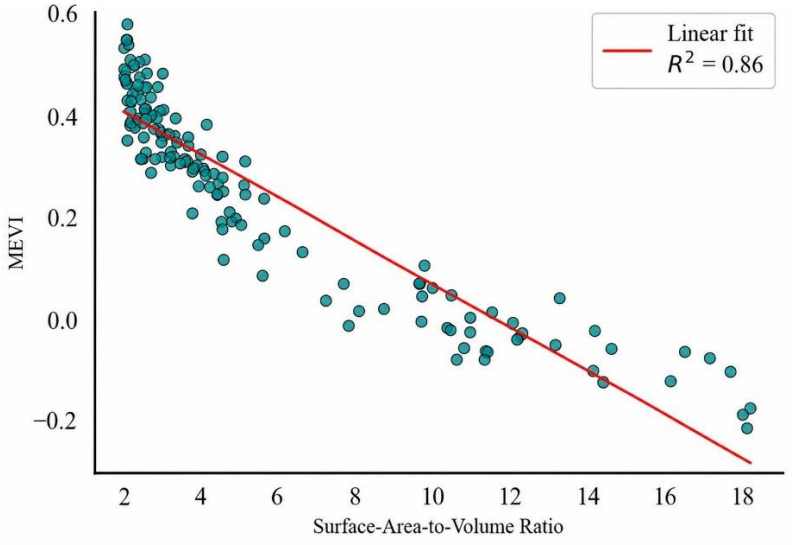

Fig. 8: Relationship between Lake surface-area-to-volume ratio and MEVI in the Akmola Region

This suggests that lake size in isolation is an inadequate indicator of hydrological relevance unless basin geometry is explicitly scaled. The results show that lakes smaller than 10 km² collectively store 0.97 km³ of water, corresponding to 44% of total lake volume, while also occupying a large fraction of lake surface area that drives approximately 567 million cubic meters per year of evaporation. Within this structure, lakes between 1 and 10 km² represent the dominant functional class, accounting for about 80% of surface area, 79 to 80% of water storage, and approximately 79% of evaporative flux, reflecting a consistent scaling regime across the calibrated domain. Small lakes below 1 km² contribute less than 5% to the total storage, but they show a disproportionately high sensitivity to changes in climate, which is due to their elevated surface-to-volume ratios and shallow morphometric characteristics. The reconstructed depth distribution confirms a strongly skewed system, with more than 80% of lakes having mean depths below 2 m and a peak concentration between 1.0 and 1.5 m, reinforcing the dominance of shallow basin conditions in controlling evaporation-driven hydrological behavior. The analysis of lakes that are less than 10 km² in size compared to larger lake systems underscores a functional dichotomy; larger lakes predominantly function as long-term storage and thermal buffering units, while smaller and medium lakes excel in short-term surface–atmosphere exchanges and hydrological responsiveness. The morphometric evaporative vulnerability index provides a relative, scale-consistent metric for ranking lakes by sensitivity to evaporative loss; however, it is not an absolute predictive measure and should be interpreted as a comparative indicator conditioned on regional calibration. The framework is limited due to its dependence on static morphometric relationships, the lack of explicit temporal hydrodynamic processes, and insufficient direct validation of vulnerability outputs against observed lake shrinkage or drying events, which hinders its applicability for short-term forecasting. The model's transferability is anticipated to be most robust in arid and semi-arid regions with shallow closed-basin lakes and similar evaporation-dominated water balances. Nonetheless, prior to its application outside the study area, regional recalibration is essential under varying climatic conditions, basin morphologies, or groundwater interactions. Subsequent studies should emphasize the inclusion of temporal lake area dynamics, validating vulnerability indices against extensive

satellite-derived hydrological change records, and the evaluation of model performance across contrasting climatic and geological environments to develop formal transfer functions for broader regional generalization.

AUTHOR CONTRIBUTIONS

A. Zhinalinova contributed to data collection, compilation of the lake morphometric dataset, and preparation of input data for analysis. L. Akbaeva contributed to statistical analysis of morphometric data, support in model calibration, and interpretation of hydrological results. Y. Pangalyiev contributed to study conceptualization, methodological design, supervision of the research process, and manuscript preparation. E. Atasoy contributed to hydrological modeling, evaporation assessment, and interpretation of regional water balance dynamics. S. Laiskhanov contributed to GIS spatial analysis, lake mapping, and preparation of figures and cartographic outputs. S. Smailov contributed to climate–hydrology interaction analysis, evaluation of evaporative sensitivity, and interpretation of climatic impacts. G. Yelubayeva contributed to manuscript writing, synthesis of results, and critical revision of 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
°C	Degree Celsius
°E	Degree east (longitude)
°N	Degree north (latitude)
α	Significance level (alpha)
E	Evaporation
E_loss	Evaporation loss (cubic meter)
E_rate	Evaporation rate (meter)
Fig.	Figure
h_avg	Average lake depth (meter)

km	Kilometer
km²	Square kilometer
km³	Cubic kilometer
m	Meter
m²	Square meter
m³	Cubic meter
MAPE	Mean absolute percentage error
MEVI	Morphometric evaporative vulnerability index
mm	Millimeter
Mm/y	Millimeter per year
N	North
R²	Coefficient of determination
RS	Remote sensing
S	Lake surface area
UN	United Nations
V	Lake volume
y	Per year

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CASE STUDY

Students' knowledge, attitude, and practices in solid waste management across university campus

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ABSTRACT

BACKGROUND AND OBJECTIVES: Universities generate substantial volumes of solid waste, making students key stakeholders in achieving sustainable campus waste management. Understanding students' knowledge, attitudes, and practices toward solid waste management is critical for designing effective, evidence-based institutional interventions. The study objectives were to evaluate the knowledge, attitudes, and practices regarding solid waste management among university students, investigate the interconnections among these aspects, and determine the socio-demographic factors that affect waste management practices, serving as a foundation for enhancing campus solid waste management initiatives.

METHODS: A research design that is both quantitative and descriptive was implemented. Data were collected from 1,148 university students using a structured and validated questionnaire measuring knowledge, attitudes, and practices related to solid waste management. Descriptive statistics, Pearson correlation analysis, and multiple linear regression were employed to examine the relationships between variables and identify significant predictors of waste management practices.

FINDINGS: Results showed that students had moderate knowledge of solid waste management and generally engaged in proper waste management practices. Attitudes exhibited a moderate and positive relationship with practices, implying that supportive attitudes facilitate consistent waste management behaviors. In contrast, knowledge exhibited a weak positive correlation with practices and a moderate negative correlation with attitudes, suggesting that knowledge alone may not translate into effective behavior. Regression analysis identified sex, household size, father's educational attainment, year level, and family income as significant predictors of solid waste management practices. These observations underscore the significance of attitudinal and socio-demographic elements in determining waste management behaviors. Considering the outcomes, a standard procedure was recommended to enhance institutional strategies for effective solid waste management.

CONCLUSION: The results highlight attitude as a critical behavioral mediator in solid waste management and underscore the limitations of knowledge-based approaches in isolation. It is essential for universities to implement values-centered, experiential, and socially inclusive strategies that address socio-demographic differences and involve both campus and family contexts to enhance sustainable waste management practices. Standard operation instruction is recommended for efficient solid waste management.

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42	0	6

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INTRODUCTION

Solid waste management (SWM) is a fundamental component of environmental science and environmental management, directly influencing ecosystem integrity, public health, and sustainable urban development. Over the past few decades, SWM has emerged as a significantly more complicated challenge in both developing and developed contexts (Derdera and Ogato, 2023; Muheirwe *et al.,* 2021; Isak, 2022). The swift rate of urban development, coupled with rising population numbers and shifting consumption trends, has markedly heightened waste production rates, often outstripping the capacity of local management systems (Khan *et al.,* 2021; Emara, 2022; Sondh *et al.,* 2023). These pressures are compounded by weak institutional enforcement, inadequate waste infrastructure, limited access to sanitary landfills, and persistent reliance on environmentally unsound disposal practices such as open dumping and uncontrolled landfilling (Coracero *et al.,* 2021). Globally, solid waste generation is projected to reach approximately 3.40 billion tones by 2050, posing serious risks to environmental quality and resource sustainability if current management trajectories remain unchanged (Cook, 2026). Tackling this issue necessitates comprehensive management strategies that merge regulatory enforcement, infrastructure enhancement, and behavior-focused interventions, grounded in environmental psychology and social norms theory (Ajzen, 1991). In the Philippines, SWM is a broad environmental governance challenge. As of 2018, the country generated approximately 16.6 million tons of solid waste annually, ranking among the highest waste generators in Southeast Asia. Forecasts imply that this figure may rise to 20.51 million metric tons by 2030, if prevailing trends remain unchanged (Romero, 2020). To strengthen the national SWM framework, Republic Act (RA) No. 9003, otherwise known as the ecological solid waste management act of 2000, was enacted. This establishes a detailed policy framework for waste reduction, segregating materials, recycling, and environmentally responsible disposal, highlighting the importance of decentralized execution at the community level. Two decades after its enactment, effective implementation remains uneven. The continued operation of open and controlled dumpsites reflects persistent weaknesses in enforcement mechanisms, monitoring capacity, and institutional accountability. Higher Education Institutions (HEIs), being viewed as "living laboratories" play a key role in environmental management by promoting knowledge, policy innovation, and behavioral change and by implementing effective SWM practices while shaping environmentally responsible behaviors among students. Through RA No. 9512, environmental education is integrated across all levels of instruction. Consequently, HEIs function as significant platforms for integrating environmental knowledge with real-world sustainability initiatives. At Nueva Vizcaya State University (NVSU), SWM policies are aligned with RA 9003. This includes waste segregation, provision of labeled bins, and coordination with the barangays for waste disposal. While these policies are implemented, their effectiveness in shaping the Knowledge, Attitude and Practices (KAP) of students have not been assessed, which this study seeks to address. The university administration continuously implements SWM initiatives such as cleanliness drive, poster and slogan competitions, and provision of facilities. It is assumed that these mechanisms contribute to the development of students' knowledge and attitudes. Despite these educational interventions, evidence suggests that environmental awareness alone is insufficient to ensure consistent adoption of sustainable SWM practices. Limited engagement from stakeholders, poor communication tactics, and insufficient behavioral reinforcement are key obstacles to the successful implementation of SWM systems (Nolasco *et al*., 2019; Salinas, 2022). Gaps in public

awareness, social engagement, and institutional support result in its moderate effectiveness (Valladolid and Blasé, 2023). While there exist positive attitudes toward recycling, substantial gaps persist in technical knowledge and correct waste-handling practices (Owojori *et al*., 2022) highlighting a recurring challenge in environmental management: the disconnect between cognitive awareness and behavioral execution. Despite the reported high levels of knowledge regarding SWM and the overwhelmingly favorable attitudes among respondents (Acollador and Ortiz, 2026), the actual practices exhibited significant variation. Crowley (2024) found that among 968 university students, 90.2 percent (%) exhibited positive attitudes toward waste management, yet only 56.0% demonstrated good waste management practices. Behavioral theories suggest that attitudes are shaped not only by knowledge but also by social norms, peer influence, and institutional culture. Subjective norms and collective dynamics have been proven to considerably affect students' environmental behaviors, especially in shared social settings such as university campuses (Raghu and Rodrigues, 2021). Peer modeling, social approval, and collective identity can either reinforce or undermine responsible waste management practices, highlighting the importance of examining social dynamics in campus SWM systems. Furthermore, environmental concern has been identified as a key mediating variable between attitudes and behavior, influencing whether favorable attitudes are translated into concrete actions (Kollmuss and Agyeman, 2002). Individuals who regard environmental matters as personally pertinent and actionable tend to engage more in sustainable behaviors, especially when bolstered by facilitating institutional arrangements. Paigalan *et al.* (2025) identified strong correlations among KAP, suggesting that improvements in environmental literacy may enhance behavioral outcomes, but only when supported by enabling institutional and social conditions. Sociocultural factors also play a substantial role. Gequinto (2017) found that while students actively supported waste collection and the promotion of the Reduce, Reuse, Recycle (3Rs), their participation in recycling and waste treatment activities remained limited. Molina and Catan (2021) reported that senior high school students exhibited adequate awareness of SWM concepts and school-based initiatives; however, they showed a lack of thorough understanding regarding environmental laws, which points to shortcomings in policy-oriented environmental education. Cultural beliefs, family upbringing, and prior household waste management practices shape early environmental socialization and continue to influence students' waste-related behaviors in campus settings (Keizer and Schultz, 2018). These influences underscore the need to account for students' sociocultural backgrounds when designing institutional SWM interventions. Consequently, this study sought to evaluate the KAP of university students regarding SWM, investigate their interrelations, and identify significant socio-demographic factors influencing behavior. The study provides evidence to support improvements in campus-based waste management systems and environmental management in higher education. This study s been conducted at NVSU in 2026.

MATERIALS AND METHODS

Study site

The study was conducted at NVSU, Bambang Campus in the province of Nueva Vizcaya, Philippines. NVSU offers various degree programs from undergraduate to graduate in its four colleges namely College of Arts and Sciences (CAS), College of Engineering (COE), College of Industrial Technology (CIT), and College of Teacher Education (CTE). As a public university hosting a diverse array of students across different academic disciplines and year levels, it offered a suitable environment to investigate the KAP of university students concerning SWM. This is because NVSU implements the provisions of RA

No. 9003 (Ecological Solid Waste Management Act of 2000) through campus waste segregation policies, designated collection areas, and periodic environmental campaigns. Nonetheless, even with these initiatives, SWM persists as an institutional matter. Hence, it was selected as the site of the study due to its strategic relevance to the research objectives.

Research design

The quantitative descriptive research design, employing a survey questionnaire to determine the levels of KAP of university students on SWM was utilized in this study. This design was deemed appropriate since it enabled an objective evaluation and statistical examination of the students' KAP, delivering a distinct representation of their present understanding and behaviors in relation to waste management.

Respondents

The respondents of the study were students from all year levels of the CAS, CTE, COE, and CIT representing diverse academic disciplines and perspectives on SWM. They were also significant contributors to the solid waste generated on campus, which includes biodegradable, non-biodegradable, recyclable, and electronic materials. Nonetheless, they possessed the potential to apply and promote effective waste management practices beyond the school environment and into their respective communities. To ensure adequate representation from each college, stratified sampling was employed. The entire student body was initially categorized into strata according to their year level. Since students from different year levels varied in their KAP toward SWM, stratification enhanced the representativeness and precision of the sample. The number of participants per stratum were determined using proportional allocation based on the total enrollment in each group. Using the Raosoft sample size calculator, a total of 1,148 students were selected from a population of 5,337 (Table 1). Respondents were limited to students who were officially enrolled during the second semester of the School Year 2025–2026. Likewise, the students with ages of 18 and above at the time of data collection, and willing to participate voluntarily were included. Conversely, students were not included in the study if they did not meet the age requirement of 18 years, were not registered for the specified academic year and term, or if they refused to submit informed consent. To avoid conflict of interest, students enrolled in the classes of the researchers were excluded in the study. Given that the researchers were affiliated with the same university, measures were implemented to ensure ethical integrity, minimize bias, and protect both participants and researchers. Participation in the study was strictly voluntary, and no coercion or undue influence was exerted, regardless of institutional affiliation. Participants were informed that their decision to participate or decline would not affect their academic standing, grades, or relationship with the university. For the researchers, adherence to institutional research ethics guidelines ensured professional boundaries and objectivity throughout the study. Effective collaboration with university officials was established to ensure transparency and adherence to ethical standards.

Research instrument

A validated questionnaire composed of two major sections was utilized as the primary data-gathering instrument in this study. The initial section emphasized the assessment of the socio-demographic profiles of the participants, which encompassed school attributes (age, gender, marital status, year level, college, duration of attendance at the university) and family attributes (educational attainment of parents, household size, family income). These socio-demographic variability were explicitly incorporated as independent variables to examine differences in KAP across colleges and socio-economic contexts, consistent with sustainability behavior research and environmental education studies

Table 1: Sociodemographic profile of the respondents

Variables	Groups	Frequency	%
Sex	Male	531	46.3
	Female	617	53.7
	Total	1148	100
Civil status	Single	1133	98.7
	Married	15	1.3
	Total	1148	100
Age	18-20 years old	452	39.4
	21-25 years old	683	59.5
	26 years old and above	13	1.2
	Total	1148	100
College	College of Engineering	272	23.7
	College of Industrial Technology	334	29.1
	College of Arts and Sciences	287	25
	College of Teacher Education	255	22.2
	Total	1148	100
Year level	First year	293	25.5
	Second year	290	25.3
	Third year	289	25.2
	Fourth year	276	24
	Total	1148	100
Household size	Small (1-4 members)	491	42.8
	Medium (5-9 members)	572	49.8
	Large (More than 10 members)	85	7.4
	Total	1148	100
Mother's educational attainment	Elementary	239	20.8
	High School	604	52.6
	College/masters/doctorate	305	26.6
	Total	1148	100
Father's educational attainment	Elementary	374	32.6
	High school	498	43.4
	College/masters/doctorate	276	24
	Total	1148	100
Family income	Less than 5,000	524	45.6
	5,000-10,000	433	37.7
	More than 10,000	191	16.6
	Total	1148	100
Number of years in the university	1 year	280	24.4
	2 years	292	25.4
	3 years	268	23.3
	4 years	283	24.7
	5 years	19	1.7
	More than 5 years	6	0.5
	Total	1148	100

(Kollmuss and Agyeman, 2002; Keizer and Schultz, 2018). The second section evaluated the students' KAP in relation to SWM. To assess the respondents' level of understanding, ten statements pertaining to SWM legislation, guiding principles, waste categorization, and health implications were introduced. Respondents rated their perceived knowledge by identifying the statements as True or False. Though the use of true or false items for knowledge assessment may introduce guessing bias, this format is widely applied in environmental KAP studies where factual comprehension is examined (Owojori *et al*., 2022). The attitude component consisted of ten statements assessing the students' disposition toward SWM. Respondents rated their attitudes

using a four-point Likert scale: *Never*, *Sometimes*, *Often*, and *Always.* For the practical aspect, ten statements were created to assess the level of respondents' involvement in SWM activities, with a particular emphasis on the principles of the 3Rs, segregation, and appropriate disposal. A four-point Likert scale was used, consisting of *Never*, *Seldom*, *Often*, and *Always.* The questionnaire underwent content validation by three experts in the fields of social science and science education. Revisions were made based on their recommendations to improve clarity, relevance, and construct alignment. Subsequently, the instrument was pilot tested on a sample of 30 university students who were not part of the actual study population. The reliability of the questionnaire's internal consistency was evaluated through Cronbach's alpha, resulting in a coefficient of 0.920, which signifies that the instrument is highly dependable for assessing KAP on SWM. Likewise, beyond internal consistency reliability, the construct validity of the instrument was examined using exploratory factor analysis (EFA). Principal component extraction with varimax rotation was applied to the attitude and practice scales. Items with factor loadings below 0.50 or cross-loadings above 0.40 were carefully reviewed. The resulting factor structure corroborated the theoretical dimensions of attitudes and practices related to SWM, consistent with prior studies. Hence, the questionnaire was deemed both valid and reliable for the purposes of this study.

Data gathering procedure

The data collection began upon the approval of the study by the University President, as endorsed by the Research, Extension, and Training (RET) Office. Following this, the researchers obtained written permission from the College Deans and College Research Coordinators of the four participating colleges—CAS, CIT, CTE, and COE. After securing the acquisition of the required approvals, a letter of consent was given to the respondents along with the survey questionnaires. The letter of consent included the purpose of the study, the procedures in their participation, the estimated duration of involvement, a declaration emphasizing that participation was voluntary, assurance of the participant's right to withdraw at any time without facing penalty, that withdrawal did not affect their academic standing, class participation and grades, and a commitment to maintaining anonymity and confidentiality. They were given sufficient time to read and understand the consent form before signing. The distribution process was carried out with the support of appointed college focal persons to guarantee systematic management and compliance with adherence to ethical research standards. They were given one week to accomplish the questionnaire although it took them 15-30 minutes to complete. Upon the completion of the period, the researchers assembled the finalized instruments for data encoding and analysis. All collected information was treated with the highest level of confidentiality and was utilized solely for the objectives of this study.

Ethical considerations

All participants were informed of the voluntary nature of their involvement in the study. Informed consent was obtained, clearly stating the purpose of the research, the procedures involved, the expected duration of participation, and the assurance of confidentiality. Respondents were informed of their right to decline or withdraw from participation at any time without penalty, and it did not affect their academic standing, class performance, and grades. To ensure anonymity and privacy, no personally identifiable information was collected. All responses were coded and analyzed in aggregate form. Data collected were stored securely and will be permanently destroyed

after five years. In accordance with institutional research guidelines, printed materials will be shredded to prevent unauthorized access and ensure total data elimination. Results of the study were shared with the university office responsible for environment and sustainability initiatives for the crafting of policy through a written report. Only the aggregate results were reported, and no individual identification was disclosed to protect the privacy and anonymity of the participants. To maintain the highest standards of research objectivity, independence, and integrity, any potential conflicts of interest were strictly avoided during this study. The researchers affirm that no financial or non-financial incentives were received that could influence the neutrality of the research process. Likewise, no personal relationships or affiliations influenced the selection of participants, data collection, analysis, or interpretation of findings. Also, to prevent potential power imbalance or undue influence, students who were currently enrolled in the researcher's classes were not included as participants during the data collection period. This protocol was implemented to guarantee that participation remained strictly voluntary, thereby eliminating any potential for perceived coercion or academic influence.

Data analysis

Data analysis was conducted using both descriptive and inferential statistics. Specifically, descriptive statistics—including frequency counts and percentages—were employed to characterize the socio-demographic profiles of the participants. Likewise, mean and Standard Deviation (SD) were utilized to describe the KAP of the students on SWM. The knowledge scores from true or false questions were categorized into adequate, moderate, and inadequate. Both attitudes and practices were gathered through a four-point Likert scale. Moreover, attitude was classified into *highly negative* (1.00-1.50); *negative* (1.51-2.50); *positive* (2.51-3.50); and *highly positive* (3.51-4.00). Furthermore, the practices were interpreted as *never* (1.00-1.50); s*eldom* (1.51-2.50); o*ften* (2.51-3.50); and a*lways* (3.51-4.00). Inferential statistics were used. Pearson's correlation coefficient (*r*) was employed to examine the relationship between students' KAP. The strength of the correlation was interpreted as follows: w*eak* (0.10-0.29); *moderate* (0.30-0.49); and *strong* (0.50-1.00). To identify significant predictors, multiple linear regression was used to model the relationship between socio-demographic variables and students' SWM practices. The model's fitness was assessed using R^2 (Coefficient of determination) and Adjusted R^2, while the F-test determined the overall significance of the model. Individual predictors were evaluated using t-values and p-values, with statistical significance set at $\alpha = 0.05$. All statistical tests were analyzed using the Statistical Package for the Social Sciences (SPSS) version 22. This study, however, did not consider relevant contextual and behavioral factors that may influence the students' KAP regarding solid waste management. Future studies should consider these underlying factors to provide a more holistic understanding of student engagement. Institutional enforcement such as monitoring and penalties among others, was not directly measured, but its influence is reflected indirectly through existing practices in the campus and considered in the interpretation of results. The availability and accessibility of waste segregation facilities were not measured as variables but are acknowledged as contextual factors influencing students' KAP. While the research instrument did not explicitly account for behavioral barriers such as inconvenience and time constraints, these elements were acknowledged as significant factors that may impede the translation of knowledge into practical application. Various

educational interventions undertaken by the university were not directly assessed in this study. The effects of curriculum-based sustainability courses, digital tools, and social media platforms were not measured and are recommended for future research. Differences in KAP between and among students from different backgrounds were partially examined using socio-demographic variables such as family income, parental education, and household size. Specific categories of solid waste were included as conceptual variables in the segregation assessment rather than being measured quantitatively.

Theoretical framework

This study was anchored on the KAP Model Framework. This framework was widely used in behavioral and social science research (Ling *et al.*, 2025). Originally designed for public health studies, it was developed to evaluate KAP particularly to examine how health education influenced health-related behaviors within populations (Li *et al*., 2020; Ling *et al.,* 2025). The KAP model was built on three core components: knowledge, attitude, and practice (Ahmad *et al*., 2020). As the primary component, knowledge provides the foundational framework for self-awareness and environmental comprehension, facilitating the analysis, evaluation, and interpretation of identity, nature, and social interactions (Ahmad *et al.,* 2020). The second component, attitude, refers to an individual's perspective and evaluation of a person, object, idea, or situation, reflecting a tendency to respond either favorably or unfavorably. It consisted of three components: cognitive (thoughts and beliefs), affective (emotions, preferences, and feelings), and behavioral (actions or intentions influenced by the cognitive and emotional responses) (Vargas-Sánchez *et al*., 2016). The third component, practice, refers to the phenomena or processes which occurs in the individual when an act is repeated, a certain kind of consciousness, the act of repeating when repetition was accompanied by gain in efficiency, or mere repetition whether accompanied by improvement (Vargas-Sánchez *et al*., 2016). It was the actionable outcome of knowledge and attitudes (Ling *et al*., 2025). Applying the KAP model supported the creation of effective environmental policies by uncovering the complex relationships between stakeholders' knowledge and actions (Ahmad *et al.,* 2020). Additionally, it provided data-driven insights that helped policymakers design improved strategies for waste management (Owojori *et al*., 2022). Although the foundation of behavioral formation is explained in the KAP model, it does not fully explain the gap between knowledge and actual behavior. For this reason, this study is further anchored on the Theory of Planned Behavior (TBP). TBP explains that behavior is directly influenced by behavioral intention—shaped by attitudes, subjective norms, and perceived behavioral control.

RESULTS AND DISCUSSION

Extent of knowledge regarding solid waste management

Table 2 presents the distribution of responses to ten knowledge statements on SWM. Respondents achieved an aggregate score of 69.08%, which signifies a moderate knowledge level according to the assessment criteria. The findings indicate that the respondents obtained a grand percentage score of 69.08%, which falls under the moderate level of knowledge category. This outcome points toward a generalized proficiency in SWM concepts, though it reveals evident limitations in the respondents' ability to apply or accurately interpret more advanced frameworks. The majority of students demonstrated adequate (high level of understanding) on key SWM concepts, including the definition of solid wastes (94.6%), composting as a method of recycling

Table 2: Extent of knowledge on solid waste management (N=1148)

Knowledge Statement	True		False		Interpretation
	F	%	F	%	
1. Solid wastes include wastes from agricultural, commercial, industrial, institutional, street sweeping, and non-hazardous industrial wastes.	1086	94.6	62	5.4	Adequate
2. All plastics can be recycled.	818	71.3	330	28.7	Inadequate
3. Composting is a method of recycling organic waste.	1028	89.5	120	10.5	Adequate
4. The "3 Rs" in waste management stands for Reduce, Reuse, and Recycle.	1056	92.0	92	8.0	Adequate
5. Plastic bottles, used papers, and plastics can be reused.	985	85.8	163	14.2	Adequate
6. Paper is non-biodegradable because it does not decompose quickly.	601	52.3	547	47.6	Inadequate
7. Waste segregation improves recycling efficiency.	971	84.6	117	15.4	Adequate
8. Plastic waste is a type of biodegradable material.	637	55.5	511	44.5	Inadequate
9. Non-biodegradable waste cannot be recycled.	692	60.3	456	39.7	Inadequate
10. "Zero waste" policies aim to eliminate waste generation entirely by recycling all materials.	962	83.8	186	16.2	Adequate
Grand Percentage Score	69.08%				Moderate

Legend: <50 Inadequate (low level of understanding); 51-75 Moderate (average level of understanding); 76-100 Adequate (high level of understanding); F: Frequency; N: Total number of respondents.

organic waste (89.5%), the "3 Rs" principle (92.0%), the reusability of plastic bottles, used papers, and plastics (85.8%), the role of waste segregation in improving recycling efficiency (84.6%), and the purpose of "zero waste" policies (83.8%). While the results indicate a generally strong grasp of fundamental SWM principles and policies, specific knowledge gaps persist. Notably, a substantial proportion of respondents held misconceptions regarding material properties; for instance, 71.3% incorrectly believed all plastics are recyclable, and over half (55.5%) identified plastic waste as biodegradable. Furthermore, confusion regarding waste processing was evident, with 60.3% erroneously stating that non-biodegradable waste cannot be recycled. These misconceptions reflect a gap between knowledge and practice, which may affect the effectiveness of waste reduction initiatives. Addressing them through targeted awareness campaigns, curriculum integration, and hands-on waste management programs can reinforce responsible consumption patterns, improve recycling efficiency, and contribute to the achievement of SDG 12 within the university context. It should be noted that the classification of "adequate" knowledge of solid waste management is based on the overall aggregate score, which reflects correct understanding of fundamental SWM concepts among most respondents. Consequently, the fallacies imply that such knowledge is fundamental and necessitates comprehension of essential concepts. This finding is consistent with the study of Liu *et al*. (2024), which identified environmental knowledge shortcomings as a major obstacle to implementing environmental education and that of Owojori *et al.* (2022) which stated that while knowledge on SWM was low, students showed readiness to participate in recycling when provided with incentives. Several Philippine studies provide evidence of moderate to average levels of awareness and understanding of SWM among university students. Usman *et al*. (2025) explicitly reported a moderate level of awareness among 100 students. These findings align with Dolipas *et al*. (2020), who observed an average level of awareness regarding biodegradable waste among university students, alongside a notable deficit in general waste classification. In contrast, Barloa *et al*. (2016) reported higher proficiency in a larger cohort of 2,528 undergraduates, where 73.4% of respondents achieved satisfactory knowledge levels and a superior overall KAP rating of 82.3%.

However, notable inconsistencies between knowledge and actual waste management practices were observed. Balaba *et al*. (2024) also documented moderate awareness levels among students enrolled in specific academic programs, such as BS criminology and BS hospitality management, suggesting that SWM awareness differs across academic disciplines and specific domains of waste management within Philippine higher education institutions.

Level of attitude on solid waste management

Table 3 presents the mean scores and corresponding interpretations of the respondents' attitudes toward SWM. The computed grand mean of 2.83 reflects an overall positive attitude among respondents. The highest mean score was observed for the item regarding confidence in waste elimination via the 3Rs (mean = 2.95, SD = 0.88), suggesting that students feel highly capable of minimizing waste through reduction, reuse, and recycling. Similarly, satisfaction with the janitors' role as partners in maintaining school cleanliness was expressed (mean = 2.88, SD = 0.96) suggesting that students recognize and value collaborative institutional efforts in maintaining campus cleanliness. Conversely, the statement concerning the utility-based recycling of PET bottles received the lowest mean score ($M = 2.74, SD = 1.00$), though it remained within the positive interpretation range. This suggests that while respondents generally have a favorable attitude toward SWM, practicing the recycling and proper disposal of PET bottles may not be as consistently observed. This lower rating may indicate limited recycling habits or a lack of emphasis on the reuse of recyclable materials within the university. Consistent with the assertions of Bernadas and Peralta (2023), this study highlights that students generally acknowledge their role in SWM; such constructive attitudes are often bolstered by institutional participation and integrated academic curricula. Taken together, these studies emphasize that while knowledge gaps exist, positive student attitudes can serve as a strong foundation for designing more effective educational and behavioral interventions in SWM. studies within the Philippine context consistently indicates that students in Catholic higher education institutions maintain positive attitudes toward SWM—a sentiment significantly correlated with their practical waste management behaviors. Similarly, attitudes toward SWM among students. Madrigal and Oracion (2018) Reyes and Madrigal (2020) found that high school students exhibited a positive attitude toward SWM, with attitude serving as a significant predictor of proper waste management practices. Supporting these findings, Barloa *et al.* (2016) documented that 71.0% of 2,528 undergraduate students attained satisfactory attitude levels, with an average attitude rating of 87.0%, further demonstrating the prevalence of positive SWM attitudes among Filipino students.

Extent of waste management practices

The results in Table 4 show that university students often engage in SWM practices, with a grand mean of 2.99, indicating often practiced. However, the classification of practices as "often practiced" does not imply full compliance. Data falling within the "often" frequency suggest a lack of behavioral uniformity. This indicates that while campus infrastructure supports SWM actions, it does not inherently guarantee the transition from situational participation to long-term behavioral internalization. Specifically, the highest-rated practice is waste segregation into recyclable and non-recyclable materials (mean = 3.12; SD = 0.83), followed closely by adherence to the clean-as-you-go (CLAYGO) rule (mean = 3.10; SD = 0.89) and participation in school clean-up drives (mean = 3.09; SD = 0.83) among the student respondents surveyed.

Table 3: Level of attitude on solid waste management (N=1148)

Attitude statement	Mean	SD	Interpretation
1. Seeing someone properly dispose of litter encourages me to value cleanliness.	2.78	1.28	Positive
2. I believe solid waste can still be useful through proper recycling and reuse.	2.82	0.28	Positive
3. I feel motivated to help address overflowing solid waste in the school.	2.82	0.94	Positive
4. I practice proper disposal and recycling of empty PET bottles because they can still be useful.	2.74	1.00	Positive
5. I encourage my friends to dispose of waste properly.	2.87	1.01	Positive
6. I appreciate when others show concern for proper waste management.	2.79	0.93	Positive
7. I take initiative in addressing solid waste seen in the corridors by disposing of it properly or reporting it.	2.83	0.99	Positive
8. I value the janitors as important partners in keeping the school clean.	2.88	0.96	Positive
9. I support and appreciate the school's waste management system.	2.84	0.89	Positive
10. I am confident that waste can be significantly reduced through the 3Rs (Reduce, Reuse, Recycle).	2.95	0.88	Positive
Grand mean	2.83		Positive

Legend: 1.00-1.50 Highly negative; 1.51-2.50 Negative; 2.51-3.50 Positive; 3.51-4.00 Highly positive

Table 4: Extent of waste management practices (N=1148)

Practices statement	Mean	SD	Interpretation
1. After eating, I throw the food residue into the kitchen waste bin and the packaging box into the corresponding bin.	3.08	0.93	Often
2. If the garbage in the trash bin is not sorted, I still insist on garbage classification.	2.82	0.89	Often
3. I segregate waste into biodegradable (e.g. papers, leaves) and non-biodegradable (e.g. plastics, cans).	3.03	0.89	Often
4. I separate wastes into recyclable (e.g. papers, plastics, bottles, cans) and non-recyclable (e.g. food wastes).	3.12	0.83	Often
5. I reduce solid waste by using Eco bags.	2.91	0.86	Often
6. I use reusable containers like plates, lunch boxes, etc.	2.98	0.84	Often
7. I reuse items such as scrap papers as memos or scratch for solving.	2.97	0.89	Often
8. I recycle items by converting old items into new products.	2.89	0.85	Often
9. I follow the clean-as-you-go or CLAYGO rule.	3.10	0.89	Often
10. I join clean up drive at school.	3.09	0.83	Often
Grand mean	2.99		Often

Legend: 1.00-1.50 Never; 1.51-2.50 Seldom; 2.51-3.50 Often; 3.51-4.00 Always

Students' pro-environmental attitudes appear to mitigate ecological impacts by driving behavioral compliance, effectively compensating for identified weaknesses in technical knowledge. The findings correspond to Molina and Catan (2021), who found that Filipino students exhibit positive SWM behaviors, especially in segregation, minimization, and proper disposal. The recurring "*Often*" interpretation across the practices suggests a developing culture of environmental responsibility, which, if further supported by school-based policies and community initiatives, can significantly advance the realization of SDGs 11 and 12. Consistent with broader academic trends in the Philippines, waste segregation emerges as the primary SWM behavior practiced by university students. Dolipas *et al*. (2018) reported that students of Benguet State University "always practice waste segregation," indicating a high level of behavioral compliance. Similarly, Paghasian (2017) found that 253 students at Mindanao State University demonstrated "good" segregation practices, reflecting generally favorable implementation of SWM at the institutional level. In a comprehensive study of 2,528 undergraduates, Barloa et al. (2016) reported a disparity between high levels of SWM knowledge (87.8%) and attitudes (87.0%) versus

actual implementation (72.5%), though waste segregation remained the most consistent behavior.

Correlation of knowledge, attitude, and practices

The Pearson correlation analysis was conducted to examine the relationships among the three core components of the KAP model: Knowledge, Attitude, and Practices (Table 5). A moderate positive correlation was found between attitude and practices ($r = 0.504$, $p < 0.01$), indicating that individuals with more favorable attitudes are more likely to engage in positive practices. This significant correlation provides empirical support for the notion that individual attitudes play a pivotal role in mediating behavioral responses. Canlas and Mendoza (2025) suggested that cultivating key concepts on SWM is necessary as it increases the likelihood of influencing their attitude. According to Pacini *et al*. (2025), didactic interventions focus on fostering knowledge and positive attitudes, which in turn facilitates student engagement in pro-environmental actions. Lastly, a very weak positive correlation was found between knowledge and practices ($r = 0.088$), indicating a negligible relationship. This finding suggests that knowledge alone does not necessarily translate into behavioral change, particularly in the absence of enabling conditions and behavioral reinforcement. The inverse relationship between knowledge and attitude suggests that heightened awareness, when decoupled from institutional support or actionable opportunities, may paradoxically diminish motivation or result in less favorable evaluations. This suggests that knowledge alone may not be a strong predictor of behavioral practices in this context. This finding may reflect reduced motivation when awareness is not supported by enabling conditions and social reinforcement. Future analysis might incorporate additional mediating variables to provide a more nuanced perspective. These include socio-demographic indicators—such as age, sex, and household income—alongside institutional factors like the availability of SWM workshops, involvement in environmental programs, and the perceived convenience of campus recycling facilities, parents' education, household size, and family income.

Influence of sociodemographic profiles on practices

The regression model in Table 6 demonstrates statistically significant predictors of SWM practices among university students, with socioeconomic and family factors emerging as primary determinants, though the overall explanatory power remains modest. The multivariate regression model achieved statistical significance ($F(10, 1137) = 9.124$, $p < .001$), identifying five significant predictors of solid waste practices. However, the model explains only a small proportion of the variance in SWM behavior (R^2=.074; Adjusted R^2= .066), meaning that about 6.66% of the behavior is accounted for by sociodemographic factors, while the remaining variation may be influenced by other determinants. Among the variables, sex ($p = .006$), year level ($p = .045$), household size ($p = .007$), father's educational attainment ($p = .004$), and family income ($p < .001$) significantly influence SWM. The data identifies household income as a critical determinant, with elevated income levels correlating to more robust waste management practices. This finding corroborates prior research emphasizing the influence of economic standing and parental educational attainment on pro-environmental habits (Seng *et al.,* 2018). Household size ($\beta = .079$, $p = .007$) and sex ($\beta = .086$, $p = .006$) also significantly predicted practices which in other research says that females have higher knowledge and attitudes on SWM than males (Cimene *et al*., 2024). However,

Table 5: Pearson correlation among attitude, practices, and knowledge (N=1148)

Variable	1. Attitude	2. Practices	3. Knowledge
1. Attitude	1.00	0.504** (p=0.000)	-0.501 (p=0.086)
2. Practices	0.504** (p=0.000)	1.00	0.008 (p=0.776)
3. Knowledge	-0.501 (p=0.86)	0.008 (p=0.776)	1.00

*p<0.05 (2-tailed); **Correlation is significant at the 0.05 level*

Table 6: Influence of socio-demographic profiles in solid waste management

Model	Unstandardized coefficients		Standardized coefficients (β)	Test Statistic (t)	Significance (Sig.)
	β (Beta)	Standard error (SE)			
(Constant)	2.345	0.180	-	13.064	0.000
Sex	0.097	0.035	0.086	2.775	0.006
Civil	0.177	0.143	0.036	1.233	0.218
Age	-0.036	0.038	-0.033	-0.949	0.343
Course	0.029	0.017	0.056	1.752	0.080
Year level	-0.059	0.029	-0.118	-2.008	0.045
Household size	0.072	0.027	0.079	2.686	0.007
Mother's educational attainment	0.013	0.027	0.016	0.481	0.631
Father's educational attainment	0.073	0.026	0.098	2.857	0.004
Family income	0.092	0.024	0.122	3.811	0.000
No. of years in the university	0.007	0.028	0.014	0.245	0.807
F (10, 1137) = 9.124, p < .000.			R^2 = 0.074;	Adjusted R^2 =0 .066	

Legend: F Overall model significance; R^2- Coefficient of determination statistic

year level showed a negative association (β = -.118, p = .045), suggesting declining engagement in higher academic years. The noted decrement in reported SWM practices among senior students may be attributable to heightened academic workloads, a diminishing sense of novelty regarding institutional mandates, or a gradual desensitization to environmental messaging; however, such conclusions remain speculative in the absence of longitudinal data. Although year level was included in the regression model, the cross-sectional data do not allow conclusions about how students' KAP evolve over time. Differences between year levels represent cohort variation rather than longitudinal change. Generally, the model's explanatory capacity was limited (R^2 = .066), indicating that 6.6% of variance in practices was explained by these demographic variables. To achieve a more comprehensive understanding of the variations in waste management practices, future research should incorporate mediating variables such as peer influence, facility accessibility, and participation in environmental programming. These elements may provide the necessary context to bridge the gap between student attitudes and actual compliance. Non-significant predictors included mother's education, age, civil status, and years at university (p>.05), suggesting that individual and institutional factors beyond demographics warrant investigation for comprehensive campus waste management interventions. Multisectoral collaboration—involving universities, local government units (LGUs), and non-governmental organizations—is essential to enhance students' KAP. By aligning institutional policies with waste management infrastructure and environmental education, stakeholders can create a more cohesive framework for sustainable behavior.

Recommended standard operation instruction

Based on the result of the study, a Standard Operation Instruction (SOI) for SWM of the NVSU is proposed for the effective implementation of

SWM. SOI is an operational guideline used in the University. This proposed SOI on SWM is drawn from the findings of the study on gaps in KAP including the role of institutional factors in shaping behavior. Integrating this element into the study underscores the transition from empirical analysis to actionable, practice-oriented recommendations within applied research for sustainable policy development and long-term institutional implementation strategies. The effectiveness of the proposed SOI was not empirically tested. The ultimate value of this construct lies in its operationalization; if properly implemented, it has the potential to significantly enhance waste management practices and should be rigorously evaluated in future adoption scenarios. Its implementation may however be constrained by limited resources, weak enforcement, and availability of infrastructure, even though it will be facilitated by strong leadership, clear policies, and active stakeholder engagement, which are critical factors in university-based waste management initiatives (Shaherani *et al.,* 2026). Its effectiveness across universities depends on the university's resource capacity, management structures, and adaptability to institutional context, reflecting the importance of environmental management behaviors and institutional sustainability frameworks in higher education (Kamolteeravit *et al.,* 2026).

CONCLUSION

This study contributes to environmental science and management research by elucidating insights into the interactions among KAP toward SWM within a higher education setting. Empirical evidence suggests that attitudes are a more potent predictor of SWM practices than knowledge alone; this is demonstrated by the moderate positive correlation identifying a significant link between student mindsets and their actual practices. This result indicates that behavioral outcomes in environmental management are partly shaped by affective and motivational factors, highlighting attitudes as a critical leverage point for improving compliance with SWM systems. In contrast, the weak relationship between knowledge and practice suggests that awareness alone may be insufficient to produce consistent behavioral change. Additionally, this negative correlation implies that current methods of delivering environmental information may be poorly framed, failing to foster the intended pro-environmental attitudes. Exposure to environmental issues without adequate opportunities for engagement, empowerment, or institutional support may contribute to reduced motivation. This finding emphasizes the critical need for integrated frameworks that bridge the gap between institutional support and individual behavior, specifically by fostering perceived efficacy and a sense of shared responsibility. The results further emphasize the importance of supportive management environments in HEIs. Effective SWM implementation appears to require not only informed individuals but also enables infrastructure and institutional coherence. The availability, accessibility, and clearly defined operation of waste segregation and collection systems are likely important in minimizing behavioral barriers and translating pro-environmental intentions into routine practices. Such ystemic conditions are instrumental in reinforcing pro-environmental behaviors across organizational environments, ensuring that individual actions align with institutional goals. Analysis of socio-demographic factors suggests that sex, year level, household size, parental education, and family income are associated with SWM practices. The data suggest that student

SWM practices are situated within a complex web of social and domestic influences, indicating that behavioral outcomes are not solely a product of individual cognitive processes. Consequently, SWM strategies may benefit from inclusive, context-sensitive approaches that consider socio-demographic variability. Campus engagement linked with families and communities may further strengthen the long-term effectiveness of institutional SWM programs. Ultimately, optimizing SWM in HEIs requires an integrated environmental framework that supports behavioral motivation through robust infrastructure and transparent governance. The findings support attitude-focused, participatory, and system-oriented interventions to narrow the knowledge–practice gap. While the study provides valuable insights, the single-campus scope may limit broader applicability. The manuscript acknowledges this limitation and potential institutional bias. Future research should incorporate longitudinal designs and evaluate institutional interventions to better inform sustainable management policies in academic environments. Comparative multi-institutional studies may further enhance the generalizability and policy relevance of the findings.

AUTHOR CONTRIBUTIONS

F. Alicante, the corresponding author, has contributed in conception and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, critical revision of the manuscript for important intellectual content, and statistical analysis of data throughout the entire research process. M. Balonquita has contributed in conception and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, and statistical analysis of data for publication preparation purposes. E. Apostol participated in critical revision of the manuscript for important intellectual content.

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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
3Rs	Reduce, reuse, recycle
B	Beta
CA	Campus administrator
CAS	College of arts and sciences
CIT	College of industrial technology
CLAYGO	Clean-as-you-go
COE	College of engineering
CTE	College of teacher education
EFA	Exploratory factor analysis
e.g.	Example
F	F-value (overall model significance)
HEIs	Higher education institutions
KAP	Knowledge, attitude, and practices
LGU	Local government unit
MRF	Material recovery facility
N	Total number of respondents
NVSU	Nueva vizcaya state university
p	P-value of significance
r	Pearson's correlation coefficient
R^2	Coefficient of determination
RA	Republic act
RET	Research, extension, and training
SD	Standard deviation
SDG	Sustainable development goal
SE	Standard error
Sig.	Significance
SOI	Standard operation instruction
SPSS	Statistical package for the social sciences
SSC	Supreme student council
SWM	Solid waste management
t	T-statistic
TBP	Theory of planned behavior

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CASE STUDY

Surface runoff modeling at the event scale, incorporating sensitivity and uncertainty analysis within a foothill watershed

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ABSTRACT

BACKGROUND AND OBJECTIVES: Foothill regions along the Himalayan belt are hydrologically complex due to rugged terrain, highly variable rainfall, and rapidly changing land cover, making them particularly prone to flash flooding. Precise estimation of runoff in ungauged basins is thus crucial for efficient management of watersheds and for mitigating floods. The study objectives were to develop a spatially distributed, uncertainty-aware framework for runoff evaluation in the ungauged Pagladiya River basin in the Himalayan foothills of Baksa District, Assam, India using the geographic information system -based soil conservation service curve number method.

METHODS: The basin was subdivided into five physiographically distinct sub-watersheds to capture spatial heterogeneity. Geospatial datasets, including land use/land cover, hydrological soil groups, slope, and rainfall records (2008–2023), were incorporated into a geographic information system environment to calculate distributed curve numbers that range from roughly 60 to 92. Event-based runoff depths were estimated using the Soil conservation service curve number model under varying antecedent moisture conditions. Sensitivity analysis was conducted to determine the primary controlling factors, and the predictive uncertainty related to the variability of curve numbers was assessed through a Monte Carlo simulation with ±5 percent perturbations to curve number values.

FINDINGS: Peak runoff depths ranged from about 40 to 160 millimeters, indicating strong event-scale variability across the basin. Runoff generation was found to be predominantly rainfall-driven, with Thiessen-weighted areal rainfall explaining over 99.88 percent of the variability in runoff (R^2 = 0.9997). Interactions between land and soil have also had a considerable impact on hydrological responses, with factors such as land use/land cover, hydrologic soil groups, and antecedent moisture conditions serving as secondary controls; specifically; antecedent moisture condition-III produced the highest discharge under saturated conditions. Runoff coefficients ranged from 59.69 percent to 79.57 percent, indicating high runoff efficiency during intense storms. Sensitivity testing confirmed rainfall, curve number, and antecedent moisture condition as primary governing parameters, while morphometric characteristics had a moderate influence, mainly on flow concentration.

CONCLUSION: The integrated geographic information system-based Soil conservation service curve number framework provides a decision-support tool for runoff estimation and flood risk assessment in ungauged Himalayan foothill basins. This strategy facilitates in watershed management and is in accordance with the requirements of other mountainous areas with limited data that encounter comparable hydrological issues.

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54	10	10

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INTRODUCTION

Estimating surface runoff in highly dynamic regions is crucial for sustainable water management, flood prevention, agriculture, and environmental conservation (Vignesh *et al.,* 2021; Roy *et al.,* 2025). Foothill regions located between mountainous areas and plains display intricate hydrological dynamics as a result of steep inclines, diverse soil types, and significantly fluctuating rainfall, which collectively lead to swift runoff production and restricted storage capacity (Bal *et al.,* 2021; Bandurin *et al.,* 2021; Barat *et al.,* 2024; Barman *et al.,* 2023a; Baruah *et al.,* 2024; Barman and Sarma, 2016). The ungauged Pagladiya River basin in Baksa District, Assam, draining from the Bhutan Himalayas, represents such a system where the absence of long-term hydrological observations restricts the application of conventional calibrated models (Bukoski *et al.,* 2021; Gupta *et al.,* 2019; Basumatary and Maji, 2023; Nsangou *et al.,* 2022; Zaremehrjardy *et al.,* 2022, Basumatary and Maji, 2026). the soil conservation service curve number (SCS-CN) approach creates an empirical relationship that connects rainfall, land use, soil characteristics, and prior moisture conditions for the purpose of estimating direct runoff (Panda *et al.,* 2025; Talukdar, 2019; Sharma *et al.,* 2021; Foda *et al.,* 2025; Biswas and Raha, 2023; Mitra and Roy, 2023; Hawkins, 1978; Sagwal *et al.,* 2024). Advances in geospatial datasets, including digital elevation models, satellite-derived land cover, and soil databases, enable spatial parameterization of this method and improve representation of watershed characteristics in data-scarce regions (Sanyal, 2023; Topno *et al.,* 2022; Tirkey *et al.,* 2016; Ahmad *et al.,* 2023; Xu and Li, 2017). Alternatively, a variety of current studies implement the method at the basin level with averaged parameters, which could potentially mask significant spatial variability in terrain, soil, and land use that controls runoff generation in complex foothill environments. Physically based hydrological models such as SWAT or HEC-HMS can represent detailed process dynamics but typically require extensive calibration, continuous discharge records, and comprehensive hydrometeorological datasets. Such data are not available for the Pagladiya basin, making the application of these models uncertain or impractical. Given these limitations, an empirical method such as SCS-CN emerges as a practical option, as long as spatial variability and parameter uncertainty are taken into account. The limitation in many previous applications therefore lies not in the model choice itself but in insufficient treatment of sub-watershed variability and uncertainty in ungauged basins. Accordingly, a clear research gap exists in event-based, spatially distributed runoff assessment that accounts for physiographic heterogeneity and quantifies uncertainty in data-limited Himalayan foothill catchments. This study addresses that gap by subdividing the Pagladiya basin into five physiographically distinct watersheds (WS1–WS5) and evaluating runoff responses using land use/land cover (LULC)- and hydrological soil group (HSG)-derived curve numbers under varying rainfall and antecedent moisture conditions. The central research question focuses on the impact of spatial variations in terrain, soil permeability, and land cover influence event-scale runoff generation in an ungauged foothill basin, extending beyond the insights provided by basin-average methodologies. The objectives of this study are to i) analyze runoff variation across sub-watersheds, ii) examine the influence of physiographic controls such as slope, soil characteristics, and land use on modeled runoff response, and iii) assess the sensitivity and uncertainty associated with curve number variability. This study seeks to offer a more detailed characterization of runoff dynamics in the Pagladiya basin by combining sub-watershed-scale analysis with sensitivity and uncertainty assessments, while also recognizing the empirical constraints of the SCS-CN

framework. These insights contribute to improved hydrological understanding and support preliminary watershed planning in data-scarce regions of Northeast India. This study was carried out in the Pagladiya River basin located in Baksa District, Assam, India, using rainfall and spatial data for the period 2008–2023.

MATERIALS AND METHODS

Location and geographical extent

The present study area is in the ungauged Pagladiya basin within the Baksa District of Assam, India. This locality is positioned on the northern bank of the Brahmaputra River and exhibits a variety of physiographic features, ranging from denudational hills to vast alluvial plains, as illustrated in Fig. 1. The study was conducted in the watersheds of the Pagladiya River basin, covering an area of about 459.34 hectares. The district shares international borders with Bhutan to the north, is bordered by Chirang district to the west, Udalguri to the east, and the districts of Nalbari, Barpeta, and Kamrup to the south. Geographically, it lies between 26°32′ and 26°40′ North latitudes and 90°56′ and 91°43′ East longitudes.

Physiography and geology

Both geomorphological and hydrological complexities shape the landscape of Baksa. The northern part of the district, adjacent to Bhutan, comprises foothill zones, characterized by steep gradients and rapid sediment transport. These Himalayan foothills form a transitional area between mountainous landscapes and flat plains, leading to a very dynamic hydrological system. The geological base mainly consists of Archaean gneisses, while the surface is layered with recent and sub-recent alluvium transported by upstream rivers from Bhutan. The continuous deposition of sediment significantly influences the alteration of fluvial patterns and water retention characteristics of the catchment (Satheeshkumar *et al.*, 2017). The basin features a mix of land uses, including agricultural fields, forested areas, and scattered rural settlements. The denudational hills possess lateritic soils and are adorned by evergreen mixed forests, while the plains are divided into older and newer alluvial zones. The northern plains, especially the narrow Bhabar zone near the Bhutan border, show coarse-textured soils with high infiltration but low water retention. South of this area lies the Terai zone, characterized by persistently saturated soils, slow-moving groundwater discharge, and frequent spring activity (Goswami and Brahma, 2019). This configuration creates both opportunities and challenges in terms of water availability and the response of surface runoff.

Hydrological challenges

Hydrologically, the region experiences intense monsoonal rainfall, causing frequent flooding during the rainy season. The ungauged watersheds of Pagladiya are susceptible to seasonal flooding, exacerbated by excessive runoff and sediment accumulation from the adjacent hills. Natural obstructions created by transported sediments like gravel, sand, and boulders block river channels, leading to flooding of low-lying areas, while also contributing to water shortages downstream (Borpujari and Bora, 2021). Another significant concern is the inadequate distribution and retention of surface water within the watersheds. Due to the hilly terrain and rocky substrata, much of the rainfall results in quick surface runoff instead of infiltration, reducing groundwater recharge and limiting water access for local communities (Birhanu *et al.*, 2022; Basumatary *et al.*, 2021). Even with significant seasonal rainfall and extensive river systems, the terrain's physical features create obstacles for sustainable water management. A key concern in the region is the lack of detailed hydrological data and monitoring systems. The absence of structured research and reliable datasets significantly hampers informed decision-making in water resources management, disaster response, and infrastructure planning. For instance, infrastructure failures like bridge collapses during

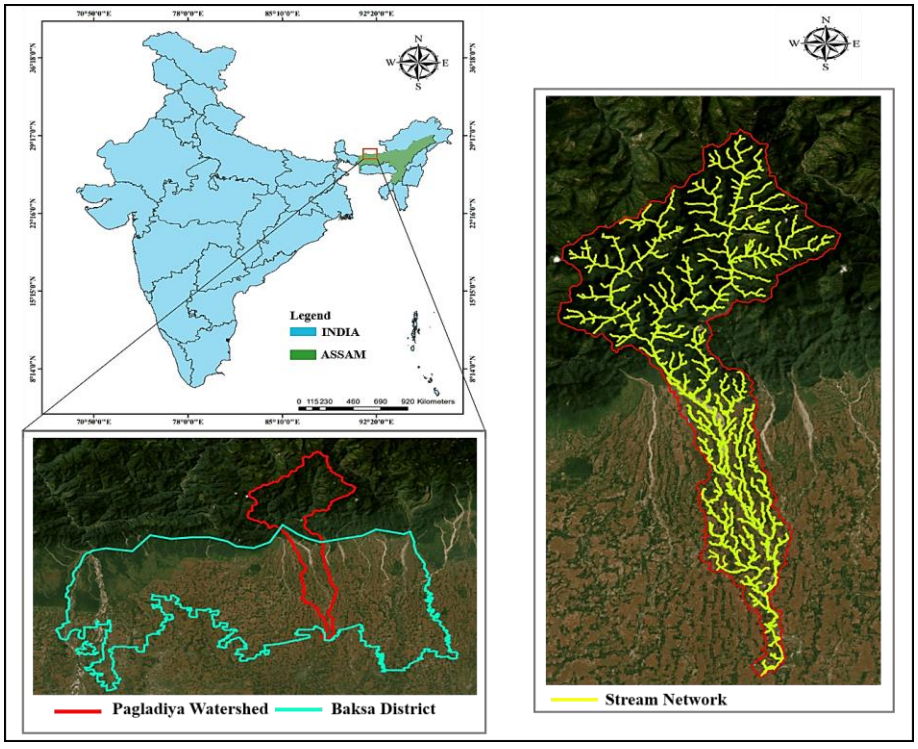

Fig. 1: Geographic location of the study area in Baksa district, Pagladiya River Basin in India

monsoon seasons are frequently associated with a lack of understanding regarding river discharge and flood dynamics (Rautela *et al.*, 2022). Given these urgent issues, the ungauged watersheds of the Pagladiya River in Baksa are a prime area for targeted hydrological study, especially in the foothill regions. The interaction between topography, sediment movement, and extreme rainfall creates unique hydrological challenges that require location-specific analysis (Rai *et al.*, 2017). In this context, the utilization of spatial tools such as geographic information system (GIS), in conjunction with hydrological models like the SCS-CN method, is essential. These methods are vital for estimating surface runoff, predicting floods, and supporting sustainable water resource planning in the ecologically and socially sensitive foothill areas of Assam. This study's methodological framework employs a systematic sequence of hydrological and spatial analyses to estimate surface runoff. It combines remote sensing, GIS, and hydrological modeling techniques tailored for foothill regions. As illustrated in Fig. 2, the procedure commences with watershed delineation, continues with data gathering and the development of thematic maps, and concludes with runoff estimation. Hydrological parameters were derived by analyzing LULC, soil texture, slope, and rainfall. For runoff estimation, CNs were assigned to each unique land LULC and HSG combination based on standard NRCS guidelines. Following Hawkins *et al.* (2008), the SCS-CN model was applied to each spatial unit within the watershed. Surface runoff (Q) was then calculated for each LULC-HSG unit using the SCS-CN equation with rainfall and specific CN values. The total basin runoff was calculated by aggregating the runoff values throughout the basin, rather than by averaging CNs. This aggregation method better captures the heterogeneity of terrain, maintaining variability in infiltration, land use, and soil properties particularly important for ungauged foothill basins like Pagladiya.

Data collection

The study focuses on the ungauged watersheds of the Pagladiya River, located in the foothill region of the eastern Himalayas, a terrain characterized by steep slopes, intense monsoonal rainfall, and a complex hydrological response system. These physiographic conditions require the utilization of comprehensive spatial datasets and hydrological models to evaluate runoff potential and water-related hazards (Subramanya, 2024). A combination of satellite-derived spatial data, meteorological records, and soil information was used for this GIS-based hydrological modeling. The primary spatial framework was established using a 30-meter resolution digital elevation model (DEM) acquired from the Bhuvan platform, which has been widely used for watershed delineation in Himalayan and sub-Himalayan basins (Tiwari *et al.*, 2022). Hydrological preprocessing and analysis, including flow direction, flow accumulation, and stream network derivation, were conducted utilizing ArcGIS. This provided the basis for accurate delineation of the Pagladiya watersheds. LULC data were sourced from the Bhuvan portal, providing spatial resolution suitable for basin-scale hydrological modeling. These classifications play a vital role in defining land surface characteristics that influence runoff, particularly in mixed-use foothill environments (Sharma *et al.*, 2018). Similar methods have been used in many SCS-CN-based runoff estimation studies in Indian watersheds (Khattab *et al.*, 2025). Rainfall data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) covering 2008-2023. The data offer daily gridded rainfall estimates at 0.25° × 0.25° resolution, beneficial in areas with limited rain gauge networks like the Himalayan foothills (Roy *et al.*, 2021). The datasets used for hydrological analysis of the Pagladiya watersheds covering spatial, meteorological, and soil parameters are listed in Table 1, including their sources, resolution, and importance for ungauged watershed modeling. The calculation of basin-specific rainfall was performed utilizing Thiessen polygon weighting in Hydro Processor, which generated an interpolated areal rainfall input for the watershed delineation. This method is frequently observed in ungauged and semi-gauged mountainous watersheds across India (Mulu *et al.*, 2025; Kumar *et al.*, 2023). All spatial data layers were aligned to the Universal Transverse Mercator (UTM) projection (Zone 46N) with world geographical system 1984 (WGS-84) datum. Remote sensing and GIS technologies facilitated efficient data extraction and integration, which are crucial for analyzing runoff in complex foothill catchments with limited data (Buragohain *et al.*, 2024).

Methods

The methodology used in this study combines geospatial techniques and hydrological modeling to estimate surface runoff in the foothill region of the Pagladiya ungauged watersheds. The process starts with collecting and preparing both spatial and non-spatial data, including DEM, LULC, soil texture, slope, and HSG, followed by watershed delineation using GIS-based tools. Rainfall data from 2008 to 2023 were sourced from the ECMWF and processed with the Thiessen polygon method to calculate areal precipitation (Subramanya, 2024). The SCS-CN approach, noted for its ease of use and applicability to ungauged catchments, was applied to calculate runoff based on CN values sourced from land use, soil, and antecedent moisture condition (AMC). This integrated GIS-based hydrological framework is especially effective for foothill catchments where limited observed data require the use of remote sensing and empirical models (Vignesh *et al.*, 2021). Its simplicity, recognition at the federal level, adaptability to data-scarce regions, and widespread acceptance in hydrological research make it particularly suitable for analyzing the runoff response of the Pagladiya watersheds. The overall methodological framework adopted in the study is illustrated in Fig. 2. conducted at the level of hydrological units, where five watersheds

Table 1: Details of datasets used for hydrological analysis in the Pagladiya River watersheds

Data Type	Source / platform	Resolution / scale	Purpose
DEM	Bhuvan geoportal	30 m	Watershed delineation, slope, and elevation mapping
LULC	Bhuvan geoportal	1:50,000	LULC classification for runoff estimation
Soil texture map	Bhuvan Geoportal	1:50,000	HSG assignment
HSG	Derived from soil map (Bhuvan)	1:50,000	CN derivation
Rainfall data	ECMWF	0.25° × 0.25° grid	Areal rainfall analysis using Thiessen Polygon method
CN map	Overlay analysis in ArcGIS	1:50,000	Runoff estimation using SCS-CN method
Projection system	UTM Zone 46N, WGS-84	–	Standardized spatial reference for all datasets
Rainfall interpolation	Hydro-processor (thiessen weighting)	Based on watershed polygons	Spatial rainfall estimation and distribution across watersheds

(WS1-WS5) were defined to enhance spatial precision in runoff estimation using the SCS-CN method. Although the SCS-CN method is well established, this study advances its application through event-based analysis, sub-watershed-scale spatial implementation, and the integration of sensitivity and uncertainty assessment in an ungauged Himalayan foothill basin.

Watershed delineation and Topographic analysis

The Pagladiya River basin, covering an area of approximately 459.34 hectares (ha), was divided into five watersheds (WS1-WS5, where WS stands for Watershed). The DEM was subjected to a series of processes such as depression filling, flow direction determination, and flow accumulation to extract stream networks and delineate watershed boundaries. The pour points were manually adjusted to ensure hydrologically correct outlets for each watershed. As shown in Figs. 3a and 3b, the basin was segmented into upstream (WS1 and WS2), midstream (WS3), and downstream (WS4 and WS5) watersheds, representing distinct physiographic settings. This subdivision of the basin allows for a more precise spatial representation of heterogeneity in LULC, hydrologic soil groups, and rainfall-runoff processes across the basin. Furthermore, the stream network was created using threshold flow accumulation and categorized into stream orders, which facilitate runoff routing and establish drainage connectivity within each unit. Such delineation is crucial for improving the accuracy of hydrological modeling based on the SCS-CN method by linking runoff contribution with physiographic controls. The details of the watershed areas are presented in Table 2.

Topography influences the spatial dynamics of surface runoff, infiltration, stream formation, and the intensity of erosion in any watershed. In foothill regions such as the Pagladiya River watersheds, the variation in topography is particularly pronounced owing to the steep gradients of the Himalayas, orographic precipitation, and the intricate relationships between hydrology and the landscape (Figs. 3c and 3d). Using a 30 meters (m) resolution DEM obtained from the Bhuvan Geoportal, slope and elevation layers were derived to analyze terrain behavior and hydrological implications. The DEM shows elevation ranges from approximately 25 m in the southern alluvial plains to over 2548 m in the northern Bhutan hills, capturing the full physiographic gradient of the river basin (Barman *et al.*, 2023b). The variations in altitude create significant gravitational forces that propel the movement of surface water, resulting in a swift concentration of flow, particularly in the foothills' transition zone (Shamsudduha and Panda, 2019). DEM-based flow direction and accumulation maps were also used for watershed delineation and stream network validation, forming the basis for slope and hydrological modeling (Table 3).

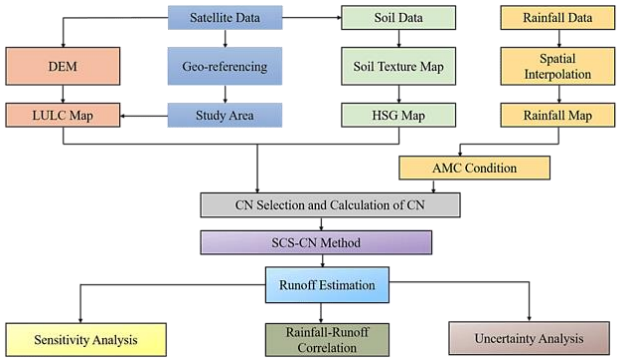

Fig. 2: Flowchart illustrating the methodological framework

Table 2: Watershed area distribution

Watershed	Area (ha)	Total area in percent (%)
WS1	126.56	27.6
WS2	98.44	21.4
WS3	98.38	21.4
WS4	82.20	17.9
WS5	53.76	11.7
Total	459.34	100

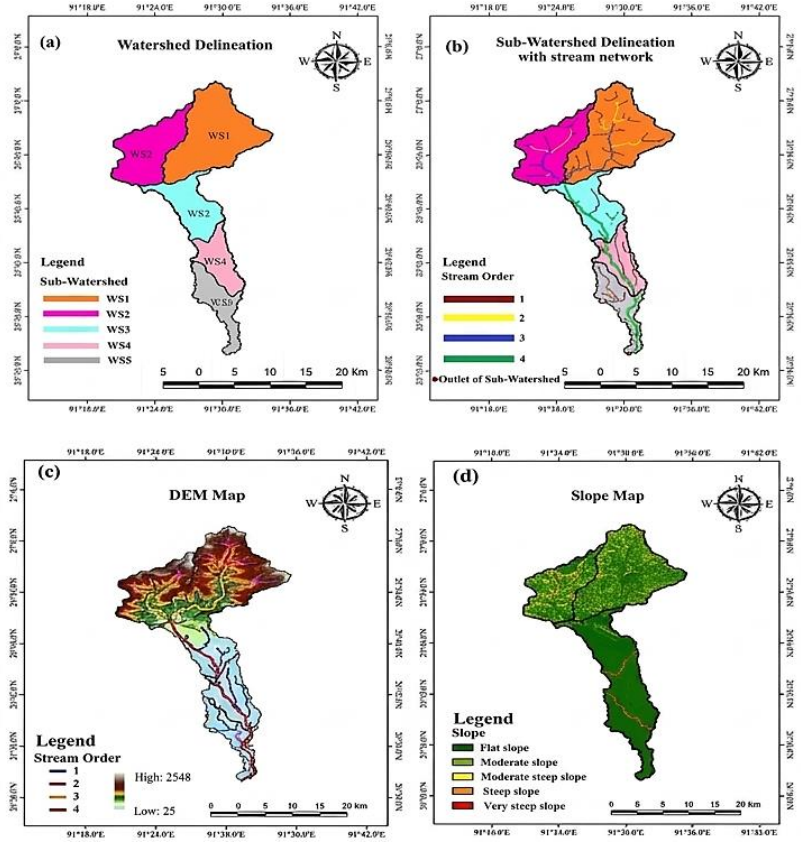

Fig. 3: Watershed characteristics showing (a) watershed and sub-watershed boundaries (WS1–WS5), (b) stream network with stream orders, (c) DEM, and (d) slope distribution of the study area

The sharp altitudinal gradient defines three major physiographic zones: i) the upper steep hill zone (Bhutan hills), which is the source of rapid runoff and sediment transport; ii) the foothill buffer zone, transitional and prone to erosion, with channel instability; and iii) the lower alluvial plains, flatter areas with flood stagnation. This gradient has a direct impact on gravitational runoff and the variability of the CN, particularly in areas where steep slopes intersect with impermeable soils and barren land. The slope derived from the DEM was classified into five hydrologically relevant classes, following Talukdar (2019) (Table 3). The alluvial plains, accounting for 34.40% of the landscape, are primarily characterized by flat slopes of 2% to 6%. This topography encourages infiltration and supports agriculture, yet it is also vulnerable to localized flood accumulation. Moderate slopes ranging from 6% to 15% account for 25.60% of the area, suggesting a balance between runoff and infiltration in transitional foothill zones. Moderately inclined slopes ranging from 15% to 25% constitute 19.80%, resulting in an increase in surface runoff and a decrease in percolation. Steep slopes, ranging from 25% to 30%, represent 12.92% of the terrain. These areas are marked by swift overland flow and an increased likelihood of rill or gully erosion. In contrast, very steep slopes, which fall between 30% and 45%, make up 7.28% of the landscape. These regions are prone to flash runoff and landslides, exhibiting a high level of sensitivity. Steep and very steep slopes are mainly found in the Bhutan foothills, where they significantly speed up surface runoff and decrease infiltration time, particularly over degraded or barren land. These zones are highly vulnerable to sheet and gully erosion (Breinl *et al.*, 2021). Conversely, the flat plains downstream function as runoff stagnation zones, contributing to temporary waterlogging during peak monsoon discharge. Watershed WS1, located at the foothill interface, it primarily has steep (25-30%) and very steep (30-45%) slopes, making it a key zone for runoff contribution. High-risk erosion due to rapid overland flow is particularly prevalent in regions where degraded forest patches adjoin barren areas. Watershed WS2: Like WS1, WS2 also features steep and moderately steep slopes, but with slightly more moderate slopes (6-15%) that allow partial infiltration. Still, erosion remains high due to the hill-foot transition. Watershed WS3: Transitional in nature, WS3 combines moderate (6-15%) and moderately steep (15-25%) slopes, leading to balanced runoff and infiltration. This zone provides both swift surface water movement from higher grounds and prolonged flow from farming areas. Watershed WS4: Located further downstream, WS4 has flat slopes (2-6%) that encourage infiltration and support agricultural activities but can also cause water stagnation during heavy monsoon rains. Localized flooding is common here. Watershed WS5: Situated entirely on alluvial plains, WS5 mostly has flat slopes (2-6%) with some moderate slope zones. It serves as a flood retention and stagnation zone, gathering runoff from upstream watersheds and exhibiting hydrological sensitivity during high monsoon discharge. The topographic diversity among the five watersheds highlights how slope influences runoff generation, erosion risk, and groundwater recharge. It also provides crucial data for CN zoning and runoff potential mapping using the SCS-CN method.

LULC, Soil texture and HSG analysis

The LULC classification plays a vital role in hydrological modeling, especially in physiographically complex regions like the Himalayan foothills overall. In the Pagladiya River basin, located in Assam's Baksa District, rapid land-use changes and altitudinal variability significantly affect surface runoff (Basumatary and Maji, 2023). Consequently, LULC mapping is crucial for assessing runoff and simulating hydrological responses within the SCS-CN framework (Subramanya, 2024). Satellite data for LULC classification were obtained from Bhuvan, used to distinguish built-up areas, forests, barren land, vegetation, and water bodies typical of the

Table 3: Slope classification and hydrological significance in the Pagladiya watersheds (Talukdar, 2019)

Slope Class	Range (%)	Area coverage (%)	Hydrological Significance
Flat	2 – 6	34.40	High infiltration capacity; suitable for agriculture but prone to flood pooling
Moderate	6 – 15	25.60	Balanced runoff-infiltration conditions; transitional slopes
Moderately Steep	15 – 25	19.80	Increased surface runoff and reduced percolation
Steep	25 – 30	12.92	Rapid overland flow with high risk of rill and gully erosion
Very Steep	30 – 45	7.28	Flash runoff conditions; landslide-prone and hydrologically sensitive zones

foothills. The imagery was projected in UTM Zone 46N (WGS 84), and classification was conducted using the Maximum Likelihood Algorithm (MLA), with signature files created from representative training areas selected through overlays and visual inspection (Saha *et al.*, 2022; Negi *et al.*, 2019). The resulting LULC map (Fig. 4) shows that forests are the dominant category (247.12 ha), followed by vegetation (111.38 ha), barren land (48.90 ha), water bodies (35.65 ha), and built-up areas (16.29 ha), totalling 459.34 ha. Furthermore, the distribution of LULC at the watershed level illustrates the diversity in land use and the impact of physiographic factors across the five watersheds. Upstream units (WS1 and WS2) are mainly dominated by forest cover with minor barren and waterbody fractions, while WS3 has a mixed composition of forest, vegetation, and small built-up patches. Downstream watersheds (WS4 and WS5) experience a greater impact from human activities, marked by increased percentages of vegetation, barren land, and developed regions. Such variations in LULC directly affect CN assignment and hydrological responses throughout the basin. The watershed-wise LULC statistics are summarized in (Table 4). Soil texture and HSG classification are essential parameters in hydrologic modeling, especially within the SCS-CN framework, as they directly influence infiltration, percolation, and surface runoff (Fig. 4). The classification of soil texture data was conducted according to USDA soil texture standards, resulting in four primary categories: sandy clay, clay loam, sandy loam, and loam. Spatial analysis in ArcGIS showed that sandy clay (HSG D) is the most prevalent in the basin, covering 202.98 ha (≈44.2%), mainly in WS1 and WS2, while clay loam (HSG C) covers 92.13 ha, mainly in WS3 and parts of the upper watersheds. The coarser sandy loam (HSG A) covers 69.96 ha, mainly in WS3 and WS4, while loam (HSG B) spans 94.27 ha, primarily in WS4 and WS5. From a hydrological perspective, the dense composition of sandy clay and clay loam soils yields a very low to low infiltration capacity, which consequently causes significant surface runoff. In contrast, loam and sandy loam soils have moderate to high infiltration potential, which reduces runoff. According to the USDA-NRCS classification guidelines, soil textures were categorized into their respective HSGs: Sandy loam → Group A (High infiltration); Loam → Group B (Moderate infiltration); Clay loam → Group C (Low infiltration); Sandy clay → Group D (Very low infiltration). The distribution across watersheds reveals spatial variation in infiltration capacity: WS1 and WS2 are predominantly covered with sandy clay (113.03 ha and 89.95 ha, respectively), with small patches of clay loam, resulting in high runoff zones. Conversely, WS3 exhibits a diverse soil composition, consisting of 70.11 ha of clay loam and 28.27 ha of sandy loam, which leads to a transitional hydrological response. WS4 has an even split between sandy loam (40.50 ha) and loam (41.70 ha), resulting in moderate infiltration. WS5, located downstream, primarily comprises loam (52.57 ha) along with a minor proportion of sandy loam, facilitating improved infiltration. Table 5 outlines the distribution of HSGs across the watersheds. This classification directly influences the CN assignment, guaranteeing that soil characteristics pertinent to hydrology are incorporated into runoff computations. This approach is consistent with Hawkins *et al.* (2008), who emphasized that runoff should be calculated for each unique LULC-HSG combination rather than relying on a single weighted CN, thereby improving physical accuracy in diverse physiographic regions like the Himalayan foothills.

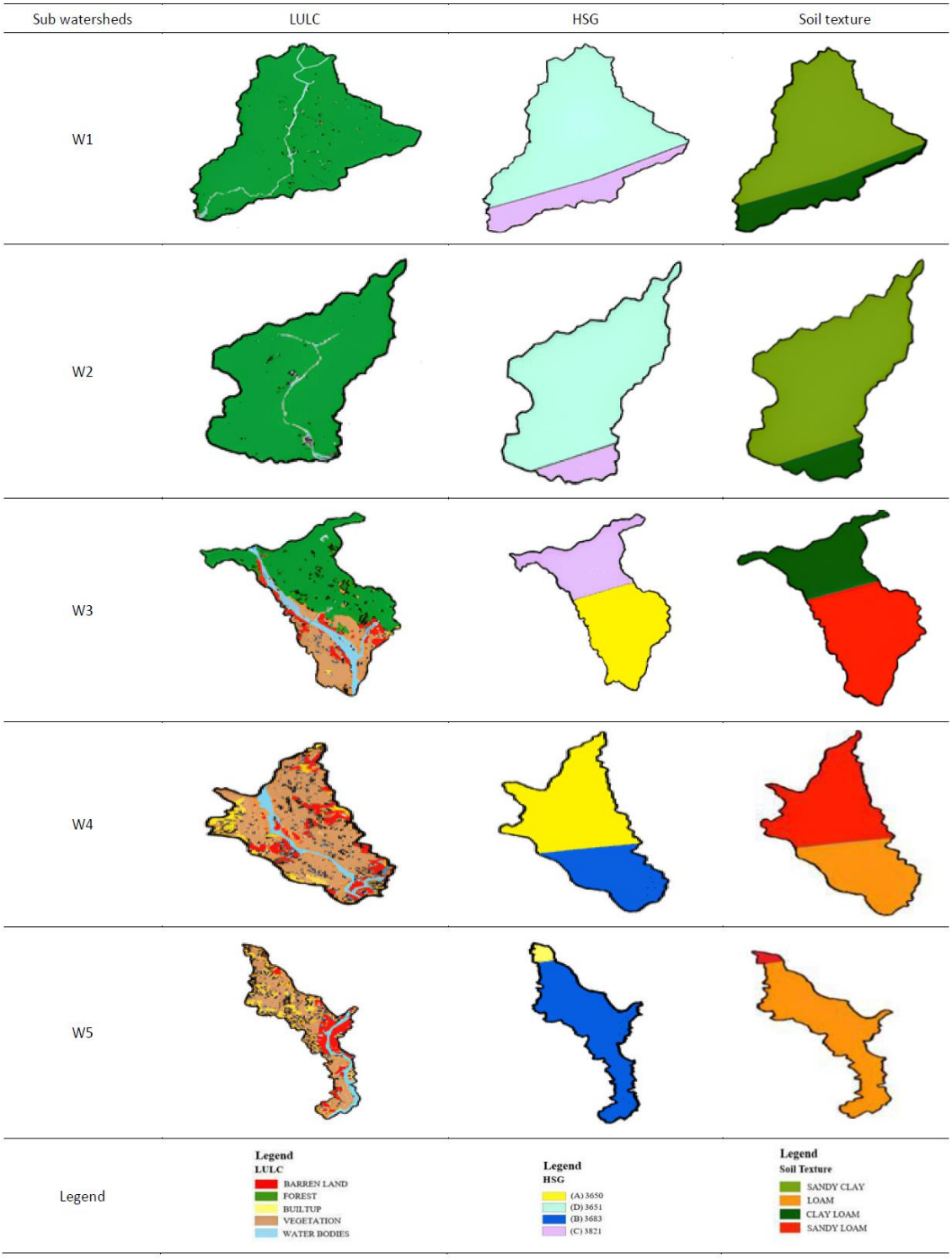

Fig. 4: Spatial distribution of LULC, HSG, and soil texture of sub-watersheds (W1-W5) of the study area

Table 4: Watershed-wise LULC distribution (area in ha)

Watershed	Forest	Vegetation	Built-up	Barren Land	Water Bodies	Total
WS1	104.44	–	–	11.39	10.73	126.56
WS2	84.67	–	–	7.73	6.04	98.44
WS3	58.01	26.07	1.80	6.50	6.00	98.38
WS4	–	50.91	9.58	14.78	6.93	82.20
WS5	–	34.40	4.91	8.50	5.95	53.76
Total	247.12	111.38	16.29	48.90	35.65	459.34

Table 5: Distribution of hydrologic soil groups (HSG) with corresponding soil textures (area in ha)

Watershed	HSG A (Sandy loam)	HSG B (Loam)	HSG C (Clay loam)	HSG D (Sandy clay)	Total (ha)
WS1	-	-	13.53	113.03	126.56
WS2	-	-	8.49	89.95	98.44
WS3	28.27	-	70.11	-	98.38
WS4	40.50	41.70	-	-	82.20
WS5	1.19	52.57	-	-	53.76
Total	69.96	94.27	92.13	202.98	459.34

Accuracy assessment of LULC classification

An evaluation of the accuracy of the LULC classification was conducted utilizing stratified random validation samples derived from high-resolution Google Earth imagery corresponding to the study period. A total of 150 reference points were distributed across the major land cover classes to evaluate classification performance. The confusion matrix analysis Table 6 yielded an overall classification accuracy of 87.6% and a kappa coefficient of 0.84, indicating strong agreement between the classified map and the reference data. These findings validate that the LULC map is adequately dependable for hydrological modeling at the watershed scale.

Rainfall analysis

Rainfall is the most crucial input variable in hydrological modeling and estimating watershed-scale runoff (Barat *et al.*, 2024). In the context of hydrological modeling for small to medium-sized watersheds, particularly in foothill areas such as the Pagladiya ungauged basin, it is crucial to choose appropriate rainfall data to ensure precise runoff estimation. Due to the limitations of the SCS-CN method in modeling long-term or annual precipitation, this study followed the guidelines proposed by Hawkins *et al.* (2008) to use storm event-based rainfall instead of yearly totals. The Pagladiya River basin was divided into five Thiessen zones, each associated with a unique rainfall grid from ECMWF. The use of maximum daily rainfall for each year aimed to illustrate the primary storm events linked to peak runoff generation; nevertheless, this method may highlight extreme conditions and should be interpreted with caution, as it might not encompass the entire range of hydrological responses. The weights ranged from 0.09 (southern plains) to 0.32 (northern Bhutan hill zone) (Fig. 5). Consequently, the highest single-day rainfall events from each year between 2008 and 2023 were identified. The spatial distribution of rainfall was analyzed using Thiessen polygon interpolation within the Hydro Processor tool to assign rainfall weights across the five watersheds. This ensured that each selected event represented relevant precipitation inputs for ungauged mountainous terrains. Although the rainfall data have a relatively coarse spatial resolution compared to the small watershed size, they were employed because there were no local gauge observations available. The issue of spatial variability was partially mitigated through Thiessen polygon weighting; however, this remains a limitation of the study. The rainfall events were chosen based on their temporal dominance and spatial relevance.

Table 6: Confusion Matrix and Accuracy Assessment of LULC Classification.

Classified \ reference	Forest	Vegetation	Built-up	Barren land	Water Bodies	Row total	User's accuracy (%)
Forest	44	2	0	1	0	47	93.6
Vegetation	3	32	1	2	0	38	84.2
Built-up	0	1	18	1	0	20	90.0
Barren Land	1	2	1	23	1	28	82.1
Water bodies	0	0	0	1	16	17	94.1
Column total	48	37	20	28	17	150	—

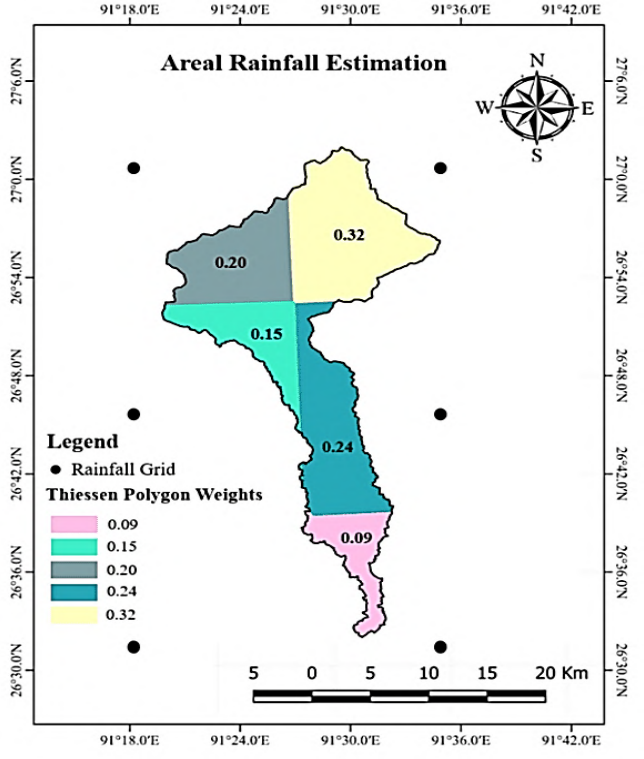

Fig. 5: Areal rainfall estimation for the Pagladiya River basin.

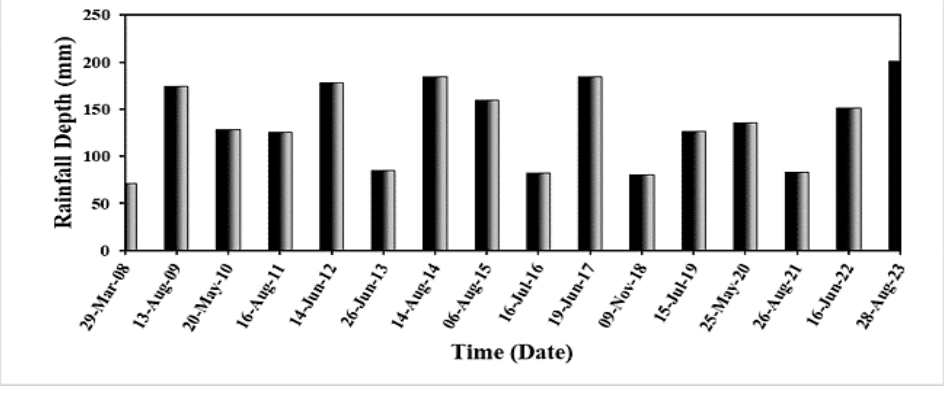

Fig. 6: Peak rainfall events (2008-2023) for the Pagladiya River basin

Although Thiessen polygons are conventionally utilized for point gauge data, they were employed in this instance to assign weight to rainfall contributions from multiple grid cells intersecting the watershed, aiming to estimate basin-average precipitation; nevertheless, this method may lead to approximation errors and should be interpreted with caution. They represent the maximum single-event peak rainfall for 2008 to 2023 (Fig. 6). This approach aligns with the intended design of the SCS-CN method, which is most effective when applied to individual storm events over small watersheds. The regression analysis was conducted between Thiessen-weighted event rainfall and SCS-CN estimated runoff, where runoff is directly calculated from rainfall and watershed parameters based on curve numbers, contributing to the strong correlation observed. The study used gridded rainfall data from the ECMWF, with a spatial resolution of 0.25° × 0.25° and daily temporal resolution, covering 2008 to 2023. This ensured consistency and coverage in a data-scarce region of the Himalayas.

Runoff calculation workflow

The estimation of surface runoff in the Pagladiya watersheds was conducted using the Soil SCS-CN method. This model relates rainfall to runoff potential by incorporating physiographic parameters such as LULC, HSG, and AMCs. The SCS-CN method is advantageous in ungauged and complex terrains, like the Bhutan foothill zones, where limited observational data hinder direct measurement approaches (Subramanya, 2024). The approach is based on the water balance equation and presumes a proportional correlation between actual and potential retention. The main equation employed to calculate direct surface runoff is represented by Eq. 1 (Chow, 1988):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad for\ P > I_a \qquad (1)$$

where: I_a= 0.3S for Indian Condition (Subramanya, 2024).

Potential maximum retention (S) is calculated, using Eq. 2 (Subramanya, 2024):

$$S = \frac{25400}{CN} - 254 \qquad (2)$$

where: Q = estimated runoff in millimeter (mm); P = rainfall (mm); I_a = initial abstraction (mm); S = potential maximum retention after runoff begins (mm); and CN = curve Number (dimensionless) based on LULC and soil properties.

AMC analysis

The surface runoff from the Pagladiya River watersheds was estimated using the Soil Conservation Service's AMC method, which indicates the relative wetness of the soil in a watershed before a rainfall event and significantly influences the amount of direct runoff generated. The soil conservation service classifies AMC into three distinct classifications: AMC-I represents dry conditions where the soil moisture is low but not at a wilting point; AMC-II reflects average soil moisture conditions; and AMC-III signifies wet conditions, usually due to substantial rainfall in the previous five days. The classification depends on the season: for the dormant season, AMC-I corresponds to less than 13 mm of rain, AMC-II to 13-28 mm, and AMC-III to more than 28 mm; for the growing season, AMC-I is defined as less than 36 mm, AMC-II as 36-53 mm, and AMC-III as over 53 mm of five-day antecedent rainfall (Subramanya, 2024). A total area of 459.34 ha was analyzed, and the CNII values were assigned based on the standard SCS tables. The values for AMC-II, AMC-I, and AMC-III conditions were calculated, using Eqs. 3 and 4 (Subramanya, 2024):

$$CN_I = \frac{CN_{II}}{2.281 - (0.0128 * CN_{II})} \qquad (3)$$

$$CN_{III} = \frac{CN_{II}}{0.427 + (0.000573 * CN_{II})} \qquad (4)$$

RESULTS AND DISCUSSION

The hydrological behavior of the Pagladiya River watersheds was evaluated using the SCS-CN method, which integrates terrain characteristics, land use, soil properties, and rainfall within a spatial runoff estimation framework. Considering the physiographic intricacies of the Bhutan Himalayan foothill region, the analysis integrated various geospatial datasets along with event-based rainfall records spanning from 2008 to 2023. CN values derived from LULC and HSG overlays were coupled with gridded ECMWF rainfall data, spatially weighted using the Thiessen polygon method (Negi *et al.*, 2019; Verma *et al.*, 2021). This methodology enables runoff estimation in basins that do not have adequate data; nevertheless, it remains vulnerable to the quality of the input data and the assumptions made by the model. To capture spatial heterogeneity, the basin was subdivided into five watersheds (WS1-WS5), allowing comparison of runoff responses under differing physiographic and land-soil conditions. Variations among sub-watersheds reflect differences in slope, infiltration capacity, drainage characteristics, and antecedent moisture rather than rainfall alone. In foothill environments, steep terrain accelerates overland flow and reduces infiltration time, whereas downstream low-gradient zones may accumulate runoff from upstream areas, increasing flow concentration. This behavior aligns with findings from other Himalayan watersheds, which are noted for their swift hydrological responses and restricted storage capacities (Sagwal *et al.*, 2024; Sharma *et al.*, 2021). However, the results should be interpreted cautiously because the SCS-CN method represents a simplified event-based approach that does not explicitly simulate subsurface flow processes, channel routing, or temporal soil moisture dynamics. Consequently, the reported runoff patterns primarily reflect modeled potential rather than fully observed hydrological behavior. Consequently, this section provides both quantitative runoff estimates and interpretive insights into spatial variability while acknowledging methodological limitations that are characteristic of ungauged foothill basins.

Composite CN

The composite CN are derived from combining LULC and HSG, which are essential inputs for runoff estimation using the SCS-CN method. The CN is determined using standard tables that consider LULC types (e.g., forest, agriculture, built-up) and the z (A, B, C, D). To assess direct runoff across various hydrological conditions, the research employed the SCS-CN method by categorizing LULC types along with their corresponding HSGs. Each land cover type (such as forest, vegetation, built-up areas, water bodies, and barren land) was further divided into four HSG categories (A, B, C, D), indicating soil permeability and runoff potential. Fig. 7 illustrates a composite map depicting the spatial distribution. This classification helped assign CN for estimating runoff using the SCS-CN method. To account for spatial differences in hydrologic behavior, the Pagladiya River basin was divided into five watersheds (WS1 to WS5). CNs were computed individually for each watershed by utilizing the intersected LULC and HSG data. Runoff (Q) was calculated using rainfall data from each hydrological event from 2008 to 2023, enabling event-specific runoff estimation for each watershed. The results were then averaged to find a representative runoff coefficient for each unit. This technique yielded a more comprehensive insight into spatial runoff patterns and enhanced the model's accuracy. The CN is a dimensionless parameter that ranges from 20 to 100. Lower values indicate high infiltration, such as in forested sandy soils, while higher values represent low infiltration, like in urban clayey areas. The CN analysis plays a vital role in the creation of spatially distributed CN maps, facilitating the effective simulation of runoff generation by watershed-scale models. By overlaying LULC and HSG layers, each distinct polygon is assigned a specific CN based on empirical SCS tables.

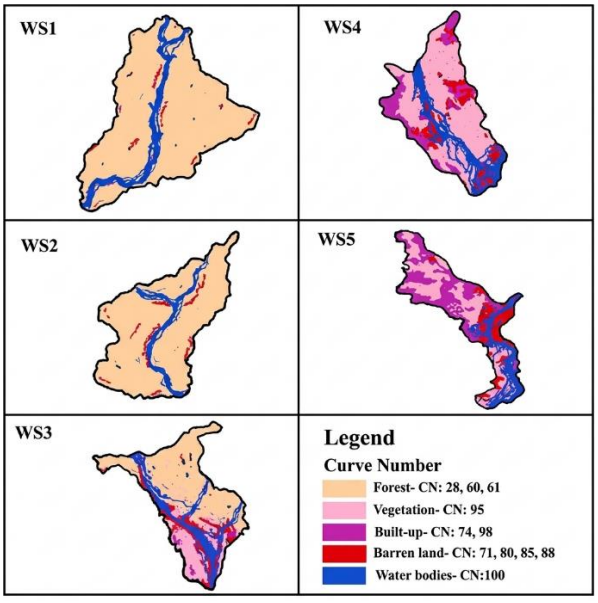

Fig. 7: CN map of the watersheds of the Pagladiya River Basin

This CN mapping supports distributed runoff simulation, illustrating spatial runoff potential based on integrated land use and soil hydrologic group data, as shown in (Fig. 7). Lower CN values correspond to high-infiltration forested uplands, whereas higher values are concentrated in the impermeable foothill plains. This facilitates SCS-CN based runoff estimation in foothill hydrology, allowing targeted watershed interventions, especially in critical runoff-producing zones. Additionally, the CN spatial framework plays a vital role in comprehending the effects of land management, soil degradation, and urban expansion on foothill runoff, especially during periods of heavy monsoonal rainfall.

Runoff of the Pagladiya River Basin

For each event, rainfall depth was processed using the SCS-CN method, considering the AMC determined by the 5-day cumulative rainfall before the event. The AMC classification (I, II, III) was established following standard thresholds (per NRCS guidelines) to represent dry, average, and wet antecedent conditions, respectively. These factors were essential in modifying CN for accurate runoff forecasting across various soil moisture conditions. The average modeled runoff Q (Avg.) was calculated in mm based on watershed area and event duration. The simulated discharge depth offers insights into the watershed's hydrological response during each year's dominant rainfall event. The runoff distribution across the five watersheds (WS1-WS5) demonstrates both temporal and spatial variability over the 16-year period (2008-2023), as shown in Table 7. Throughout all years, WS4 and WS5 consistently produce the highest runoff depths, exceeding 110 mm in wet years (for instance, 2009, 2012, 2014, 2017, 2023), which can be attributed to their larger contributing areas and prevalence of low-infiltration soils (HSG A and B transition zones). WS1 and WS2 generate relatively lower runoff values, typically between 25 and 115 mm, reflecting smaller contributing areas and less rainfall concentration. WS3 demonstrates intermediate runoff responses, similar to WS2, but exhibits a slight increase during years of extreme rainfall. From a temporal perspective, the maximum runoff was registered in 2023, with a measurement of 190.59 mm in WS5, while the minimum was documented in 2018 at 35.16 mm in WS1. This demonstrates the inter-annual variability in both rainfall intensity

Table 7: Runoff depth for each watershed

Year	Runoff depth (mm)				
	WS1	WS2	WS3	WS4	WS5
2008	28.37	26.89	34.45	60.86	62.32
2009	115.96	113.86	117.45	162.60	164.60
2010	74.31	72.40	79.90	116.60	118.84
2011	71.76	69.86	75.49	113.70	115.52
2012	119.04	116.93	120.39	165.93	167.93
2013	38.54	36.92	44.10	74.12	75.70
2014	124.88	122.74	125.96	172.21	174.23
2015	102.31	100.26	104.45	147.76	149.71
2016	36.77	35.17	42.43	71.87	73.44
2017	124.92	122.78	126.00	172.25	174.27
2018	35.16	33.58	40.90	69.81	71.36
2019	72.84	70.94	76.51	114.93	116.76
2020	81.30	79.35	84.51	124.49	126.36
2021	37.07	35.47	42.71	72.25	73.83
2022	94.68	92.67	97.21	139.38	141.31
2023	140.15	137.97	140.57	188.53	190.59

and preceding soil moisture. Overall, the analysis suggests that downstream watersheds (WS4 and WS5) are more prone to increased flood responses, whereas upstream watersheds (WS1-WS2) demonstrate relatively lower runoff contributions. Table 8 presents event-wise average hydrological estimates for the Pagladiya River basin from 2008 to 2023, focusing on peak rainfall events derived through Thiessen polygon-weighted interpolation of ECMWF data. The analysis of rainfall and runoff from 2008 to 2023 reveals significant fluctuations in both the intensity of rainfall and the response of runoff. Peak rainfall in the Pagladiya River basin ranged from 71.33 mm (2008) to 200.54 mm (2023), with corresponding average runoff depths between 42.58 mm and 159.56 mm. Most events occurred under AMC III (saturated soil condition), resulting in consistently high runoff coefficients, generally above 70%, which indicates limited infiltration and a strong flood potential. Significantly, the years 2009 and 2016 diverged from this pattern, characterized by AMC I and AMC II conditions, respectively, during which the preceding soil moisture levels were comparatively low. Notwithstanding this, the runoff coefficients continued to be moderate to high (62-77%), indicating that rainfall intensity is the primary factor influencing runoff in the basin. The years 2012, 2014, 2017, and 2023 experienced extreme events characterized by both high rainfall and high AMC values, leading to the most significant runoff coefficients (>77%), which reflects a considerable flood risk under such conditions. Overall, the dataset confirms that the basin is highly responsive to rainfall, with an average runoff coefficient of about 70%. This phenomenon arises from the common occurrence of low-infiltration soils (HSG C and D) and the predominance of saturated AMC III conditions during the monsoon-growing season. The correlation between peak rainfall events (Thiessen-weighted) and the modelled average runoff from 2008 to 2023 was evaluated using linear regression. As illustrated in Fig. 8, a robust linear correlation was identified, with a coefficient of determination $R^2 = 0.9997$, indicating that nearly 99% of the variability in runoff can be attributed solely to the magnitude of rainfall. The near-perfect rainfall-runoff correlation arises from the deterministic structure of the SCS-CN method, in which runoff is computed directly from rainfall and watershed parameters rather than independent discharge observations. This consistent rainfall-runoff response is typical of the Pagladiya River ungauged basin, which is affected by steep topography, low infiltration capacity, and high CN zones common to the Himalayan foothill region.

Table 8: Final average surface modelled rainfall runoff of the Pagladiya River basin

Year	Peak rainfall (mm)	5-Day AMC (mm)	AMC	Season	Runoff (Q, mm)	Runoff coefficient (%)
2008	71.33	64.47	AMC III	Growing	42.58	59.69
2009	174.46	30.07	AMC I	Growing	134.89	77.32
2010	128.08	65.02	AMC III	Growing	92.41	72.15
2011	125.14	70.00	AMC III	Growing	89.27	71.34
2012	177.81	126.46	AMC III	Growing	138.04	77.64
2013	84.93	101.47	AMC III	Growing	53.88	63.44
2014	184.13	113.55	AMC III	Growing	144.00	78.21
2015	159.51	204.10	AMC III	Growing	120.90	75.79
2016	82.63	38.52	AMC II	Growing	51.94	62.85
2017	184.17	151.92	AMC III	Growing	144.04	78.21
2018	80.52	74.25	AMC III	Growing	50.16	62.30
2019	126.38	379.46	AMC III	Growing	90.40	71.53
2020	136.04	255.87	AMC III	Growing	99.20	72.92
2021	83.02	101.46	AMC III	Growing	52.27	62.96
2022	151.07	385.78	AMC III	Growing	113.05	74.83
2023	200.54	191.87	AMC III	Growing	159.56	79.57

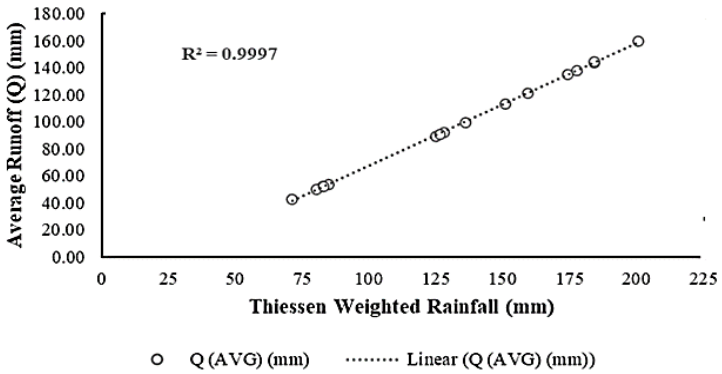

Fig. 8: Linear regression between Thiessen-weighted average rainfall and SCS-CN estimated average runoff (Q)

The predominance of AMC III events throughout the study period highlights how high antecedent wetness increases surface runoff. Such saturated conditions, along with soils that have low permeability, reduce infiltration, leading to increased peak flows, heightened flood risks, and restricted potential for groundwater recharge. Such a near-perfect correlation reflects the deterministic structure of the SCS-CN model and does not fully represent the complex hydrological processes such as infiltration variability, soil moisture dynamics, land use effects, and storage mechanisms that influence runoff in foothill basins. Elevated runoff coefficients (>70% in most years) further demonstrate the watershed's diminished capacity for subsurface storage. Overall, the findings support the use of event-based hydrological modelling with the SCS-CN method under spatially integrated rainfall and watershed conditions. From a management standpoint, the outcomes underscore the basin's susceptibility to severe rainfall occurrences and stress the significance of planning at the watershed scale for grasping flood risks.

Hydrological sensitivity and uncertainty analysis of runoff response

The analysis indicates that runoff in the Pagladiya River basin is primarily controlled by rainfall magnitude, the spatial distribution of CN values derived from LULC and HSG, and AMCs. The relative influence of these parameters on runoff generation is summarised in Table 9. Morphometric characteristics hold a somewhat

Table 9: Influence Level of Key Parameters on Runoff Generation in the Pagladiya River Basin

Parameter category	Parameter	Role in SCS-CN / Hydrological process	Influence level	Justification in the present Study
Rainfall characteristics	Peak event rainfall	Primary driver of direct runoff	High	Very strong rainfall–runoff correlation (R^2 = 0.9997); explains >99.88% variability
	Thiessen-weighted Rainfall	Spatial rainfall distribution control	High	Improved spatial representation across WS1–WS5
	Rainfall intensity	Controls infiltration-excess runoff	High	High-intensity storms increased runoff coefficients (up to 79.57%)
Catchment surface characteristics	LULC	Determines CN	High	Built-up/agricultural areas increased CN (60–92 range)
	HSG	Governs infiltration capacity	High	HSG-C/D areas showed higher runoff response
	AMC	Soil saturation condition	High	AMC-III generated highest discharge under wet conditions
	Slope	Influences runoff velocity and concentration time	Moderate–High	Steep foothill slopes enhanced rapid runoff response
Morphometric parameters	Drainage density	Flow concentration efficiency	Moderate	Higher density areas responded faster to rainfall
	Basin shape and relief	Affects peak timing	Moderate	Elongated basin reduced peak synchronization except WS5
	Stream order	Flow accumulation control	Low–Moderate	Secondary control compared to CN and rainfall
Model-derived parameters	CN	Composite runoff potential index	High (Dominant)	Core controlling parameter integrating LULC + HSG
	Runoff coefficient	Output response indicator	High (Response Parameter)	Ranged 59.69–79.57%, highest in WS5
Sub-basin variability	WS5 physiography	Flood-prone zone identification	High	Highest runoff depth and vulnerability
	Transitional zones (WS3–WS4)	Moderate flood susceptibility	Moderate–High	Intermediate CN and soil saturation behavior

subordinate position; nonetheless, they often enhance runoff response during intense storm events.

Sensitivity analysis

The weighted radar (spider) diagram presents the relative influence of hydrological, land surface, and morphometric factors on surface runoff within the watershed under the GIS–SCS–CN framework. The degrees of influence were allocated based on process dominance, model sensitivity, and observed hydrological response. Fig. 9a indicates that peak rainfall, areal rainfall estimated using the Thiessen polygon method, and the CN exert the strongest control on runoff generation. This observation strengthens the comprehension that the extent and geographical distribution of rainfall are the primary factors influencing direct runoff. Because the SCS–CN approach is fundamentally event-based, the estimated runoff depth is particularly sensitive to precipitation intensity as well as to CN values representing catchment characteristics. The second tier of influence comprises LULC, hydrologic soil group (HSG), and AMC, all of which regulate infiltration capacity and overall runoff potential. Modifications in LULC, including the transformation of forested regions to agricultural land or urbanized surfaces, can greatly influence CN values and, therefore, runoff yield. In addition, soil texture and prior moisture conditions affect initial abstraction and the portion of rainfall that becomes effective runoff. Morphometric characteristics, including slope, drainage density, and basin relief, exhibit a moderate level of influence. These factors primarily govern runoff concentration time, flow velocity, and peak discharge rather than the total runoff volume.

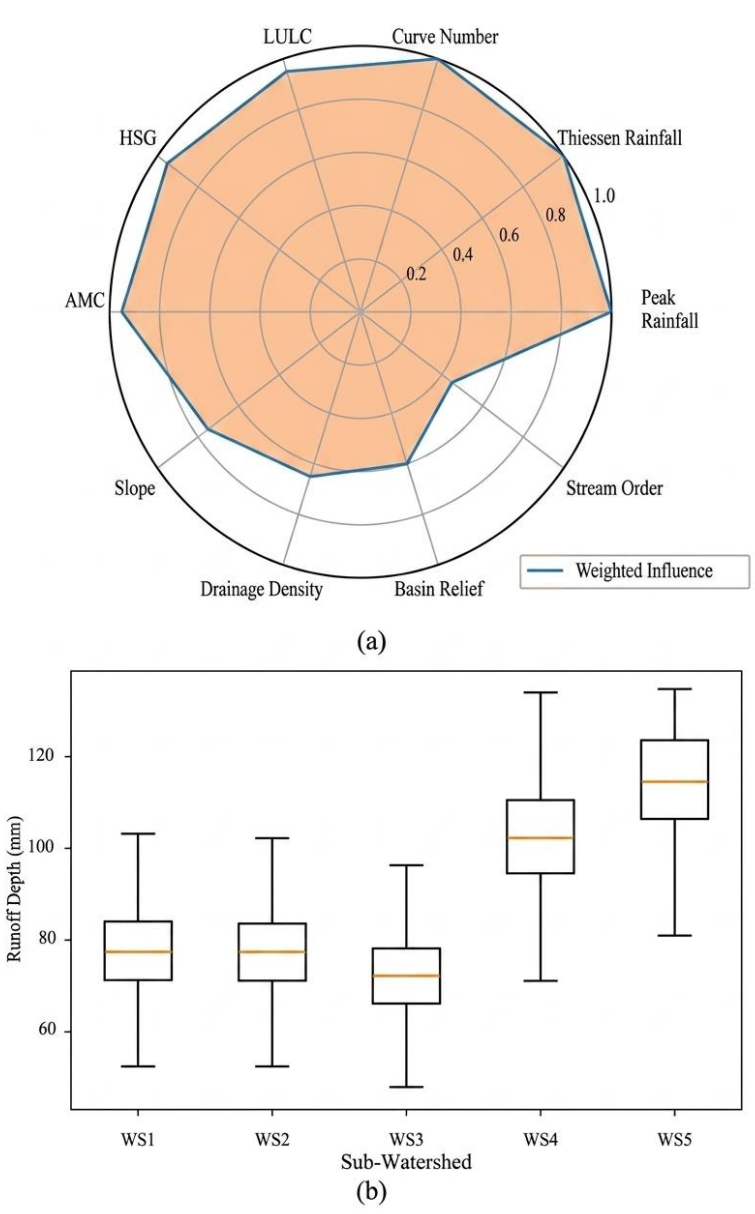

Fig. 9: a) Weighted sensitivity Radar diagram and b) Monte Carlo runoff uncertainty (Boxplot) for Pagladiya river basin (GIS-SCS-CN model)

More inclined landscapes and more complex drainage systems generally enhance the hydrological response; however, their impact on total runoff is still minimal when the amount of rainfall remains constant. Stream order shows the lowest sensitivity in this assessment; while it affects channel routing and the shape of the hydrograph, its direct role in runoff generation within the SCS-CN framework is minimal. Overall, the radar diagram suggests that the watershed is predominantly rainfall-driven, with strong interactions between land surface characteristics and soil properties, while morphometric attributes play a secondary yet meaningful role. The derived sensitivity emphasizes the significance of precise rainfall estimation and dependable CN values in enhancing model performance and reducing related uncertainties.

Interpretation of uncertainty

- Estimated runoff uncertainty varies from approximately 39.7% to 48.9% across the watershed.
- Sub-watershed WS3 exhibits the greatest relative sensitivity, indicating a strong influence of CN variability on runoff estimates.
- Although WS5 generates the highest runoff volumes, it shows comparatively lower relative uncertainty, likely due to consistently high CN values that reduce variability in model response.
- A ±5% perturbation in CN values results in a substantial spread in runoff estimates, reaching nearly 49%.
- The SCS-CN method's nonlinear structure heightens uncertainty, particularly in the context of moderate rainfall conditions.

To assess the predictive uncertainty associated with variability in CN, a Monte Carlo simulation approach was employed. For each sub-watershed (WS1-WS5), the composite CN was permitted to fluctuate within ±5% of its average value, based on the assumption of a normal distribution. A total of 5,000 simulation runs were conducted using the average peak rainfall conditions observed during 2008-2023, and the corresponding runoff depths were estimated using the SCS-CN method. The results of the simulation reveal significant uncertainty in the runoff estimates throughout the basin, as illustrated in Table 10. The derived 95% confidence intervals correspond to a relative variability of approximately 39.7% to 48.9% around the mean runoff values. A Monte Carlo simulation with 5,000 iterations was performed, where composite CN values were varied using a normal distribution within ±5% of the mean, and uncertainty was quantified using the resulting 95% confidence intervals of simulated runoff values. Among the sub-watersheds, WS3 demonstrated the greatest sensitivity to CN fluctuations, which can be ascribed to its diverse land use patterns and soil characteristics. In contrast, WS5 produced comparatively lower relative uncertainty despite generating higher runoff volumes, suggesting that consistently high and uniform CN values tend to stabilise model response. The nonlinear relationship between CN and the potential retention parameter (S) further amplifies deviations in runoff estimates, particularly under moderate rainfall conditions. Thus, even slight inaccuracies in the categorization of land use or soil types can result in considerable mistakes in the anticipated runoff. Overall, the uncertainty assessment highlights the critical importance of accurate CN determination for reliable runoff modelling, especially in ungauged Himalayan foothill basins. Incorporating probabilistic techniques such as Monte Carlo simulation improves the hydrological analysis and provides a stronger basis for informed water-resource planning and decision-making as shown in Fig. 9b. In the Monte Carlo simulation, composite CN values were varied within ±5% of their mean using a normal distribution to represent plausible parameter uncertainty; rainfall inputs were kept constant, and the 95% confidence intervals were derived from the percentile range (2.5th–97.5th) of the simulated runoff outputs. This study creates a framework that is both spatially distributed and sensitive to uncertainty for the evaluation of runoff in the ungauged Pagladiya River basin, which is found in the dynamic context of the Himalayan foothills. By integrating the SCS-CN method with GIS-based spatial datasets and event-scale rainfall records (2008-2023), the approach addresses limitations associated with improper CN weighting and the conventional dependence on average annual rainfall. The division of the basin into five physiographically unique sub-watersheds (WS1-WS5) further enhances the depiction of spatial diversity and improves the comprehension of runoff variability in this intricate landscape. The results indicate that rainfall is the dominant driver of runoff generation, with Thiessen-weighted areal rainfall explaining more than 99.88% of runoff variability

Table 10: Mean runoff and uncertainty (95% CI) across sub-watersheds (WS1–WS5).

Sub-watershed	Mean Runoff (mm)	95% CI lower (mm)	95% CI Upper (mm)	Uncertainty (%)
WS1	77.38	59.38	96.97	48.58%
WS2	77.40	60.02	96.27	46.84%
WS3	71.73	55.35	90.45	48.93%
WS4	102.63	80.12	127.35	46.02%
WS5	114.07	89.07	134.36	39.70%

(R^2 = 0.9997). Land-soil interactions also play a significant role in shaping the hydrological response. LULC, HSG, and AMC (AMC) emerge as secondary controlling factors, with AMC-III producing the highest discharge under saturated conditions. Runoff coefficients between 59.69% and 79.57% indicate a high level of runoff efficiency during severe storm events. Spatial assessment identifies WS5 as the most flood-prone sub-watershed, followed by the transitional zones WS3 and WS4. Sensitivity analysis verifies that rainfall, CN, and AMC are the primary governing factors, whereas terrain characteristics like slope and drainage density have a moderate impact on flow concentration processes. Monte Carlo simulations demonstrate that a ±5% perturbation in CN can lead to a 39-49% variation in runoff depth, highlighting the nonlinear behaviour inherent in the SCS-CN model. Sub-watersheds characterised by greater land-soil heterogeneity show higher predictive uncertainty, underscoring the importance of accurate LULC and soil datasets. Overall, the integrated GIS-based hydrological modelling framework provides a practical decision-support tool for flood risk assessment in ungauged Himalayan foothill basins. The integration of probabilistic uncertainty analysis improves runoff forecasts and facilitates more robust water-resource planning in the context of changing climatic conditions.

- Developed a GIS-integrated SCS-CN framework for ungauged Himalayan foothill basins.
- Rainfall explains >99% runoff variability (R^2 = 0.9997) in the Pagladiya basin.
- LULC, HSG, and AMC-III strongly control runoff amplification and flood risk.
- Monte Carlo analysis shows ±5% CN variation induces up to 49% runoff uncertainty.

Model validation and reliability assessment

Direct validation of the SCS-CN model using observed discharge data was not feasible because the study watershed is ungauged. Consequently, the dependability of the simulated runoff was assessed via indirect validation by contrasting the findings with published research carried out in hydrologically similar contexts. Fig. 10 illustrates the rainfall-runoff relationships observed in the current study, juxtaposed with previously published findings from analogous ungauged basins. All datasets exhibit a strong positive response, with the present study representing moderate storm events relative to the extreme conditions reported in the literature. The rainfall-runoff relationship obtained in the present study exhibits a strong positive correlation ($r \approx 1$), which is expected because runoff is computed as a deterministic function of rainfall and catchment characteristics within the SCS-CN framework. Comparable studies employing observed or long-term datasets likewise reveal robust correlations between rainfall and runoff. Satheeshkumar *et al*. (2017) estimated annual runoff in the Pappiredipatti watershed using the SCS-CN method and reported runoff values of approximately 170-190 mm under rainfall conditions ranging from about 440 to 1685 mm. Their findings revealed a robust correlation between rainfall and runoff that aligns with the hydrological response at the basin scale. In addition, event-based analysis in an ungauged basin reported runoff values ranging from about 25 mm to over 460 mm for storm rainfall between

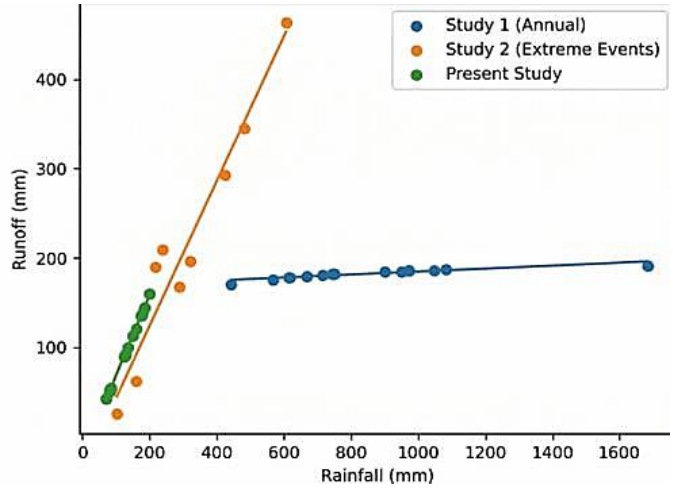

Fig. 10: Comparison of rainfall-runoff relationships between the present study and previously published datasets

approximately 100 mm and 600 mm, depending on antecedent moisture conditions (Nageswara Rao, 2020). The runoff depths obtained in the present study (approximately 50–160 mm) fall within this range, indicating that the simulated events represent moderate hydrological responses relative to extreme flood conditions documented in the literature (Aness *et al.,* 2026). A comparative analysis of rainfall-runoff correlations further supports the validity of the model results. Previous studies reported strong correlations of r ≈ 0.92 (annual data) and r ≈ 0.97 (extreme events), whereas the present study produced a near-perfect correlation due to the mathematical structure of the SCS-CN model. The nearly flawless correlation between rainfall and runoff is attributed to the deterministic characteristics of the SCS-CN method, where runoff is computed directly from rainfall through the use of curve number-based watershed parameters, instead of relying on independent discharge measurements. This agreement in trend, despite differences in magnitude, suggests that the model reproduces realistic runoff behavior for the watershed. Differences among studies may be attributed to variations in catchment size, terrain, rainfall intensity, land use, soil characteristics, and antecedent moisture conditions (Syaifullah *et al.,* 2025; Marisi *et al.,* 2025). Overall, the consistency of runoff magnitude, range, and rainfall-runoff relationship with published studies provides confidence that the model outputs are hydrologically plausible despite the absence of local discharge measurements.

CONCLUSION

This study analyzed surface runoff characteristics at the event scale of the ungauged Pagladiya River basin in the Himalayan foothills using a GIS- based SCS- CN approach and rainfall data from 2008 to 2023. The basin was divided into five physiographically distinct sub-watersheds (WS 1–WS 5) to capture spatial variability in land use, soil properties, and terrain. The findings indicate that the response of runoff is significantly affected by the magnitude of rainfall, prior moisture conditions, and the characteristics of land and soil (LULC and HSG), with AMC-III conditions yielding the highest simulated runoff. Runoff coefficients ranged from 59. 69% to 79. 57%, indicating high runoff efficiency during intense storm events. Downstream sub-watersheds, particularly WS 5, demonstrated a

greater modeled runoff potential in comparison to upstream regions; however, this conclusion is derived exclusively from simulation results. Sensitivity analysis emphasises the importance of accurate rainfall and curve number estimation for reliable runoff prediction, while Monte Carlo simulations reveal considerable uncertainty, with ± 5% variation in CN causing approximately 39–49% variability in runoff estimates. These results emphasize the nonlinear characteristics of the SCS-CN approach and the influence of spatial heterogeneity on the outputs of the model. However, the results should be interpreted with caution due to key limitations. The basin lacks gauging, which hinders direct validation against observed discharge data. Additionally, the application of coarse-resolution rainfall data in relation to the small size of the watershed, along with possible uncertainties in land use and land cover (LULC) classification, may further influence runoff estimates. Although comparisons with published studies suggest that the simulated values are within acceptable ranges, the broader applicability of the framework cannot be fully confirmed without field- based observations. This study provides an initial evaluation of runoff dynamics in a basin with limited data and illustrates the value of spatially distributed analysis for comprehending hydrological variability. Future studies should focus on establishing hydrometeorological monitoring networks, incorporating higher-resolution rainfall data, and validating models against observed streamflow to enhance reliability and support better watershed management decisions.

AUTHOR CONTRIBUTIONS

S Maji contributed to supervising the first author in data analysis, interpreting the results, and preparing the manuscript. S Basumatary prepared all the maps and figures and interpreted the results. Both authors participated in the preparation of the manuscript.

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CONFLICTS 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
AMC	Antecedent moisture condition
ArcGIS	Geographic information system software
CN	Curve number
DEM	Digital elevation model
ECMWF	European Centre for Medium-Range Weather Forecasts
FAO	Food and Agriculture Organization
GIS	Geographic information system
HSG	Hydrological soil group
ISRO	Indian Space Research Organisation
LULC	Land use/land cover
MLA	Maximum likelihood algorithm
mm	Millimeter
NBSS-LUP	National Bureau of Soil Survey and Land Use Planning
NRCS	Natural Resources Conservation Service
Q	Runoff
R^2	Coefficient of determination
SCS-CN	Soil conservation service curve number
USDA	United States Department of Agriculture
USDA-NRCS	United States Department of Agriculture Natural Resources Conservation Service
UTM	Universal transverse mercator
WGS-84	World Geographical System 1984
WS	Watershed (WS1–WS5)

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CASE STUDY

Eco-friendly pollination dynamics, humidity-driven activity, and service contributions in tropical highland shallot

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ABSTRACT

BACKGROUND AND OBJECTIVES: Pollination in tropical agricultural systems remains less documented than in temperate crops, limiting the development of environmentally safe and locally adapted pollination management. The study objectives were to assess pollinator diversity, environmental drivers, temporal dynamics, and service contribution in tropical highland shallot (*Allium cepa* variety *Aggregatum*) across three flowering seasons in Batu, East Java, Indonesia. The aim of this initiative is to pinpoint ecological conditions that facilitate sustainable production while minimizing reliance on chemicals.

METHODS: Sampling was replicated across 8 permanent plots, 7 consecutive days per flowering season, 3 flowering seasons, and 6 standardized daily time windows, generating 1,008 possible observation units. Of these, 948 observation events recorded flower visitors and were retained for analysis. A total of 1,078 flower visitor records were documented. These records covered 12 species, 8 families, and 3 orders. Community composition and temporal visitation patterns were analyzed. The calculation of diversity indices was conducted, alongside testing the correlations between pollinator abundance and microclimatic variables. Additionally, nonparametric statistics and correlation methods were utilized.

FINDINGS: Diptera dominated the assemblage numerically (58.5 percent). Hymenoptera followed at 40.3 percent. This pattern differs from bee-dominated communities in temperate Allium systems. This denotes a specific community structure. Relative humidity was the sole environmental variable that showed a consistent and positive correlation with core pollinator abundance (Pearson r = +0.494, Probability < 0.0001), whereas temperature and wind speed did not demonstrate significance within the observed range. Visitation was concentrated in the morning, with 68.1 percent of core pollinator activity occurring between 06:00 and 12:00. Seasonal diversity increased over time, and five core species accounted for most pollination activity, with three species contributing 77.2 percent of total service.

CONCLUSION: Tropical highland shallot pollination is influenced more by moisture than by temperature. This highlights the need for ecofriendly practices. These include proper irrigation scheduling, habitat conservation, and reduced pesticide use during peak pollinator activity. These conclusions present a practical ecological foundation for the management of sustainable pollination in tropical highland agriculture and promote biodiversity-focused strategies for crop production that is environmentally resilient.

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40	3	4

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INTRODUCTION

Pollinators are vital for crop reproduction, yield stability, and resilience. This is especially true in tropical agriculture with high biodiversity. Pollinator diversity improves crop quantity and quality. It also supports ecosystem functions under threat (Cusser *et al.,* 2021; Senapathi *et al.,* 2021; Millard *et al.,* 2021). It is important for sustainable agriculture to acknowledge all pollinators, rather than focusing exclusively on managed bees. Local insect communities are essential to this ecosystem. In tropical areas, pollination is shaped by microclimate conditions and the distribution of resources. Additionally, the structure of the landscape significantly influences pollinator activity (Hoehn *et al.,* 2010; Kremen and Miles, 2012; Vergara and Badano, 2009). Shallot (*Allium cepa* L. *Aggregatum* group) is a valuable horticultural crop. Its production is increasingly shifting to seed-based propagation. Genuine shallot seed systems enhance sustainability by reducing pathogen carryover and boosting plant vigor (Pangestuti *et al.,* 2023; Tabor, 2018). Shallot umbels produce numerous small flowers with nectar rewards that attract diverse insects, yet the identity, ecological reliability, and temporal stability of those visitors remain insufficiently understood in tropical highland systems (Morales *et al.,* 2017; Prasifka *et al.,* 2018). Shallot exhibits limited self-pollination capacity, so insect visitation is essential for reliable seed production. This reliance renders the conservation of pollinators an essential aspect of environmentally sustainable management, as the reproduction of crops is enhanced by consistent insect-mediated pollen transfer (Devi *et al.,* 2015; Endarto *et al.,* 2024). Recent studies have identified diverse pollinator assemblages visiting Allium umbels. *Apis cerana* Fabricius, 1793 (Hymenoptera: Apidae) and *Lucilia sericata* (Meigen: 1826) (Diptera: Calliphoridae) are effective pollinators, though *A. cerana* demonstrates superior efficiency in promoting shallot seed production (Endarto *et al.,* 2024; Sajjad *et al.,* 2008). Honeybees (*Apis mellifera* L.) are considered the most valuable onion pollinators among 267 species documented visiting umbels (Devi *et al.,* 2014; Morales *et al.,* 2017). Despite this, studies concerning *Allium* pollination have largely concentrated on Hymenoptera, particularly managed honeybees, while Diptera demonstrate a numerical predominance in various tropical agroecosystems. Dominance of certain species may reflect functional traits such as body size, foraging flexibility, and tolerance of humid tropical conditions. For flies, morphology and life-history traits are important predictors of pollination potential in horticultural crops (Cook *et al.,* 2020). The observed fluctuations in diversity and evenness across seasons reflect temporal turnover during the study period, yet they fail to show any long-term directional change. Continued monitoring would be required to detect sustained shifts in dominance or community composition (Domínguez-Garcia *et al.,* 2024). Their roles in seed production are also unclear. Most studies come from temperate or intensively studied systems. Tropical shallot systems remain poorly quantified (Devi *et al.,* 2014; Devi *et al.,* 2015; Eeraerts *et al.,* 2020). Conversely, tropical agroecosystems typically sustain a more diverse range of visitor assemblages, such as Diptera, which may deliver considerable pollination services in warm and humid conditions. Climate change may reinforce a Diptera-dominated system if warm humid conditions persist, but it could also disrupt it if moisture declines or rainfall becomes more erratic. Consequently, the current results indicate a pollination system that is potentially influenced by climate, as opposed to a stable community state (Davis *et al.,* 2025). This difference matters because management recommendations derived from temperate bee-centered systems may not adequately represent tropical pollination ecology. Dipteran pollinators can be abundant, behaviorally flexible, and

ecologically important in crop systems, yet their contribution is still undervalued in many pollination studies (Walker *et al.,* 2011; Cook *et al.,* 2020; Davis *et al.,* 2023). Consequently, a more comprehensive understanding of pollination is required to enhance biodiversity-focused and ecologically sound crop management. nevertheless, most studies still prioritize temperature, leaving the humidity-related activity patterns insufficiently examined (Corbet and Smith, 1993; Alquichire-Rojas *et al.,* 2024; Maeda *et al.,* 2023; Von Arx, 2013). Surrounding land-use composition and semi-natural habitat patches can influence pollinator persistence by providing nesting sites, larval resources, and alternative foraging resources. Forest edges may also maintain higher pollinator abundance and richness and increase network robustness as forest area declines. In tropical highland systems, moisture-retaining microhabitats can buffer short-term desiccation stress and support activity stability (Ren *et al.,* 2023; Cook *et al.,* 2020). This establishes a crucial knowledge deficiency for management. Moisture factors could be more significant than temperature. Irrigation and canopy structure can more effectively support pollinators. The retention of moisture in the landscape is also vital. Another gap is functional redundancy and stability. Resilient systems rely on multiple pollinator taxa. Alternative floral resources can sustain visitor abundance and reduce temporal competition among taxa. In tropical agroecosystems, floral continuity can help maintain pollinator activity across flowering periods and support mixed Diptera–Hymenoptera assemblages (Davis *et al.,* 2025; Cook *et al.,* 2020). Even though fly pollination and humidity impacts have been observed in other contexts, this study is groundbreaking in its association of these factors with tropical highland shallot throughout three flowering seasons with standardized diel sampling. Few studies test if services come from few species. It is unclear if they are spread across many. Temporal diversity may enhance resilience by allowing species to substitute for one another across seasons and daily time windows (Hufnagel *et al.,* 2020; Senapathi *et al.,* 2021). Pollination dynamics were examined in tropical highland shallot across three flowering seasons. It analyzes community composition, temporal activity, environmental drivers, and service contribution. It was anticipated that Diptera would prevail, with humidity being more important than temperature. Temporal diversity and redundancy were also tested. Results aim to support stable and reliable pollination services. The results emphasize the necessity for management practices that are moisture-based, promote biodiversity, and utilize low chemical inputs. This strategy enhances the ecological foundation for sustainable production. This study aims to assess pollinator diversity, environmental drivers, temporal dynamics, and service contribution in tropical highland shallot across three flowering seasons, and was conducted in Batu, East Java, Indonesia in 2023 during the post-pandemic recovery. The findings are expected to support sustainable agricultural practices and pollinator conservation in tropical highland ecosystems.

MATERIALS AND METHODS

Study Area and Sampling Design

The study was conducted in commercial shallot (*A. cepa* L. *Aggregatum* Group) fields in Batu, East Java, Indonesia with 7°52 degrees south (°S), 112°31 degrees east (°E), at approximately 800 meters (m) above sea level. The location showcases a tropical highland agroecosystem distinguished by consistently warm temperatures, elevated atmospheric moisture, and significant daily microclimatic fluctuations throughout the flowering period. Observations were carried out across three flowering seasons spanning September 2023 to May 2024 to capture seasonal turnover in pollinator communities and environmental conditions.

Study design, replication, and sampling unit

A replicated observational design was used to capture spatial and temporal variation in pollinator activity. The field was divided into 8 permanent observation plots of 50 square meters (m^2) each, and sampling was repeated across 7 consecutive days per flowering season and 3 flowering seasons. Within each day, observations were conducted in 6 standardized time windows: 06:00–08:00, 08:00–10:00, 10:00–12:00, 12:00–14:00, 14:00–16:00, and 16:00–17:00. This produced 1,008 possible observation units (8 plots × 7 days × 3 seasons × 6-time windows). Of these, 948 observation events recorded at least one flower visitor and were retained for community and environmental analyses. The design utilized replicated plots, along with repeated days, repeated seasons, and standardized diel windows to effectively capture structured temporal variation. This improves comparability across space and time, but activity outside the observation windows was not measured and therefore cannot be inferred directly from the present dataset. Temporal patterns in pollinator biodiversity were assessed through the Shannon diversity index (H'), which considers both species richness and the evenness of abundance distributions, as outlined in Eq.1 (Oksanen *et al.,* 2022):

$$H' = -\Sigma(p_i \times \ln(p_i) \quad (1)$$

where, p_i is the proportional abundance of species i. Shannon diversity indices (J') were calculated separately for each season (S-1, S-2, S-3) and for each daily time period (06:00-08:00 through 16:00-17:00) at the sampling unit level (defined as unique combinations of season × day × time) to reveal patterns at both temporal scales using the vegan package version 2.6-4 (Oksanen *et al.,* 2022) in R. Elevated H' values reflect a higher level of diversity, factoring in both the species count and the evenness of their distribution. The analysis was based on the sampling unit defined as the combination of plot× day × season, and time window combination. The importance of this definition lies in its clarification that counts were not considered at the flower level, which could lead to pseudo replication. Instead, visitation was compiled at the observation-period level, facilitating an analysis that accurately reflects repeated but systematic sampling across space and time. The design therefore provided replication at four nested levels: plot, day, season, and 24-hour light–dark cycle (diel) period.

Pollinator observation and identification

Pollinator observations were conducted during anthesis, when shallot florets were open and receptive to visitation. Standardized visual census methods were used to record all insects that contacted the floral reproductive structures. Visitors were captured using sweep nets whenever feasible, or they were photographed in their natural environment for subsequent verification when capturing them would have interfered with their ongoing activities. Captured specimens were killed, pinned, labeled, and identified in the laboratory using taxonomic keys, with difficult specimens confirmed by an expert taxonomist. Voucher specimens were deposited in the Museum Zoologicum Bogoriense. All observations adhered to the same time frame and protocol, guaranteeing uniform counts. Each insect was documented once per encounter, with repeat visits counted only if there was new flower contact. This approach made data comparable across plots, days, and seasons.

Environmental data collection

At each observation period, ambient temperature, relative humidity, and wind speed were recorded using a Kestrel 3000 Pocket Weather Meter positioned 1.5 m above ground near the observation plots. Measurements were taken at the start of each 2-hour (h) observation

period so that environmental conditions could be matched directly to the corresponding visitation data. These variables were chosen due to their established influence on insect flight behavior, floral manipulation, and pollination efficiency, particularly in tropical highland ecosystems where moisture levels can fluctuate significantly despite relatively stable temperatures.

Data handling and statistical analysis

To test for significant differences in pollinator visitation patterns across seasons and days, this study employed chi-square (χ^2) goodness-of-fit tests for key pollinator species using the base R stats package (R Core Team, 2026). For seasonal analysis, the observed distribution of individuals across three seasons were tested (S-1, S-2, S-3) differed significantly from an expected uniform distribution (equal abundance across seasons). In conducting daily analysis, the distribution observed over seven consecutive days was assessed. The sampling days numbered 1 to 7 (D-1 to D-7) were found to differ from the expected equal distribution. Effect sizes for significant chi-square tests were quantified using Cramer's V calculated with the companion package version 2.4.30, using Eq. 2 (Oksanen *et al.,* 2022):

$$V = \sqrt{(\chi^2/n)} \quad (2)$$

where, n is the total number of observations. Cramer's V values were interpreted as small ($V < 0.1$), medium ($0.1 \leq V < 0.3$), or large ($V \geq 0.3$) effects. Species were classified into functional groups based on their temporal visitation patterns: consistent pollinators (no significant seasonal or daily variation, coefficient of variation (CV) < 25 percent (%), seasonal specialists (significant seasonal variation with absence or very low abundance in one or more seasons), and variable species (significant daily variation or moderate seasonal variation with CV > 25%). This study quantified flower visitation and temporal consistency rather than direct pollen deposition. Visitors were perceived exclusively as service-providing candidates when there was a consistent and repeated contact with reproductive structures across the sampling units. The Service Contribution Index is a prioritization tool, not a direct measure of single-visit effectiveness (Eeraerts *et al.,* 2020). Visiting rate was calculated as the mean number of individuals observed per observation period for each species across all sampling events where that species was recorded. Community composition's composition was encapsulated by species richness, family richness, order-level abundance, and total visitation. Temporal diversity was measured using the Shannon index by season and time window. Seasonal differences were tested with nonparametric methods and corrected post-hoc. The significance of the study in terms of the environment is rooted in the identification of a pollination system that is sensitive to microclimate variations, which can be enhanced through habitat preservation, moisture conservation, and minimized pesticide exposure. These measures connect biodiversity conservation directly with crop-sustaining ecosystem services (Cook *et al.,* 2020). Temperature, relative humidity, and wind speed were recorded at the start of each observation period to standardize field conditions. The interpretation is restricted to the observed climatic range and does not test extreme weather events or deliberate weather manipulation (Maeda *et al.,* 2023). This index was used as a prioritization tool, no direct seed set, fruit set, or yield assay was conducted in this study. Reproductive service is concluded from the presence of abundance, recurrent visitation, and temporal dependability, while direct validation ought to be explored in subsequent experiments.

Statistical interpretation and limitations

The study design included repeated observations across plots, days, seasons, and time

windows, which strengthens inference by capturing both spatial and temporal variability. Simultaneously, the study was observational in nature, thus the findings ought to be understood as patterns of association instead of experimental tests of mechanism. The explicit identification of the observation period as the unit of analysis, together with the separation of diversity, correlation, and service-contribution analyses, improves transparency and reduces ambiguity about replication structure. Future studies that add direct pollination-success measurements, such as pollen deposition or seed set, would strengthen causal interpretation and extend the present community-level findings. As observations were confined to daytime hours, nocturnal and crepuscular visitors were excluded from the sampling process. Consequently, the present study characterizes diurnal visitation only, and additional night surveys would be needed to evaluate the full pollinator assemblage. Minuscule or subtle visitors might be inadequately documented under visual census protocols, especially when they swiftly navigate among florets. The present results therefore emphasize the dominant and repeatedly detected taxa, while rare or cryptic species may be underestimated (Walker *et al.,* 2011). This study is based on visitation structure rather than a full bipartite network analysis, so keystone status cannot be formally assigned. Nevertheless, the core species that are observed with high frequency are credible central taxa in the network due to their contribution to most of the repeated visitation (Bascompte and Scheffer, 2023).

RESULTS AND DISCUSSION

Pollinator community structure and the main ecological message

The results show that tropical highland shallot pollination in Batu is organized differently from the bee-centered model often assumed for Allium crops in temperate systems. Diptera constituted the predominant visitors in terms of numbers. A total of 1,078 distinct flower visitors, encompassing 12 species from 8 families and 3 orders were recorded during 948 observation events (Table 1). recorded during seven Hymenoptera species (primarily bees), four Diptera species (flies), and one Coleoptera species (beetle). Diptera dominated numerically with 631 individuals (58.5%), followed by Hymenoptera (434 individuals, 40.3%) and Coleoptera (13 individuals, 1.2%) (Fig. 1A). *Chrysomya megacephala* (Fabricius, 1775) (Calliphoridae) was the most abundant visitor (317 individuals, 29.4%). Temporal constancy analysis revealed substantial variation in visitor reliability (Fig. 1B). Five species exhibited high constancy (≥49% of sampling units): *C. megacephala* (83.3%), *Tetragonula iridipennis* Smith, 1854 (77.5%), *S. ribesii* (61.7%), *Episyrphus balteatus* (Fabricius, 1781) (59.2%), and *Apis cerana* Fabricius, 1793 (49.2%). One species showed moderate reliability (*Trigonula* sp.) 26.7%), while six species occurred sporadically (< 25%) (Fig. 1C). Five species exhibited high abundance and constancy: *C. megacephala*, *T. iridipennis*, *E. balteatus*, *S. ribesii* (Linnaeus, 1758), and *A. cerana*. These species accounted for 784 individuals, representing 72.7% of total visitation. Among them, three belonged to Diptera (*C. megacephala*, *E. balteatus*, and *S. ribesii*) and two to Hymenoptera (*T. iridipennis* and *A. cerana*). The remaining seven species contributed 294 individuals (27.3% of total visits), with *Trigonula* sp. (8.5%) exhibiting the highest abundance within this group. Subsequent analyses focus on these five high-abundance, high-constancy species across different flowering and environmental conditions, owing to their dominant contribution to overall floral visitation patterns.

Table 1: Flower-visiting insects recorded on shallot umbels in Batu, East Java, Indonesia, during September 2023–May 2024

No.	Order	Family	Species	Common Name
1	Diptera	Calliphoridae	*Chrysomya megacephala*	Oriental latrine fly
2	Hymenoptera	Apidae	*Tetragonula iridipennis*	Indian stingless bee
3	Diptera	Syrphidae	*Episyrphus balteatus*	Marmalade hoverfly
4	Diptera	Syrphidae	*Syrphus ribesii*	Common syrphid fly
5	Hymenoptera	Apidae	*Apis cerana*	Asian honeybee
6	Hymenoptera	Apidae	*Trigonula sp.*	Stingless bee sp.
7	Hymenoptera	Halictidae	*Nomia sp.*	Alkali bee sp.
8	Diptera	Muscidae	*Musca domestica*	House fly
9	Hymenoptera	Vespidae	*Vespula vulgaris*	Common wasp
10	Hymenoptera	Vespidae	*Polistes chinensis*	Paper wasp
11	Coleoptera	Coccinellidae	*Menochilus sexmaculatus*	Six-spotted ladybird
12	Hymenoptera	Apidae	*Amegilla nr zonata*	Blue-banded bee

The outcome bolsters the claim that tropical pollination systems must be evaluated according to their specific ecological characteristics instead of relying on assumptions derived from temperate systems. In practical terms, this means that environmentally safe pollination management in tropical crops must account for flies as well as bees, especially when management aims to reduce pesticide dependence and conserve functional biodiversity. Although pesticide application frequency was not directly quantified, the pronounced morning activity peak suggests that broad-spectrum spraying during high visitation periods should be avoided. This suggestion is in accordance with the guidance on pollinator protection, which stresses the importance of reducing exposure during the peak activity periods of pollinators (Karbassioon and Stanley, 2023a). These findings can be translated into sustainable practice by integrating moisture-conserving field management, diversified floral resources, and reduced broad-spectrum spraying. Such actions enhance the delivery of ecosystem services and encourage production methods that are beneficial to biodiversity. Peak morning humidity coincided with the highest visitation window, indicating a period of maximum pollinator activity. Furthermore, the lack of direct assessment of yield and seed-quality data leads the current study to view this as a pattern of service delivery rather than a confirmed yield mechanism (Maeda *et al.,* 2023). Based on visitation frequency and temporal constancy, five species were identified as core pollinators (Vanbergen and Initiative, 2013). However, this classification indicates stable contribution to visitation-based service rather than experimentally verified single-visit pollination efficiency. The dominance of *C. megacephala* and the strong contribution of syrphid flies support this interpretation. Despite being frequently disregarded in studies of crop pollination, the high numbers and consistent visits of flies can result in significant contributions at the population scale. This is consistent with broader evidence that Diptera can be major pollinators in horticultural systems and that their ecological roles become especially important where bee communities are less dominant or more sensitive to local conditions (Cook *et al.,* 2020; Davis *et al.,* 2023). In this study, the Service Contribution Index indicated that a limited number of species accounted for most of the pollination activity. Nevertheless, the core assemblage included both Diptera and Hymenoptera, which points to cross-taxonomic redundancy instead of reliance on a single guild.

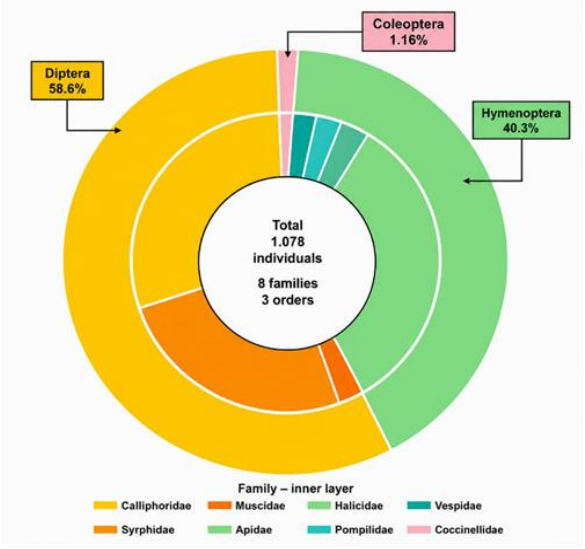

Fig. 1.A

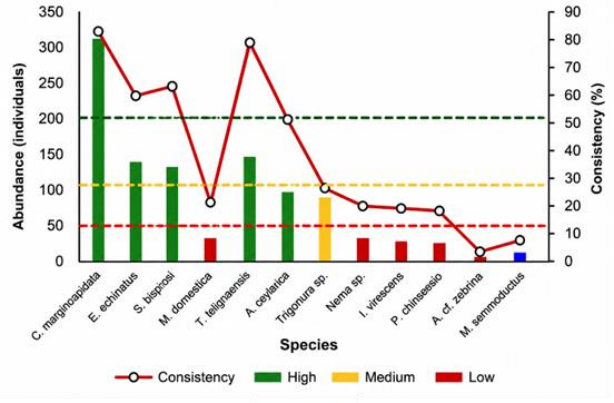

Fig. 1.B

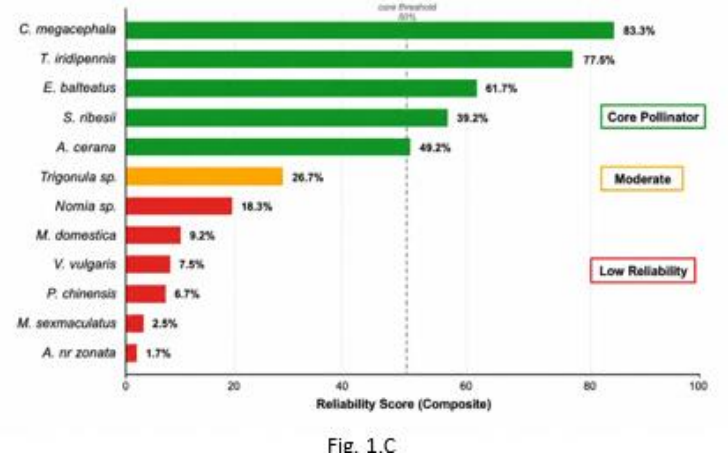

Fig. 1.C

Fig. 1: Pollinator community structure and reliability in shallot fields (A) Taxonomic composition of flower-visiting insects recorded on shallot umbels in Batu, East Java, Indonesia. (B) Abundance and visitation constancy of each recorded species across the sampling period. (C) Reliability classification of species based on abundance and constancy, identifying the core pollinator group

Humidity as the key environmental driver

The pattern suggests that moisture conditions were more important than thermal variation in structuring short-term pollinator activity in this tropical highland system. This finding has two important implications. First, it suggests that tropical highland pollinators may already be operating within a relatively favorable temperature envelope, so small temperature differences may not be sufficient to alter activity strongly. Second, humidity is likely to influence both the physiology of insects and the conditions of flowers, which encompass water balance, flight efficiency, and cues related to nectar. Floral humidity has been recognized as a biologically relevant signal in pollination ecology, not merely a background atmospheric condition (Von Arx, 2013). The present results therefore support the interpretation that moisture is a key ecological filter in tropical highland pollination systems. The association between humidity and visitation also has direct management relevance. Moisture-based practices may support pollinators better than temperature-based scheduling. These methods encompass irrigation management and canopy retention. Such strategies improve pollination while avoiding an increase in chemical pressure. This supports environmentally safe agriculture. The findings align with recent studies. Pollinator responses to weather are taxon-specific and context-dependent (Karbassioon *et al.,* 2023b).

Temporal structure, functional redundancy, and resilience

The five core species collectively represented 784 individuals across 114 observation events (Table 2). Shannon diversity (H') among these species increased from 1.06 in Season 1 (September-November 2023) to 1.36 in Season 3 (March-May 2024), representing a 28.2% increase. The evenness (J') rose from 0.77 to 0.98 during the same timeframe. The total abundance varied from 220 individuals in Season 1 to 305 in Season 2, and then to 259 in Season 3. (Fig. 2A). Diel activity patterns showed temporal concentration during morning hours (Fig. 2B). The 08:00-10:00 period was most active, accounting for 28.6% (224 individuals) of core species visits, followed by 10:00-12:00 (18.5%, 145 individuals) and 06:00-08:00 (21.0%, 165 individuals). The morning hours, spanning from 06:00 to 12:00, accounted for 68.1% of the total daily activity. Throughout the afternoon hours, activity saw a steady decline, particularly between 16:00 and 18:00, when the lowest visitation was recorded at 4.6%, equating to 36 individuals. Four species (*C. megacephala, T. iridipennis, S. ribesii, A. cerana*) showed peak activity at 08:00-10:00 (80% synchronization); *E. balteatus* peaked earlier at 06:00-08:00 (27.1% of its activity). Species-specific temporal patterns indicated differences in activity concentration. *A. cerana* exhibited the most focused profile, with 52.9% of activity at the 08:00-10:00 peak. The three Diptera (*C. megacephala, E. balteatus, S. ribesii*) displayed broader distributions across multiple periods. All core species showed minimal afternoon presence (< 12% during 16:00-17:00). Pollinator activity was concentrated in the morning, mainly from 06:00 to 12:00. Species showed overlapping activity, indicating functional redundancy. The presence of this overlap boosts resilience to disturbances. Over time, there has been an increase in seasonal diversity and evenness, which implies a greater balance and stability in the community (Senapathi *et al.,* 2021). Increasing evenness improves interpretation of community structure. It reduces dominance by a single species. This lowers vulnerability to species loss. The community is becoming more balanced. The increasing diversity and uniformity indicate a broader functional distribution. It is not merely about the number of individuals. These trends enhance resilience and stability. Various taxa contribute to supporting pollination throughout different seasons and over time.

Table 2: Seasonal dynamics of core pollinators in tropical shallot fields

Season	Period	Total abundance	Species richness	Shannon Diversity (H')	Change (%)	Evenness (J')	Change (%)
S-1	Sep-Nov 2023	220	5	1.06	-	0.77	-
S-2	Dec 2023-Feb 2024	305	5	1.34	+26.40	0.97	+26.00
S-3	Mar-May 2024	259	5	1.36	+28.30	0.98	+27.30
Total	Sep 2023-May 2024	784	5	—		—	

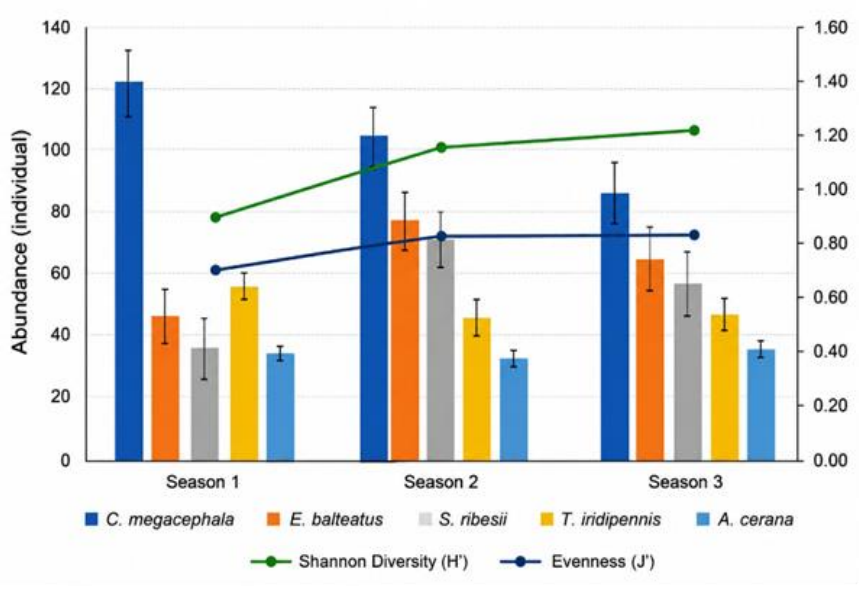

Fig. 2A

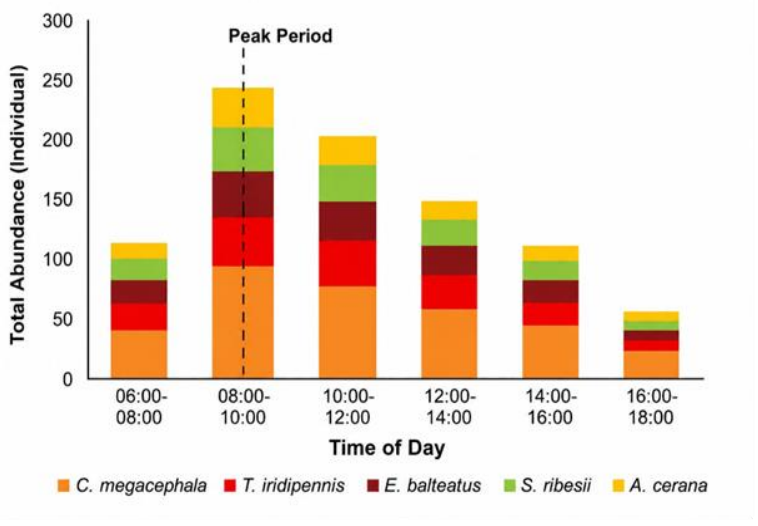

Fig. 2B

Fig. 2: Seasonal and diel activity patterns of core pollinators (A) Seasonal changes in abundance, diversity, and evenness across three flowering periods (Season-1= Sep-Nov 2023; Season-2= Dec 2023-Feb 2024; Season-3= Mar-May 2024) (B) Daily visitation rhythms of the core pollinator species across standardized observation windows

Environmental correlates of core pollinator activity

The second hypothesis is supported by the strong positive correlation found between core pollinator abundance and relative humidity across 113 observation events (Table 3). Pearson correlation analysis revealed r = +0.494 (P < 0.0001), while Spearman rank correlation was ρ = +0.515 (P < 0.0001). High-activity periods (>10 individuals, n = 25 events) were observed at a humidity level of 90.0 ± 1.7%, in contrast to low-moderate activity periods (1-10 individuals, n = 88 events; 86.9 ± 3.8%). This represents a difference of 3.1% points (Kruskal-Wallis H = 16.18, P < 0.001; (Table 4). Humidity ranged from 74% to 93% (mean 87.6 ± 3.6%). Analyses focused on 113 events with core pollinators. Temperature showed no correlation with abundance. It ranged from 22.0–34.1 degrees Celsius (°C) (mean 28.8 ± 2.8°C). No difference was found between activity levels. Wind speed had no effect, ranging from 0.8 to 5.5 m/s, with a mean of 3.3 ± 1.0 m/s. Activity remained unchanged regardless of wind conditions. Only humidity showed a significant correlation (P < 0.001). Temperature and wind were not significant. Across all statistical evaluations, relative humidity emerged as the sole consistent predictor of pollinator abundance, acting as a primary environmental filter. Contrary to expectations, peak activity was driven by higher humidity levels rather than warmer temperatures or calmer wind conditions (Von Arx, 2013). The ecological meaning is likely twofold. Higher humidity may reduce desiccation stress during flight. This can prolong active foraging under warm conditions. Insect activity is closely linked to water balance. Humidity may also reflect favourable floral conditions. It is often associated with fresh flowers and rewards. The positive effects of humidity aren't the same for everyone! Different pollinators react in their own unique ways depending on their type and environment. For instance, many studies on bees have found that they tend to be less active when humidity levels rise. This often happens on cloudy days or low-radiation conditions. Differences among taxa are also important. Bumblebees are often more resilient than honeybees. Here, humidity remained within a favourable range (74–93%). The pattern demonstrates variation under appropriate conditions, rather than adverse weather (Karbassioon *et al.,* 2023b). The analysis focused on 113 events with core pollinators present which examined variation within the active community, not total absence. Thus, humidity distinguished higher from lower activity levels. It did not just co-occur with pollinators. This makes the inference more precise. Humidity is the key driver of abundance among active taxa. From a service viewpoint, it clarifies the changes in pollination delivery. It pinpoints the most pertinent environmental factor (Karbassioon *et al.,* 2023a). Temperature showed no effect on pollinator abundance and did not influence activity levels or patterns. The observed range (22.0–34.1°C; mean 28.7 ± 2.8°C) likely stayed within tolerance. Consequently, temperature did not function as a limiting factor. Its effects are frequently nonlinear and taxon-specific, with some groups exhibiting strong responses while others remain unaffected. In this instance, temperature fluctuations were less pronounced than humidity, serving as a secondary background factor rather than a primary driver (Karbassioon *et al.,* 2023b). A similar argument applies to wind speed, which also failed to explain variation in core pollinator abundance. Wind is widely recognized as a constraint on insect flight because it increases energetic costs, reduces manoeuvrability, and can lower floral handling efficiency. Experimental work on honeybees has shown that increasing wind speeds can reduce visit rates and alter foraging behavior. However, the wind regime recorded in this study was relatively moderate and narrow with 0.8–5.5 m/s mean 3.3 ± 1.0 m/s, with nearly identical means between activity classes. Given these circumstances, the wind might not have reached the necessary threshold to inhibit activity in the primary pollinator taxa. Community responses to

Table 3: Correlation between environmental variables and core pollinator abundance

Environmental variable	Pearson r	Pearson p-value	Spearman ρ	Spearman p-value	Significance
Humidity	+0.494	< 0.0001	+0.5150	< 0.0001	
Temperature	-0.056	0.5591	-0.0680	0.4715	ns
Wind speed	+0.027	0.7801	-0.0030	0.9720	ns

Note: Significance was assessed at α = 0.05; results with P < 0.05 were considered significant, while P ≥ 0.05 were non-significant (ns).

Table 4: Environmental conditions during different core pollinator activity levels

Environmental variable	Low-moderate activity (1-10)	High activity (>10)	Kruskal-Wallis H-statistic	P-value	Significance
Humidity	86.9 ± 3.8	90.0 ± 1.7	16.1800	0.0001	-
Temperature	28.7 ± 2.8	29.2 ± 2.5	0.7700	0.3807	ns
Wind speed	3.3 ± 1.0	3.4 ± 1.0	0.1300	0.7216	ns

Note: Significance was assessed at α = 0.05; results with P < 0.05 were considered significant, while P ≥ 0.05 were non-significant (ns).

weather can be muted by species differences. Some pollinators tolerate conditions that limit others. Species vary in responses to temperature, humidity, and wind. These differences reduce sensitivity at the community level. The data suggest that increased humidity within the observed range correlates with a higher abundance of pollinators; however, they do not specify a definitive optimum or threshold. A controlled humidity experiment would be needed to identify any upper or lower limit for activity (Maeda *et al.,* 2023). Thus, aggregated abundance may mask individual patterns. Divergent species responses can balance overall activity (Hennessy *et al.,* 2020). Core pollinator activity was influenced more by humidity than by temperature or wind, emphasizing moisture as the primary factor. From an ecological perspective, pollinators functioned within established thermal and wind tolerances, yet they maintained a high sensitivity to humidity and floral availability. For effective management, it is essential to prioritize the maintenance of humid, buffered habitats particularly within mixed pollinator systems. Such environments can be effectively sustained through strategic canopy cover and diverse vegetation. Irrigation and landscape features also help retain moisture (Karbassioon *et al.,* 2023b). Weather effects should not be generalized across all pollinators. Different taxa have distinct tolerances and behaviors. The present data supports complementary rather than directly comparable pollination roles for Diptera and Hymenoptera. Dipteran dominance in visitation does not by itself prove higher per-visit efficiency, but it does show that flies can contribute substantially to the total visitation pool (Cook *et al.,* 2020). Many studies focus on honeybees. However, community-level outcomes depend on diverse groups, which suggests sensitivity to microclimatic dryness. Pollination may be more vulnerable to drying than warming. This is key for predicting stability and guiding habitat management. The presence of overlap in diel activity among the key species implies some level of redundancy, while their varying temporal peaks point to complementarity. This mixture can stabilize visitation across the morning period and reduce reliance on a single taxon (Domínguez-Garcia *et al.,* 2024).

Service contribution and the role of core species

Core pollinator species demonstrated significant differences in their contribution to services, measured by a composite index that combines relative abundance and temporal consistency (Fig. 3A). *C. megacephala* ranked first (service index = 40.4; 40.4% abundance, 100% consistency),

followed by *T. iridipennis* (index = 19.1; 19.1% abundance, 100% consistency), *S. ribesii* (index = 17.7; 17.7% abundance, 100% consistency), *E. balteatus* (index = 12.2; 18.4% abundance, 66.7% consistency), and *Apis cerana* (index = 1.4; 4.3% abundance, 33.3% consistency). The top three species together represented 77.2% of the overall service contribution. Visitation frequency varied among core species (Fig. 3B). *C. megacephala* occurred in 87.7% of observation events (100 of 114 events, mean 3.17 individuals/event). *T. iridipennis* showed 81.6% frequency (93 events, mean 1.61 individuals/event). *S. ribesii* and *E. balteatus* exhibited intermediate frequencies (64.9% and 62.3%, respectively), while *A. cerana* occurred in 14.0% of events (16 events, mean 2.12 individuals/event). Taxonomic order-level analysis showed Diptera majority (Fig. 3C). Three Diptera species (*C. megacephala, E. balteatus, S. ribesii*) collectively contributed 600 individuals (76.5%) with combined service index of 70.4 (77.3% of total service). Two Hymenoptera species (*T. iridipennis, A. cerana*) accounted for 184 individuals (23.5%) with combined service index of 20.6 (22.7% of total service). Mean visitation frequency was 71.6% for Diptera and 47.8% for hymenoptera. The Diptera: Hymenoptera service ratio was 3.4:1. The Service Contribution Index showed that service was concentrated in a small number of species but not confined to a single order. This outcome is crucial because it implies that management is crucial because it implies that service-providing assemblage, rather than solely the most abundant visitor. *C. megacephala* ranked highest, but stingless bees and syrphid flies also contributed substantially to total service. The primary three species comprised most of the assessed contribution, demonstrating that pollination in this system is both centralized and somewhat varied. At the same time, the Service Contribution Index should be interpreted carefully. It is a useful prioritization tool because it combines abundance and temporal constancy, but it does not directly measure pollen deposition, fruit set, or seed quality. Therefore, the index identifies likely core contributors rather than definitive single-visit effectiveness. This limitation is important for reviewer scrutiny and should be stated clearly to avoid overclaiming.

Implications for ecofriendly and environmentally safe management

This study has clear value for ecofriendly management. Pollinators are moisture-sensitive and most active in the morning. Management should maintain water regimes and conserve flowering habitats. To safeguard biodiversity, pesticide application must be minimized during periods of peak activity. Implementing these targeted practices facilitates pollination more effectively than routine broad-spectrum spraying. Furthermore, a diversified approach to pollination strategies is essential for long-term ecosystem resilience. Both Diptera and Hymenoptera contributed to the service. Management should support multiple taxa, not only bees. Habitat features for flies and stingless bees are important. This is especially important in tropical highland agriculture, where climate variability and land-use change can shift pollinator composition over time. Conservation of hedgerows, non-crop vegetation, and semi-natural habitat patches can consequently contribute to stabilizing service delivery while minimizing reliance on synthetic inputs. Supporting H1, Diptera accounted for 58.5% of flower visitors and 76.5% of core pollinator abundance, with a 3.4:1 Diptera: Hymenoptera service ratio contrasting sharply with temperate Allium systems where honeybees typically dominate (Devi *et al.,* 2015; Divija and Kamala Jayanthi, 2022; Eeraerts *et al.,* 2020). This change in taxonomy probably indicates that Calliphoridae are flourishing in warm, humid tropical highland environments (Cook *et al.,* 2020) and Syrphidae benefiting from year-round aphid

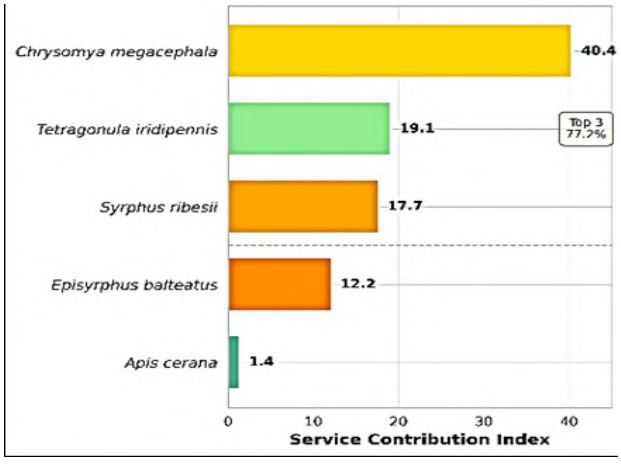

Fig. 3(A)

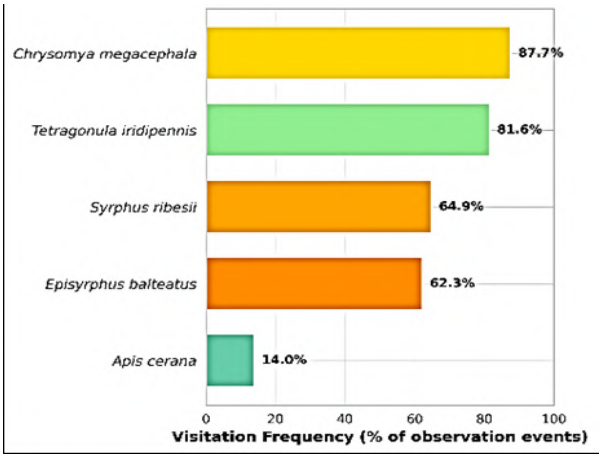

Fig. 3(B)

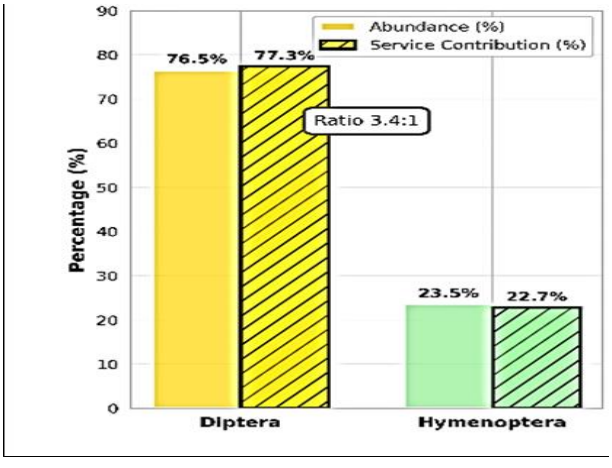

Fig. 3(c)

Fig. 3: Service contribution analysis showing (A) Service index (abundance × consistency); (B) Observation event frequency (n = 114 events); (C) Order comparison: Diptera (3 species) versus Hymenoptera (2 species) with 23.5% and 22.7% respectively

availability for larval development (Davis *et al.,* 2023), while *A. cerana* populations may be constrained by limited nesting sites in intensively managed landscapes. Supporting H4, five key species contributed to 77.2% of pollination services, however, this concentration was counterbalanced by cross-taxonomic redundancy. The two productive Hymenoptera species, *T. iridipennis and A. cerana*, provided vital insurance against threats specific to the order, such as diseases affecting Hymenoptera and differing susceptibilities to pesticides (Kaiser-Bunbury *et al.,* 2017). The Service The present study does not establish a universal minimum threshold of abundance or visitation frequency for optimal production. It does, however, show that a small set of consistently present species accounted for most visitation, suggesting that maintaining these core taxa is a practical management priority. Contribution Index combined abundance and temporal consistency. It identified key pollinator priorities. However, this method does not quantify per-visit pollen efficiency, necessitating validation through seed set experiments. It is important to note that population-level effects can compensate for diminished per-visit efficiency, as increased visitation frequency and consistency often enhance overall service. For example, *C. megacephala* outperformed *A. cerana*. This was due to higher visitation and temporal stability (Cook *et al.,* 2020). Supporting H2, relative humidity showed strong positive correlation with core pollinator abundance ($r = +0.494$, $P < 0.0001$) while temperature showed no significant association despite 12°C thermal variation, contrasting fundamentally with temperature-dominated temperate systems. This pattern likely reflects tropical pollinators operating within their thermal optimum range where performance remains stable across observed temperature variation (Abrahamczyk *et al.,* 2011; Shrestha *et al.,* 2018), while humidity varied substantially (74–93%) and influences multiple aspects of pollination biology including nectar availability, pollen adhesion, and flight energetics. These findings indicate that tropical highland ecosystems are subject to unique vulnerabilities to climate change when compared to temperate areas, as climate forecasts for Southeast Asian tropical highlands predict greater variability in precipitation and possible reductions in humidity during essential flowering periods (Millard *et al.,* 2023). Supporting H3, temporal diversity provided functional redundancy through two distinct mechanisms: morning activity synchronization and seasonal diversity increases. The pronounced morning activity concentration, with 80% of core species showing peak activity at 08:00–10:00 (68.1% of total daily activity), likely reflects shared responses to optimal foraging conditions and provides functional redundancy through response diversity. The narrowly focused *A. cerana* (52.9% of activity at peak period) was complemented by broadly distributed Diptera species, creating insurance against suboptimal conditions (Bascompte and Scheffer, 2026). The seasonal Shannon diversity increase (28.3% from Season 1 to Season 3), alongside stable total abundance and evenness increasing from 0.77 to 0.98, suggests competitive coexistence through temporal niche partitioning rather than exclusion (Domínguez-Garcia *et al.,* 2024). This phenomenon could be enhanced by the extended flowering duration (9 months), leading to temporal resource heterogeneity (Dritz *et al.,* 2023). This functional redundancy explains the system's capacity to maintain stable pollination despite shifting community structure, although extreme precipitation events can drastically alter nectar availability and foraging efficiency (Frigero *et al.,* 2025), suggesting limits to temporal buffering capacity. These findings enable immediate, targeted interventions for tropical highland shallot pollination management. Species-specific habitat management should address distinct core pollinator requirements: composting sites for Calliphoridae larval development, selective aphid tolerance on non-crop vegetation for Syrphidae

(Davis *et al.,* 2023), and preserved trees for stingless bee nesting, with habitat quality improvements proving as effective as quantity increases (Bishop *et al.,* 2025). Temporal pesticide imitations that safeguard the essential morning period of 08:00–10:00, during which 68.1% of activity takes place, can significantly decrease pollinator exposure by more than 50% through afternoon applications or pre-bloom treatments, all while ensuring effective pest management (Karbassioon and Stanley, 2023a; Phan *et al.,* 2025). Long-term monitoring of core pollinator populations, seasonal diversity patterns, and humidity-activity correlations will be essential for detecting early warning signals and triggering adaptive responses in tropical highland agricultural systems facing intensifying climate variability. Critical research gaps include: (1) per-visit pollen deposition experiments to validate Service Contribution Index assumptions and integrate single-visit effectiveness with population-level patterns; (2) landscape-scale studies examining how semi-natural habitat configuration on Diptera population dynamics and the availability of larval resources; (3) experimental humidity manipulations to test causal relationships and identify critical thresholds for pollinator activity; and (4) comparative studies across elevation gradients to test generalizability of humidity-driven patterns.

Limitations and future research

The analysis encompasses visitation patterns and the prioritization of services, yet it does not include direct measures of reproductive success measures such as pollen deposition, fruit set, or seed yield. The nested sampling structure strengthens replication, but the current analysis does not fit a hierarchical mixed-effects model. Future studies should model plot, day, season, and time window as random or nested effects to better partition variance. These improvements would reinforce inference and increase comparability among different sites and cropping systems. Future studies should therefore combine the present community-level approach with experimental tests of humidity thresholds, direct pollination effectiveness assays, and comparative surveys across elevation gradients. Changes in rainfall and temperature in the future may indirectly affect pollinator behavior by modifying the frequency of humid morning conditions. The current study has determined that humidity is the primary factor associated with activity; therefore, alterations in moisture levels are expected to have greater implications than slight increases in temperature within the observed range (Maeda *et al.,* 2023). Cross pollination is likely important for maintaining seed production in shallot, but the present study did not quantify genetic diversity or progeny resilience. Such effects should be tested in future work using genetic markers and seed-performance assays. Conducting this work would aid in identifying whether the moisture-driven patterns identified in this tropical highland context are exclusive to it or can be generalized to other shallot cultivation area. Despite these limitations, the study provides a solid ecological foundation for sustainable pollination management in tropical highland agriculture. Per-visit pollen deposition, seed set, and fruit set were not measured in the present study, so species-specific pollination efficiency cannot be quantified here. Future study should integrate visitation frequency with direct reproductive assays to verify species-level efficacy (Davis *et al*., 2025). This approach underscores that sustainable crop production requires more than just pest mitigation and input regulation; it also necessitates the conservation of pollinator communities and the specific microclimates required for their survival. Although the study covered three flowering seasons, it remains a single-site observational dataset in terms of broader climatic generality. Multi-year monitoring across additional sites and diverse ecological regions will be required to test whether the same humidity activity pattern persists seasonally.

CONCLUSION

1,078 flower visitors representing 12 species, 8 families, and 3 orders were recorded, with Diptera forming the numerically dominant group and Hymenoptera contributing an important but secondary component of the pollinator assemblage. The findings indicate that shallot pollination within this tropical highland ecosystem is supported by a taxonomically diverse assemblage rather than being exclusively bee dependent. This underscores the necessity of incorporating non-bee taxa into frameworks for sustainable agricultural production. Relative humidity emerged as the most important environmental correlate of pollinator abundance, while temperature and wind speed were not significant within the observed range. This finding is especially important for environmentally safe agriculture because it suggests that microclimatic moisture, rather than thermal variation, is the main short-term driver of pollinator activity in this system. The practical implication is clear: irrigation scheduling, moisture-conserving field practices, and conservation of surrounding vegetation may help sustain pollinator visitation without increasing reliance on synthetic inputs. These patterns indicate that service delivery is not uniform throughout the day or across seasons but is instead structured by both floral phenology and pollinator response to local conditions. The observed functional redundancy between Diptera and Hymenoptera, coupled with a temporal increase in community evenness, indicates that the pollination system possesses inherent resilience against the loss of specific pollinator taxa. This is a valuable ecological property for tropical agriculture, where climate variability and field management can alter visitor composition across seasons. The Service Contribution Index identified a small set of core species that accounted for most of the pollination activity, providing a practical basis for prioritizing conservation and management actions. Sustainable management protocols should emphasize irrigation scheduling that maintains morning humidity levels, the preservation of semi-natural vegetation, and the restriction of pesticide applications during periods of maximum pollinator activity. Supporting both fly and bee pollinators will likely improve stability under tropical highland conditions. At the same time, the index should be interpreted as a community-level screening tool rather than a direct measure of pollen deposition or seed set. Despite these limitations, the present study establishes a robust framework for environmentally responsible management by identifying the pollinator species most critical to maintaining service stability under existing field conditions. Protecting pollinator diversity, preserving morning activity windows, and avoiding unnecessary pesticide exposure are likely to improve both ecological sustainability and crop performance.

AUTHOR CONTRIBUTIONS

O. Endarto contributed to the conceptualization and design of the study, acquisition, analysis and interpretation of data, drafting of the manuscript, and statistical analysis. H. Tarno contributed to the conceptualization and design of the study, drafting of the manuscript, and supervision. Nurindah contributed to acquisition of data and analysis and interpretation of data. R. Ubaidillah contributed to acquisition of data, critical revision of the manuscript for important intellectual content, and administrative, technical, or material support. A. Afandhi contributed to critical revision of the manuscript and data interpretation. B.T. Rahardjo contributed to statistical analysis and manuscript preparation/editing.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
°C	Degrees Celsius
ρ	Spearman rank correlation coefficient
°E	Degrees East
°S	Degrees South
A. cerana	*Apis cerana*
C. megacephala	*Chrysomya megacephala*
CV	Coefficient of variation
diel	24-h light–dark cycle
D-1 to D-7	Sampling days 1 to 7
E. balteatus	*Episyrphus balteatus*
Fig.	Figure
h	Hour
H	Kruskal–Wallis test statistic
H'	Shannon diversity index
J'	Evenness index
m	Meter
m²	Square meter
m/s	Meter per second
n	Number of observations/sample size
nr	Near (taxonomic designation)
ns	Not significant
p_i	Proportional abundance of species i
P	Probability value
r	Pearson correlation coefficient
R	Statistical computing software
S-1 to S-3	Flowering seasons 1 to 3
S. ribesii	*Syrphus ribesii*
SCI	Service Contribution Index
sp.	Unspecified species
T. iridipennis	*Tetragonula iridipennis*
V	Cramer's V
χ^2	Chi-square statistic

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CASE STUDY

Tributary-induced heavy metal pollution and water quality dynamics in river systems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Rivers flowing through large industrial cities experience significant anthropogenic pressure that can alter their ecological condition. Tributaries that accept industrial and municipal wastewater typically function as conduits of pollutants, which in turn impacts the water quality of larger rivers upon their merging. The objectives of this study were to evaluate the influence of the Ulba River on the ecological state of the Irtysh River within the city of Ust-Kamenogorsk using hydrochemical parameters, biological indicators, and the composition of bottom sediments.

METHODS: Seasonal water sampling was conducted during 2025 at 4 monitoring sites located along the Ulba River and the Irtysh River before and after their confluence. The study encompassed an examination of salt composition, major anions, heavy metals, nutrients, and markers of organic pollution. The evaluation of water quality through biological means was conducted utilizing biotesting with aquatic organisms and bioindication derived from macrozoobenthos communities.

FINDINGS: The waters of both rivers were characterized as low-mineralized hydrocarbonate waters dominated by calcium. Mineralization in the Ulba River fluctuated between 75 milligrams per liter to 205 milligrams per liter, while in the Irtysh River it varied from 136 milligrams per liter to 211 milligrams per liter. The hydrogen index ranged from 7.2 to 8.3, indicating weakly alkaline conditions. Increased concentrations of heavy metals were recorded near the Ulba Bridge and downstream from the confluence. Manganese in the Ulba River reached 0.037 milligrams per liter, while zinc reached 0.045 milligrams per liter. Following the confluence, the concentration of manganese in the Irtysh River attained 0.014 milligrams per liter, while copper reached a level of 0.0046 milligrams per liter. Nitrate concentrations varied from 0.33 milligrams per liter to 3.59 milligrams per liter. Bottom sediments showed significant accumulation of metals, where cadmium ranged from 6 milligrams per kilogram to 9 milligrams per kilogram and zinc reached 511 milligrams per kilogram, exceeding permissible levels by about 5 times.

CONCLUSION: The findings indicate that the Ulba River functions as a conduit for transit pollution impacting the Irtysh River in the urban environment. Industrial activity within the Ulba basin drives downstream transport of manganese, zinc, and copper and their accumulation in water and bottom sediments, with post-confluence increases in concentrations and sediment enrichment exceeding Kazakhstani permissible levels.

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31	5	6

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INTRODUCTION

Surface water quality is a fundamental component of environmental sustainability and ecosystem stability. River systems are characterized by their dynamic nature, responding to natural processes as well as human-induced factors. Among the key factors affecting river water quality, tributaries play a significant role by transporting water, dissolved substances, and pollutants into main channels (Anh *et al.,* 2023). These inputs can influence the physicochemical equilibrium and lead to variations in the spatial distribution of water composition. Industrial discharge, urban runoff, and land-use changes intensify the pressure on tributary systems (Mkilima *et al.,* 2024; Tang *et al.,* 2024; Zhang *et al.,* 2025). Consequently, contaminants introduced via tributaries can have a substantial impact on the quality of water further downstream. Comprehending these interactions is vital for the effective administration of water resources. It also helps in identifying pollution sources and predicting their environmental impact. Therefore, integrated studies of tributary–river systems are necessary. Such approaches support sustainable environmental planning and protection strategies. Heavy metals such as manganese (Mn), zinc (Zn), and copper (Cu) are among the most critical pollutants in aquatic systems (Singh *et al.,* 2023; Xie *et al.,* 2025; Zhong *et al.,* 2018). These substances are long-lasting, detrimental, and have the potential to build up in sediments and living organisms. Their sources include natural weathering processes and anthropogenic activities, particularly industrial and municipal operations within river basins. In the case of the Ulba River, tributary inflow plays a significant role in influencing the ecological status of the Irtysh River, especially within the urban-industrial zone of Ust-Kamenogorsk, by transferring pollutants and altering downstream water quality. The discharges from industrial and municipal sources within the Ulba River basin greatly affect the transport, transformation, and bioavailability of heavy metals and nutrients in interconnected river systems. Once introduced into rivers, heavy metals have the potential to be carried over extensive distances. This process leads to transit pollution, where contaminants from tributaries influence downstream sections. The confluence zone between tributaries and main rivers acts as a critical control point, where changes in hydrodynamics, sediment interactions, and chemical conditions drive shifts in water quality, ecological stress, and contaminant redistribution. The transport of heavy metals is determined by several factors, including the hydrogen Hydrogen ion concentration (pH) level and the concentration of organic matter. Seasonal fluctuations likewise impact their distribution and concentration in water bodies. Elevated levels of these metals pose risks to aquatic ecosystems and human health (Hama Aziz *et al.,* 2023). Therefore, their monitoring is essential for environmental assessment. Comprehending their actions aids in formulating efficient pollution management strategies. Hydrochemical parameters are widely used to characterize water quality and assess environmental conditions (Arpine and Gayane, 2016; Patil *et al.,* 2022; Subba Rao *et al.,* 2024). Indicators such as pH, mineralization, major ions, and biochemical oxygen demand over five days (BOD_5) provide essential information. These parameters indicate the influence of natural processes as well as external pollution contributions. In addition to chemical analysis, biological indicators offer insights into ecological health. Organisms such as Daphnia magna are used in biotesting to evaluate water toxicity (Jeong *et al.,* 2024; Jeong and Simpson, 2019). Macrozoobenthos communities serve as reliable indicators of long-term environmental conditions (Ndale *et al.,* 2021; Rodrigues *et al.,* 2023). Their structure and diversity respond sensitively to pollution levels. Combining hydrochemical and hydrobiological methods improves assessment accuracy. This cohesive method offers a broader insight into aquatic systems. It also allows better

evaluation of ecological risks and environmental changes. Sediments play a crucial role in the dynamics of aquatic ecosystems (Hauer *et al.,* 2018). They function as receptacles for pollutants, encompassing heavy metals along with other types of contaminants. Over time, sediments accumulate substances that reflect the history of pollution in a river system (Alfee and Bloor, 2025; Jaskuła *et al.,* 2021). However, under changing environmental conditions, these pollutants can be released back into the water. This procedure leads to additional pollution and extends ecological hazards. Sediment composition provides valuable information about long-term contamination trends. It also influences nutrient cycling and biological activity in aquatic environments. The interaction between water and sediments is therefore highly dynamic (Madsen *et al.,* 2001). Assessing sediment quality is essential for a complete understanding of pollution processes (Xu *et al.,* 2018). Incorporating sediment analysis improves the dependability of water quality studies. Seasonal variability significantly influences the behavior of pollutants in river systems. Changes in flow rate, temperature, and precipitation affect pollutant concentration and distribution. During periods of low flow, diminished dilution results in elevated levels of contaminants. Conversely, conditions of high flow may dilute pollutants while simultaneously increasing their transport. These variations create complex spatial and temporal patterns in water quality. Biological processes within aquatic ecosystems also vary with seasons. Temperature changes influence chemical reactions and biological activity (Kazmi *et al.,* 2022). Consequently, it is essential to conduct multi-seasonal monitoring for precise evaluation. Neglecting seasonal factors might result in insufficient incomplete conclusions. Temporal analysis is thus a key component of environmental studies. Despite advances in monitoring techniques, data interpretation often relies on descriptive approaches. Such methods may not fully capture complex relationships among variables. Integrating statistical and graphical analyses facilitates better interpretation of results. This approach boosts the objectivity and trustworthiness conclusions. Modern analytical approaches are therefore essential in environmental research. They support more informed decision-making in water management. Particular attention is given to Mn, Zn, and Cu as key pollutants. Spatial and seasonal variations of these elements are examined. The study further evaluates the extent of degree pollution that arises from tributary inflow. Statistical tools, including correlation analysis and boxplots, are applied for data interpretation. This approach improves the understanding of relationships among environmental variables. The findings provide insights into pollution mechanisms in river systems. They also support the development of effective management strategies. In conclusion, the study plays a significant role in the protection of sustainable water resource protection. The aims of this study are to evaluate the influence of a tributary on river water quality and ecological status. The study integrates hydrochemical, hydrobiological, and sediment analyses. This study has been carried out in Irtysh–Ulba River system in the industrial region of Ust-Kamenogorsk, Kazakhstan in 2025.

MATERIALS AND METHODS

Study area and monitoring design

The study was conducted within the Irtysh–Ulba River system in the industrial region of Ust-Kamenogorsk, where the confluence of a major river and its tributary forms a hydrochemically complex mixing zone influenced by metallurgical and municipal discharges. The examined stretch of the Irtysh River spans roughly 30 Kilometer (km) within the city limits, featuring an average width of 168 m and depths varying from 2.65 to 4.0 m. The Ulba River, a right-bank tributary approximately 100 km in length with a catchment area of 4,990 km², represents a major pathway for industrial effluents entering the Irtysh system. A monitoring network comprising of four sampling

stations was created to illustrate the longitudinal gradient of pollutant transport. Station U1 was located upstream on the Ulba River to represent background conditions with minimal direct industrial influence. Station U2 was situated on the Ulba River roughly 1–2 km upstream of the confluence to evaluate the combined effects of industrial and municipal discharges. Station I1 was located on the Irtysh River upstream of the confluence to represent baseline conditions of the main river. Station I2 was positioned 3–5 km downstream of the confluence, beyond the estimated complete mixing length derived from average flow velocity and channel geometry, thereby ensuring representative post-mixing conditions. The sites selected were influenced by hydrological and geomorphological factors, which encompass flow velocity, channel morphology, proximity to discharge points, and anticipated mixing behavior inferred from hydraulic characteristics. Despite the spatial resolution is restricted to four stations, this design was opted for to enable a process-based evaluation of pollutant transfer at the junction of the tributary and the main river, instead of providing a detailed mapping of spatial heterogeneity along the entire reach. Water sampling was conducted in March, July, September, and December 2025 to represent key hydrological phases, including spring high flow associated with snowmelt, summer low flow conditions, autumn transitional flow, and winter low flow under ice-influenced conditions. These sampling intervals were chosen to reflect the prevailing seasonal fluctuations in dilution and concentration processes. While this temporal resolution captures broad seasonal trends, it does not resolve short-term pollution events, which is acknowledged as a limitation. Bottom sediment samples were obtained in June 2025 during periods of relatively stable hydrological conditions to ensure a representative assessment of contaminant accumulation. This approach allows evaluation of spatial differences in sediment contamination but does not support temporal trend analysis (Fig. 1).

Sampling procedures and field measurements

Surface water samples were collected from a depth of 0–0.5 meter (m) using acid-washed polyethylene bottles. At each station, three independent replicate samples were collected and analyzed separately to ensure statistical reliability. Field duplicates and blanks were compiled to evaluate the possibility of contamination during sampling and transport. Bottom sediment samples were collected from the upper 0–10 Centimeter (cm) layer using a stainless-steel tubular corer, targeting the biologically active zone where recent deposition and contaminant interactions are most significant. Sediment samples were homogenized, placed in pre-cleaned containers, and stored at a temperature of 4 degrees Celsius (°C) prior to analysis. Immediately following sample collection, in situ measurements of water temperature, pH, dissolved oxygen, and electrical conductivity were carried out using calibrated multiparameter probes. Calibration was conducted prior to each field campaign using certified standard solutions. The performance of the instrument was confirmed by conducting repeated measurements at designated stations. All samples were transported to the laboratory under cooled conditions and processed within recommended holding times to maintain chemical integrity.

Laboratory analysis of physicochemical and hydrobiological parameters

Major ions, including calcium ion (Ca^{2+}), magnesium ion (Mg^{2+}), sodium ion (Na^{+}), hydrocarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), and Chloride (Cl^{-}), were determined using standard titrimetric and ion chromatographic methods to characterize hydrochemical facies and mineralization. Nutrients, including ammonium (NH_4^{+}), nitrite (NO_2^{-}), nitrate (O_3^{-}), phosphate (PO_4^{3-}), total phosphorus, and dissolved iron (Fe), were measured using spectrophotometric methods based on standard colorimetric procedures. The incorporation of iron was warranted due to its ecological significance and its

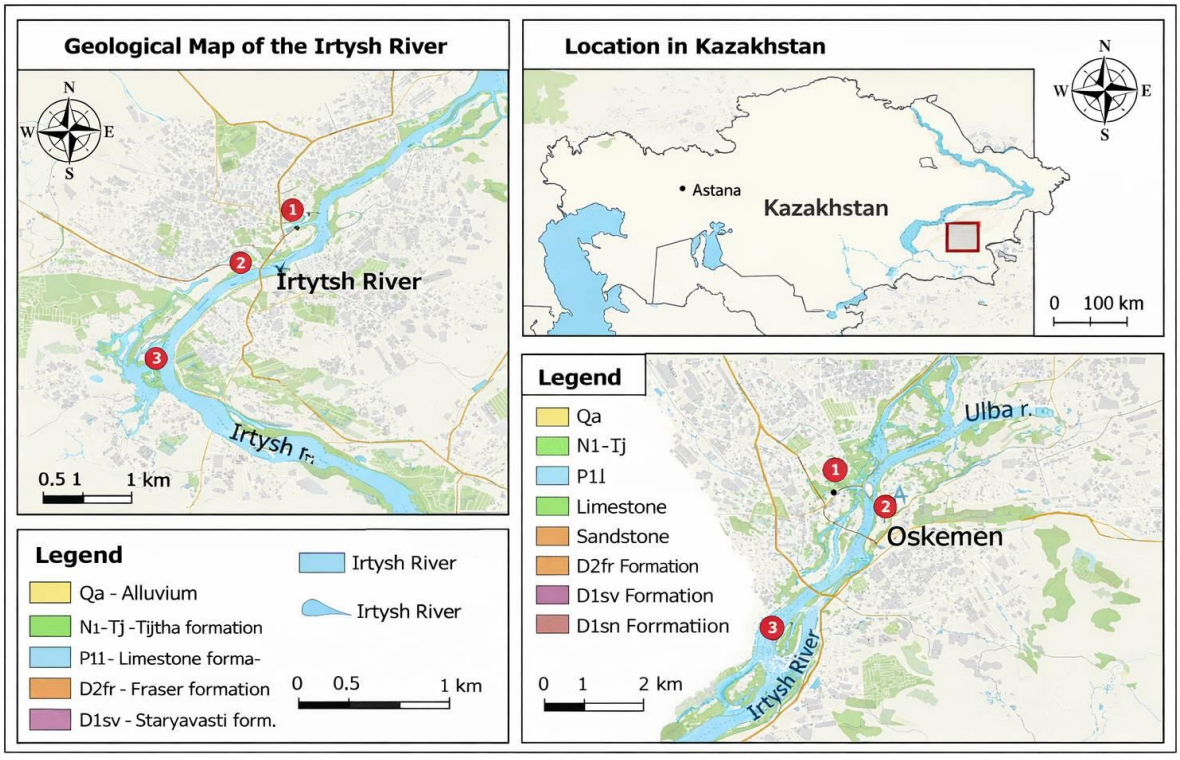

Fig. 1: Geographical location of the study area in the Irtysh–Ulba River system of Ust-Kamenogorsk, Kazakhstan

responsiveness to redox conditions, especially in river systems affected by industrial and urban discharges. Biochemical oxygen demand over five days (BOD_5) and chemical oxygen demand (COD) were analyzed to assess organic pollution and the balance between biodegradable and non-biodegradable organic matter. Heavy metals, specifically manganese (Mn), zinc (Zn), and copper (Cu), were selected based on their association with regional metallurgical activities, contrasting geochemical behavior, and ecological significance related to toxicity and bioaccumulation. Water samples were acidified with nitric acid to pH below 2 immediately after collection to preserve dissolved metal fractions. Both water and sediment samples were subjected to microwave-assisted acid digestion utilizing a blend of concentrated nitric acid and hydrochloric acid, conducted under regulated temperature and pressure conditions. Metal concentrations were determined using atomic absorption spectrometry. Calibration was performed using multi-point standard curves with correlation coefficients exceeding 0.995. Detection limits for each analyte were determined before the analysis was conducted. Analytical precision was maintained within ±5 percent (%) based on replicate measurements, and accuracy was verified using certified reference materials with recovery rates ranging from 85% to 110%. Quality assurance and quality control processes encompassed the examination of procedural blanks, duplicate samples, and calibration verification standards during each analytical run to ensure reliability and reproducibility of results.

Biological assessment and integration with physicochemical data

Macrozoobenthos samples were collected using a standard benthic sampler with consistent sampling effort across stations. Organisms were identified to family or genus level using taxonomic

keys. The Woodiwiss biotic index was determined by analyzing taxa composition, abundance, and their sensitivity to pollution, thereby delivering a comprehensive assessment of ecological status. To ensure consistency with hydrochemical data, macrozoobenthos data corresponding to comparable seasonal periods were used. Acute toxicity tests were conducted using Daphnia magna under controlled laboratory conditions. Test organisms were subjected to water samples for periods of 24 and 48 hours at a temperature of 20 ± 2°C, maintained under a regulated light environment. Each test was performed in triplicate and included control samples. Mortality rates were recorded and used to assess the combined toxic effects of contaminants. Physicochemical and biological datasets were interpreted together to evaluate ecological status. The concentrations of pollutants were characterized by water chemistry, whereas sediment data demonstrated accumulation and potential secondary sources. Macrozoobenthos indicated long-term ecological consequences, and toxicity tests supplied information regardingshort-term biological responses.

Sediment quality assessment

The evaluation of sediment contamination was conducted using sediment quality guidelines, which encompass threshold effect concentrations and probable effect concentrations, in order to evaluate ecological risk. Measured concentrations were also compared with regional geochemical background values to determine enrichment levels and anthropogenic influence.

Statistical analysis, correlation assessment, and data visualization

Descriptive statistics, including mean, median, standard deviation, and range, were calculated for all variables. Pearson correlation analysis was used to evaluate relationships between heavy metals and physicochemical parameters, with statistical significance defined at $p < 0.05$. Seasonal differences were interpreted in relation to hydrological conditions, with higher flows associated with increased dilution and transport capacity, whereas low-flow conditions were associated with higher pollutant concentrations. Boxplots were employed to illustrate the distribution of heavy metal concentrations across various sampling locations and seasons. All statistical analyses were performed using R (version 4.3.1) and IBM statistical package for the social sciences (SPSS) statistics (version 26).

Methodological integration and justification

The methodological framework encompasses hydrological conditions, water chemistry, sediment contamination, and biological indicators to furnish a detailed appraisal of ecological status. This combined approach allows evaluation of pollutant transport, accumulation, and biological effects, which is particularly important in river confluence zones where mixing processes strongly influence environmental conditions.

RESULTS AND DISCUSSION

All reported values represent the mean of three replicate measurements, with relative standard deviations generally within 3–7%, indicating good analytical precision. The degree of variability between replicates was found to be the least for major ions, in contrast to trace metals, which exhibited higher variability, particularly in areas impacted by industrial discharge. Statistical comparison using analysis of variance confirmed that differences between upstream and downstream sites for Mn and Zn were significant at $p < 0.05$, particularly during winter and spring conditions.

Salt composition and hydrochemical characteristics

The hydrochemical composition of the Ulba River demonstrates clear seasonal variability associated with changes in hydrological conditions and sources of river feeding. Throughout the

observation period, the concentration of dissolved ions ranged from 75 to 205 milligrams per liter (mg/L), with the lowest concentrations observed in spring as a consequence of dilution from snowmelt runoff, and the highest concentrations noted in autumn when there is a reduction in river discharge and an increase in groundwater influence. Water hardness ranged from 1.07 to 2.60 milliequivalent per liter (meq/L), indicating that the river water can be classified as soft. The ionic composition is dominated by calcium and magnesium, with calcium concentrations ranging from 15.6 to 35.3 mg/L and magnesium from 2.8 to 10.2 mg/L. Calcium exceeded magnesium by approximately three to five times, which is typical for river systems with hydrocarbonate calcium water composition. The hydrogen index demonstrated seasonal variability, characterized by near neutral conditions throughout winter and spring, and weakly alkaline conditions during the summer and fall seasons. Similar hydrochemical characteristics were observed in the Irtysh River at the investigated monitoring sites. The pH values ranged from 7.72 to 8.21, reflecting stable weakly alkaline conditions associated with carbonate equilibrium processes. Hydrocarbonates dominate the anionic composition and exhibit seasonal variability, with higher concentrations observed during the spring period. Calcium is also the dominant cation in the Irtysh River, with concentrations ranging from 20.4 to 38.5 mg/L, while magnesium and sodium concentrations varied between 3.9 to 7.8 mg/L and 5.6 to 8.9 mg/L respectively. Total mineralization in the Irtysh River fluctuated from 136 to 211 mg/L influenced by seasonal hydrological conditions, and water hardness ranged from 1.39 to 2.08 meq/L, indicating that the river water is classified as soft. These hydrochemical characteristics reflect the influence of both natural hydrological processes and local anthropogenic factors within the studied river basin (Cao *et al.,* 2026; Li *et al.,* 2025) (Table 1).

Main anions and heavy metals

During the study period, the concentrations of major anions, particularly chlorides and sulfates, in both rivers remained generally low, indicating limited overall mineral pollution. An observable surge in these ions was recorded close to the Ulba Bridge area, which is related to the outflow of treated industrial wastewater and demonstrates localized human influence. In the Ulba River, sulfate concentrations showed clear seasonal variability, reaching a maximum value of 32.6 mg/L in autumn and declining to a minimum of 5.6 mg/L in spring. Chloride concentrations also fluctuated throughout the year, ranging from 1.1 to 10.3 mg/L in winter and decreasing to as low as 0.5 mg/L during summer. Among the anions, hydrocarbonates were dominant in the Ulba River system, with concentrations varying between 27.5 and 104 mg/L. This dominance highlights the significance of carbonate weathering processes in influencing the hydrochemical composition. Seasonal hydrological changes, including variations in discharge and temperature, likely contributed to the observed fluctuations. The comparatively low levels of chlorides and sulfates indicate that dilution processes are largely effective throughout most of the year (Szalińska *et al.,* 2025). However, localized increases point to the need for continued monitoring of industrial impacts. Overall, the Ulba River demonstrates both natural geochemical control and measurable human influence. In the Irtysh River, the levels of chloride consistently remained low and stable at both monitoring locations, fluctuating between 2.8 and 6.8 mg/L during the entire study period. The average chloride concentration was approximately 3.7 mg/L, indicating minimal external contamination and relatively uniform water quality conditions. Sulfate concentrations were moderately higher than chlorides but still remained within a controlled range of 16.7 to 30.1 mg/L. These values indicate a consistent hydrochemical regime with minimal seasonal fluctuations when compared to the Ulba River.

Table 1: Salt composition of water in the Irtysh and Ulba Rivers within Ust-Kamenogorsk (2025)

Sampling Site	Season	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Hardness (mg/L)	Mineralization (mg/L)
Ulba River (Kamenny Karyer settlement)	Winter	6.96	15.6	3.5	2.6	3.5	1.07	97
	Spring	7.23	17.8	2.8	2.4	0.5	1.12	75
	Summer	8.36	20.9	3.4	3.1	0.6	1.32	105
	Autumn	8.29	32.1	10.2	3.5	0.8	2.44	193
Ulba River (1 km upstream from mouth; 0.36 km downstream of Ulba Bridge)	Winter	7.36	25.6	4	4	1	1.61	142
	Spring	7.29	17.6	3.9	6.1	0.8	1.2	90
	Summer	8.08	23.1	3.8	4.4	1.3	1.47	124
	Autumn	8.33	35.3	10.2	4.5	0.4	2.6	205
Irtysh River (0.5 km downstream from Kondensatorny Plant discharge)	Winter	7.83	22.8	4.4	8.2	1.5	1.53	148
	Spring	8.06	38.5	6.3	8.9	2.44	1.99	211
	Summer	8.02	24.5	4.4	8.2	1.58	1.39	151
	Autumn	7.68	20.4	7.5	6.3	0.8	1.64	144
Irtysh River (3.2 km downstream from Ulba confluence)	Winter	7.72	23.6	4.5	8.6	1.5	1.55	149
	Spring	7.51	28.5	3.9	5.6	1.6	1.74	142
	Summer	8.21	25.8	4.5	6.7	1.1	1.66	136
	Autumn	7.78	26.5	7.8	6.5	0.6	2.08	173

The consistency in ion concentrations reflects the larger volume and higher dilution capacity of the Irtysh River. Natural geological factors appear to play a dominant role in determining its chemical composition. Human-induced effects, although evident, are not as significant as those found in smaller tributaries. Seasonal changes did not significantly alter the overall ionic balance in the river. This stability highlights the buffering capacity of the Irtysh River system. Overall, the data suggest that the Irtysh River exhibits a fairly stable water chemistry with only slight variations (Table 2).

Spatial gradient and confluence impact

To explicitly evaluate the role of the Ulba River in modifying the hydrochemical regime of the Irtysh River, a comparative analysis of upstream (I1) and downstream (I2) conditions was performed. The findings demonstrate quantifiable modifications in multiple parameters following the confluence, thereby affirming the Ulba River's contribution as a source of pollutant influx. For manganese, concentrations increased from 0.008 mg/L at the upstream Irtysh site (I1, winter) to 0.014 mg/L at the downstream site (I2), corresponding to an increase of approximately 75%. A similar pattern was observed in spring, where Mn concentrations increased from 0.0056 mg/L to 0.014 mg/L, representing an increase of more than 100%. Zinc concentrations also showed consistent enrichment downstream of the confluence, increasing from 0.002–0.0038 mg/L at I1 to 0.011–0.018 mg/L at I2 depending on season, indicating a 3–5-fold increase. Copper displayed more gradual variations yet continued to demonstrate a steady increase downstream, especially in the spring season, where levels rose from 0.0013 mg/L to 0.0046 mg/L. These results demonstrate that the Ulba River significantly contributes to the transfer of heavy metals into the Irtysh River. The magnitude of increase varies by element and season, reflecting differences in geochemical behavior and hydrological conditions. The confluence zone functions as an essential control point, where contaminant inflows from the tributary change the chemical structure and ecological environment of the main river.

Heavy metal distribution in water

Trace elements represent a diverse category of chemical constituents found in natural bodies. These elements are inherent components of aquatic ecosystems and are crucial for various biological and biochemical functions. Nevertheless, increased levels of heavy metals, especially those resulting from human activities, can have detrimental impacts and disturb the stability of ecosystems (El-Sharkawy *et al.,* 2025).

Table 2: Content of main anions and heavy metals (mg/L) in surface waters of the Irtysh and Ulba Rivers within Ust-Kamenogorsk (2025)

Sampling site	Season	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	Mn (mg/L)	Zn (mg/L)	Cu (mg/L)
Ulba River (Kamenny Karyer settlement)	Winter	61	9.1	1.1	0.016	0.019	0.003
	Spring	42.7	5.6	1.3	0.0062	0.001	0.0043
	Summer	54.9	10.4	0.5	0.011	0.013	0.0025
	Autumn	104	25.1	4.4	0.007	0.023	0.0016
Ulba River (1 km upstream from mouth; 0.36 km downstream of Ulba Bridge)	Winter	79.3	12.8	10.3	0.037	0.031	0.003
	Spring	27.5	19.2	2.5	0.011	0.017	0.0032
	Summer	64.1	15.9	2.1	0.014	0.02	0.0026
	Autumn	97.6	32.6	9.6	0.017	0.045	0.0019
Irtysh River (0.5 km downstream from Kondensatorny Plant discharge)	Winter	88.5	19.2	3.3	0.008	0.002	0.003
	Spring	120	28.8	4.7	0.0056	0.001	0.0013
	Summer	79.3	21.5	3.2	0.002	0.0038	0.0018
	Autumn	70.2	26.9	6	0.004	0.002	0.0015
Irtysh River (3.2 km downstream from Ulba confluence)	Winter	85.4	20.2	3.9	0.014	0.011	0.004
	Spring	79.3	16.7	4.5	0.014	0.018	0.0046
	Summer	70.2	19.9	2.8	0.0095	0.014	0.0024
	Autumn	85.4	30.1	6.8	0.001	0.018	0.0019

In this study, Mn, Zn, Cu, and Cd were selected due to their strong association with emissions from non-ferrous metallurgy and their ecological relevance in industrially impacted river systems. The findings demonstrate significant spatial and seasonal fluctuations in metal concentrations. In the Ulba River, Mn concentrations ranged from 0.011 to 0.037 mg/L near the Ulba Bridge, with winter values exceeding permissible limits by approximately threefold, while in summer and autumn exceedances averaged around 15 percent (%). In the Irtysh River, Mn concentrations reached 0.014 mg/L downstream of the Ulba confluence during winter and spring, exceeding standards by about 14%, indicating that the Ulba River acts as a significant source of Mn input. Zn concentrations in the Ulba River ranged from 0.001 to 0.023 mg/L at the reference site, surpassing allowable limits by about twofold, while consistently elevated levels, reaching a maximum of 0.045 mg/L in autumn, were observed near the Ulba Bridge. Cu concentrations ranged from 0.0025 to 0.0043 mg/L in the Ulba River and from 0.0013 to 0.0046 mg/L in the Irtysh River, exceeding regulatory thresholds throughout all seasons. The heat map visualization emphasizes distinct seasonal trends and specific contamination hotspots, showing that the highest concentrations of Mn and Cu observed in winter at the downstream impact location, while the lowest concentrations are typically noted in autumn at the more distal site. Compared to background conditions, manganese and zn concentrations at the impacted site exceeded normative values year-round, while elevated levels at the downstream Irtysh site further confirm transboundary influence. Cu exceedances remained relatively stable, with a notable increase in spring at the downstream site (Fig. 2).

Seasonal patterns of heavy metals

The distribution of heavy metals across seasons exhibits evident and organized variability, which mirrors the joint effects of hydrological factors, industrial discharge, and natural geochemical processes throughout the year. Analysis of the average concentrations indicates that the highest levels of heavy metals are consistently observed during the winter season, which can be attributed to reduced river discharge, limited dilution capacity, and an increased relative contribution of wastewater under low-flow conditions. During this period, the buildup of pollutants is more evident because of ice cover and diminished mixing processes, resulting in increased concentrations in the water column.

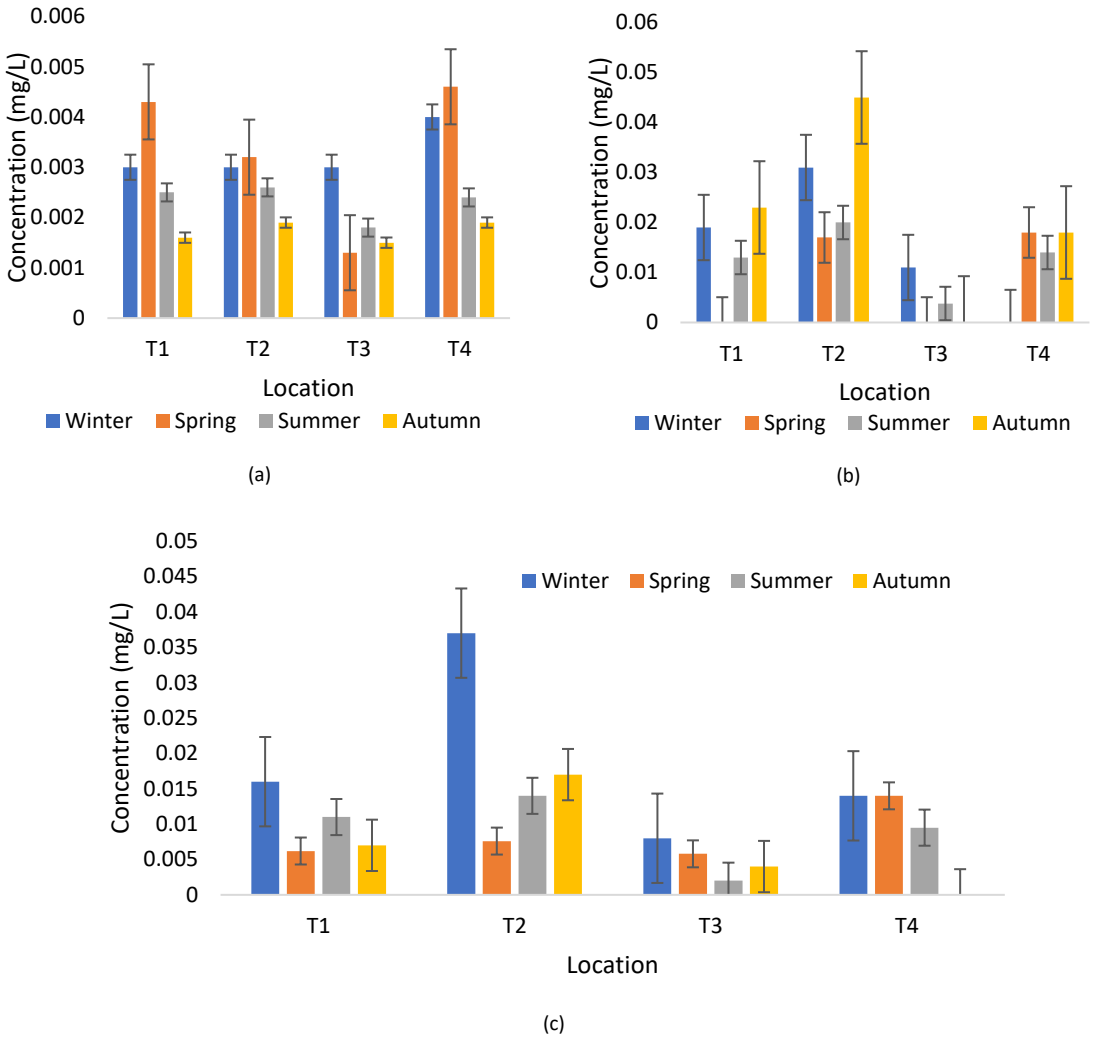

Fig. 2: Contamination by seasons across monitoring sites (a) Cu (b)Zn (c) Mn

The reduced self-purification capacity of the river system further contributes to the persistence of contaminants during this season. Conversely, the spring season brings about heightened runoff as a result of snowmelt, which facilitates the movement of dissolved substances while simultaneously enhancing dilution conditions. Summer is typically characterized by relatively stable flow and moderate dilution, while autumn may show transitional behavior depending on precipitation patterns. These seasonal contrasts clearly demonstrate the dependence of heavy metal concentrations on hydrological regime and climatic factors. Variations in flow velocity, water temperature, and sediment interaction also influence the mobility and distribution of metals (Poot *et al.,* 2007). Consequently, fluctuations in concentration over time are influenced not only by external factors but also by internal river dynamics. Understanding these dynamics is essential for accurate interpretation of monitoring data. The spatial and temporal variability of these metals is visually supported by graphical representations of seasonal trends (Fig. 3).

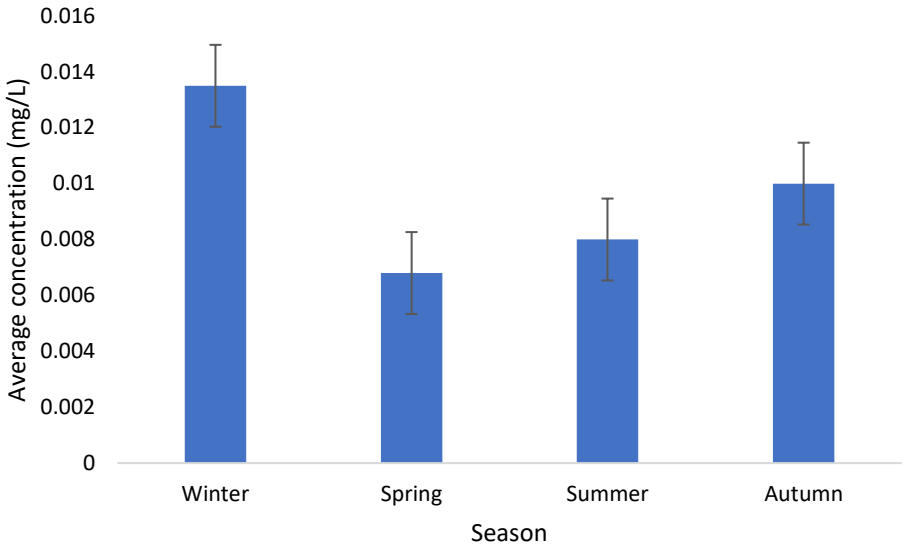

Fig. 3: Average concentration of heavy metals by seasons

The overall ranking of metals based on their average concentrations follows the order Zn greater than Mn greater than Cu, highlighting Zn as the dominant contaminant in the study area. This hierarchy illustrates the degree of human-induced contributions as well as the geochemical characteristics of each element within aquatic ecosystems. Zn concentrations tend to peak during winter and autumn, which may be associated with with increased industrial discharge and reduced dilution capacity during these periods. Mn concentrations show a clear maximum during winter, consistent with stagnant hydrological conditions and the possible release of Mn from bottom sediments under low-oxygen conditions. In contrast, Cu concentrations reach their maximum levels in the spring season, likely owing to heightened surface runoff and the movement of pollutants from adjacent soils and urban areas (Maphanga *et al.,* 2024). Seasonal fluctuations in redox conditions and pH may also influence the speciation and bioavailability of these metals. These observed patterns emphasize the importance of seasonal dynamics in controlling heavy metal distribution. They also emphasize the necessity for ongoing and seasonally adjusted monitoring programs. Such an approach allows for more accurate assessment of ecological risks and pollution sources. The distribution patterns of individual metals are illustrated in detail in Fig. 4.

Correlation analysis

Pearson correlation analysis revealed statistically significant relationships between heavy metals and key physicochemical parameters. Manganese demonstrated a negative relationship with dissolved oxygen ($r = -0.68$, $p < 0.05$), suggesting enhanced mobility in conditions of reduced oxygen conditions, particularly during winter. Zinc exhibited a positive correlation with mineralization ($r = 0.72$, $p < 0.05$) and sulfate concentrations ($r = 0.65$), suggesting association with industrial effluent inputs. Copper showed moderate correlation with organic matter indicators, including COD ($r = 0.58$), indicating partial association with organic complexes. No strong correlation was observed between heavy metals and pH within the observed range, reflecting relatively stable weakly alkaline

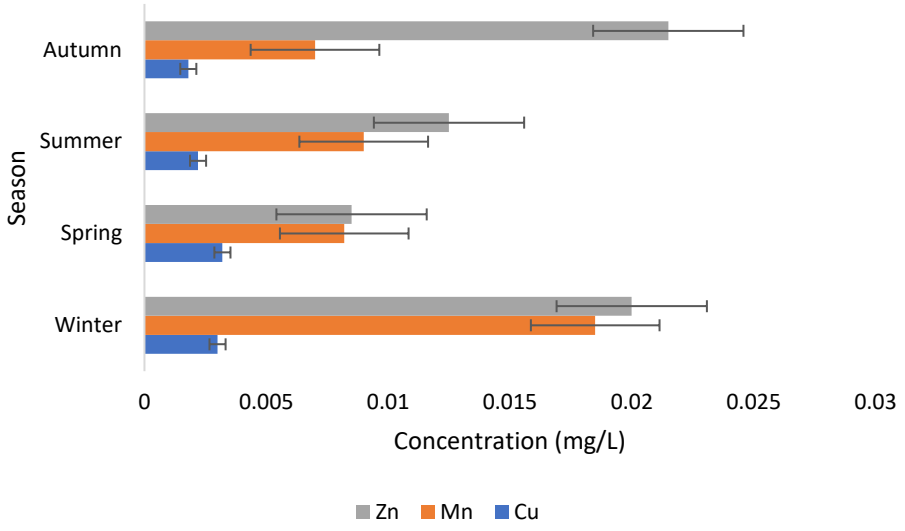

Fig. 4: Analysis of seasonal distribution of heavy metals

conditions across the study area. These connections validate that both geochemical processes and anthropogenic inputs affect the distribution of metals within the river system (Table 3).

Organic matter, nutrient, and iron concentrations

In the Ulba and Irtysh Rivers, the dynamics of organic matter and nutrient levels indicate the presence and behavior of nitrogen and phosphorus compounds, essential for fostering biological productivity in aquatic ecosystems (Joel Mihale, 2015). Among the nitrogen species assessed, nitrates were the most prevalent, exhibiting concentrations between 0.33 to 3.59 mg/L. The highest total phosphorus concentration (0.018 mg/L) was recorded in the Irtysh River downstream of the Ulba confluence during spring, although this increase was not directly linked to inflow from the Ulba River. Phosphate concentrations ranged from 0.011 to 0.14 mg/L in the Ulba River and from 0.009 to 0.049 mg/L in the Irtysh River. Iron levels exceeded the permissible limit for fishery water bodies (0.1 mg/L) during spring, with recorded concentrations of 0.25 mg/L at the Ulba upstream site, 0.27 mg/L near the Ulba Bridge, and 0.20 mg/L in the Irtysh River after the confluence, indicating a measurable influence of the Ulba River on iron levels in the Irtysh. Dichromate oxidizability (COD) ranged from 6.5 to 11 mg/L in the Ulba River and from 5.9 to 8.1 mg/L in the Irtysh River, classifying both as “polluted” waters; however, based on BOD_5 values, both rivers fall under the “clean waters” category, suggesting relatively low concentrations of readily biodegradable organic matter (Table 4).

Water biotesting

Biological indicators of water quality, particularly water biotesting, emphasize the significance of biological responses in demonstrating ecosystem stability amidst anthropogenic pressure (Qu and Peng, 2025). The toxicity of river waters was evaluated using Daphnia magna as a test organism, with a total of 48 water samples analyzed during the study period. The analysis revealed that the test organisms did not exhibit any acute toxic effects, although a minor level of mortality was documented in 20 samples, with percentages ranging from 3.3% to 20%. The

Table 3: Pearson correlation coefficients (r) between heavy metals and selected physicochemical parameters ($p < 0.05$)

Parameter	Mn (mg/L)	Zn (mg/L)	Cu (mg/L)
Dissolved Oxygen (DO)	−0.68	−0.21	−0.34
Mineralization	0.41	0.72	0.29
Sulfate (SO_4^{2-})	0.38	0.65	0.26
COD	0.22	0.33	0.58
pH	−0.12	0.09	0.15

Table 4: Content of organic and nutrient substances (mg/L) in surface waters of the Irtysh and Ulba Rivers within Ust-Kamenogorsk

Sampling site	Season	COD	BOD_5	NH_4^+	NO_2^-	NO_3^-	P (total)	Fe	PO_4^{3-}
Ulba River (Kamenny Karyer settlement)	Winter	11	1.66	0.3	0.04	3.32	0.008	0.19	0.024
	Spring	7.4	2.96	0.12	0	0.33	0.006	0.25	0.016
	Summer	7.1	2.33	0.12	0	0.44	0.005	0.03	0.012
	Autumn	6.5	1.1	0.08	0.005	1.62	0.004	0.07	0.011
Ulba River (1 km upstream of mouth; 0.36 km downstream of Ulba Bridge)	Winter	10.8	1.8	0.15	0.05	3.59	0.007	0.16	0.017
	Spring	8.2	2.38	0.38	0	1.26	0.005	0.27	0.014
	Summer	7.6	2.63	0.13	0.011	0.58	0.006	0.03	0.011
	Autumn	6.7	2.44	0.06	0.006	1.86	0	0.04	0.013
Irtysh River (0.5 km downstream of Kondensatorny Plant discharge)	Winter	6.7	1.55	0	0.01	1.37	0.004	0.03	0.004
	Spring	6.3	2.3	0.11	0.002	0.57	0.009	0.05	0.009
	Summer	6	2.33	0.14	0.008	0.4	0.006	0.15	0.006
	Autumn	8.3	1.86	0.09	0.003	1.17	0.004	0.07	0.011
Irtysh River (3.2 km downstream of Ulba confluence)	Winter	8.1	2.15	0.35	0	0.93	0.004	0.03	0.009
	Spring	7.9	2.22	0.23	0	0.37	0.018	0.2	0.049
	Summer	5.9	2.18	0.08	0.007	0.36	0.007	0.1	0.012
	Autumn	8	1.85	0.1	0.003	1.64	0.004	0.09	0.011

average mortality of Daphnia magna in the Irtysh River ranged from 0.3% to 5.0%, while in the Ulba River it ranged from 1.9% to 5.8%. Despite these observations, all tested waters were classified as non-toxic in terms of acute toxicity thresholds (Table 5). When considered alongside the hydrochemical data, the lack of acute toxicity corresponds to relatively moderate concentrations of heavy metals (Mn, Zn, Cu) and nutrients, which which typically remained below levels established to trigger short-term lethal consequences. However, the consistently higher mortality rates observed in the Ulba River compared to the Irtysh River are consistent with the elevated concentrations of Zn and Mn recorded downstream of industrial influence zones, indicating a sub-lethal biological response to chemical stressors. These results indicate that although chemical contamination does not lead to immediate toxicity, it can still cause observable biological stress, thereby emphasizing the necessity for a combined chemical–biological evaluation when assessing the ecological condition of the river system.

Bioindication using macrozoobenthos

Bioindication using macrozoobenthos is an essential component of modern environmental monitoring, as aquatic organisms integrate and reflect the cumulative impacts of environmental factors on water quality over time (Chazanah *et al.,* 2020). Macrozoobenthos communities serve as highly dependable indicators because their taxonomic composition, abundance, and biomass to long-term ecological changes. In this study, macrozoobenthos data from Kazhydromet monitoring programs for the period 2021–2025 were analyzed. The results show that the Irtysh

Table 5: Results of biotesting for acute toxicity of surface waters of the Irtysh and Ulba Rivers

Site	01	02	03	04	05	06	07	08	09	10	11	12
Ulba River (Kamenny Karyer settlement)	6.7	10	3.3	0	0	0	0	0	0	3.3	0	0
Ulba River (1 km upstream of mouth; 0.36 km downstream of Ulba Bridge)	20	20	13.3	0	0	0	0	3.3	0	6.7	6.7	0
Irtysh River (0.5 km downstream of Kondensatorny Plant discharge)	0	0	0	0	0	0	3.3	0	0	0	0	0
Irtysh River (3.2 km downstream of Ulba confluence)	10	6.7	6.7	3.3	6.7	0	6.7	0	3.3	0	13.3	3.3

River within Ust-Kamenogorsk was consistently classified as Class III ("moderately polluted") based on macrozoobenthos indicators. In contrast, the upstream section of the Ulba River displayed Class II ("clean") water quality, while downstream of the industrial discharge zone, conditions deteriorated to Class III ("moderately polluted"). Overall, the macrozoobenthos indicate that the ecological conditions in the Irtysh River have remained relatively stable over the last five years (Table 6).

Sediment contamination

The sediment contamination is a critical aspect of aquatic ecosystem assessment, as sediments function both as sinks and potential secondary sources of pollutants (Mazilamani *et al.,* 2025). In this study, heavy metals including cadmium, Mn, Zn, and Cu were analyzed to evaluate long-term contamination in river sediments. Furthermore, the lack of established MPC for river sediments necessitated the assessment of contamination levels through the application of soil maximum permissible concentrations (MPC) values along with geochemical background (Clarke values). In the Irtysh River, cadmium concentrations ranged from 6 to 9 mg/kg, exceeding the soil MPC (2 mg/kg) by three to four times, while in the Ulba River, concentrations ranged from less than 5 to 8 mg/kg, also surpassing permissible levels by approximately four times. Mn concentrations remained below the soil MPC (1500 mg/kg), ranging from 630 to 680 mg/kg in the Irtysh River and 670 to 790 mg/kg in the Ulba River. Zn levels in the Irtysh River reached 511 mg/kg, exceeding the soil MPC (100 mg/kg) by about five times and Clarke values by 6.8 times, indicating significant technogenic accumulation, whereas in the Ulba River, Zn concentrations ranged from 254 to 270 mg/kg, reflecting a moderate degree of contamination. Cu concentrations in the Irtysh River varied between 50 and 59 mg/kg, slightly exceeding the soil MPC (55 mg/kg) at the downstream site, suggesting low-level pollution. Ultimately, these observations affirm that sediments on the bottom function as enduring accumulators of heavy metals, showcasing the repercussions of industrial activity in the Ust-Kamenogorsk region (Fig. 5).

It should be noted that the spatial resolution of the monitoring network and the seasonal frequency of sampling limit the detection of short-term pollution events and fine-scale spatial variability. The chosen design adequately identifies the primary processes involved in pollutant transport, mixing, and ecological impact within the Ulba–Irtysh confluence zone.

CONCLUSION

The present study provides an integrated assessment of the hydrochemical, hydrobiological, and sedimentological conditions of the Ulba–Irtysh river system, focusing on tributary–mainstream interactions and their influence on downstream water quality.

Table 6: Average values of the Woodiwiss biotic index (BI) and water quality class (QC) in the Irtysh and Ulba Rivers within Ust-Kamenogorsk (2021–2025)

Site	2021	2022	2023	2024	2025	Average
Ulba River, within the settlement of Kamenny Karyer	6.7/II	6.8/II	6.9/II	7.4/II	8.0/II	7.2/II
Ulba River, 1 km upstream from the mouth of the Ulba River; 0.36 km downstream of the Ulba Bridge	3.9/IV	5.0/III	7.5/III	7.1/III	7.0/III	6.1/III
Irtysh River, 0.5 km downstream from the wastewater discharge of the Kondensatorny Plant	4.7/III	5.6/III	4.7/III	5.0/III	5.4/III	5.1/III
Irtysh River, within the city limits; 3.2 km downstream from the confluence of the Ulba River	6.6/II	6.0/III	6.4/III	5.8/III	5.9/III	6.1/III

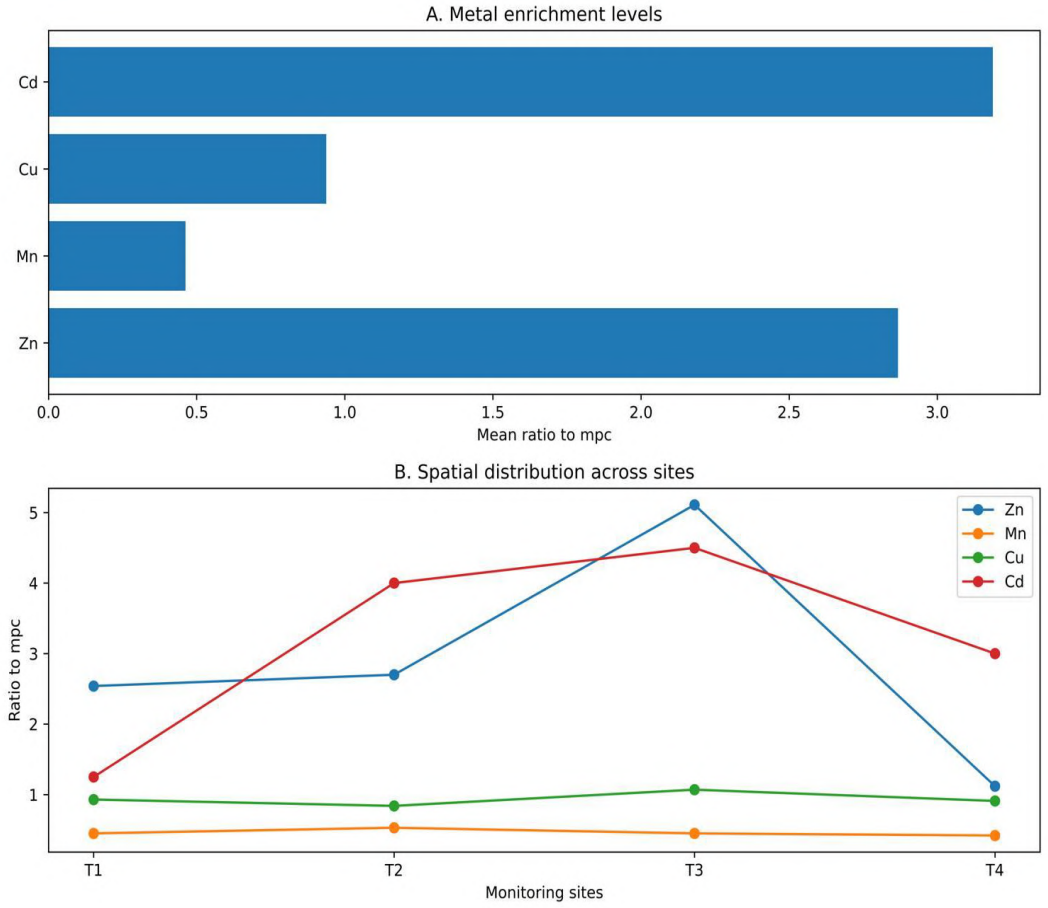

Fig. 5: Sediment contamination

The findings indicate that the Ulba River serves as a notable yet spatially limited source of transit pollution, leading to increased levels of Mn, Zn, and Cu in the Irtysh River within the urban-industrial zone of Ust-Kamenogorsk. This influence is most pronounced at the confluence and immediately downstream, particularly near the Ulba Bridge, where hydrodynamic mixing and localized discharge inputs jointly control contaminant redistribution. Nonetheless, the effects observed are not consistent throughout the Irtysh River, suggesting that the Ulba River is

neither the sole nor the primary factor in the overall decline of water quality in the basin, but instead serves as a significant contributor within a specific mixing corridor. Seasonal variability emerged as the primary regulator of pollutant dynamics. Winter conditions were associated with higher metal concentrations due to reduced discharge and limited dilution capacity, whereas spring and summer flows promoted partial dilution and downstream transport. These patterns suggest that the hydrological regime controls short-term variability; however, it does not eradicate ongoing anthropogenic contributions, as demonstrated by the consistent exceedances of guideline values for Zn and Mn at impacted sites. Sediment analysis confirms long-term contaminant retention, with elevated accumulation of Zn and Mn indicating that bottom sediments function both as sinks and potential secondary sources. This creates a linked water-sediment system where internal loading can maintain contamination even when external inputs are diminished, thus prolonging ecological exposure beyond immediate discharge occurrences. ecological impact. Although Daphnia magna assays indicated no acute toxicity, site-specific mortality differences and macrozoobenthos-based classification suggest moderate ecological impairment in the Ulba River and downstream sections of the Irtysh River. These findings indicate that the system is characterized primarily by chronic sub-lethal stress rather than acute toxic conditions, consistent with sustained exposure to elevated metal concentrations. The combined chemical and biological evidence indicates that various stressors, including nutrients, organic matter, and heavy metals, operate simultaneously within the system. Although statistical correlations suggest co-occurrence and potential coupling, the absence of process-based flux modeling restricts the mechanistic quantification of these interactions. Increased levels of nutrients (nitrates and phosphates) along with moderate COD levels indicate a continued impact from urban and industrial effluents, which may indirectly influence the mobility of metals by altering redox conditions and complexation processes. From a system standpoint, the confluence zone acts as a dynamic mixing interface that regulates the redistribution of pollutants between tributary and main river flows, rather than a simple accumulation point. This highlights the importance of spatially resolved monitoring for capturing non-linear changes in water quality across river continua. Another notable constraint of this study is the limited temporal resolution, which encompasses merely four seasonal campaigns, as well as a low spatial sampling density. These factors impede the detection of short-term pollution events and fine-scale spatial variability. In addition, the absence of direct hydrodynamic flux measurements prevents quantification of pollutant loads and transport rates. From a risk management standpoint, the findings suggest that the accumulation of heavy metals in both water and sediments poses a dual environmental concern: dissolved fractions signify short-term exposure risk, while sediment-bound metals constitute a long-term reservoir that can potentially release secondary contaminants under varying environmental conditions. Furthermore, effective oversight of industrial river systems should focus on the comprehensive monitoring of water and sediment compartments, as well as the specific control of industrial discharges in tributary catchments including the Ulba River. Future studies ought to concentrate on high-resolution temporal monitoring, integrated hydrodynamic–water quality modeling, and metal speciation analysis to enhance comprehension of transport mechanisms, bioavailability, and long-term ecological risk. Such approaches are essential for

developing predictive tools for pollutant fluxes and for supporting evidence-based river basin management.

AUTHOR CONTRIBUTIONS

G. Mamyrbekova contributed to the conceptualization of the study, coordination of data collection, and preparation of the manuscript. Y. Kalybekova participated in the development of methodological approaches related to transport safety aspects, supported data interpretation, and contributed to manuscript drafting. V. Kolpakova participated in the interpretation of hydrological and environmental data, contributed to the analysis of river water quality dynamics, and supported manuscript preparation. Y. Yeremeyeva, as the corresponding author, supervised the overall research process, coordinated contributions from all co-authors, performed critical interpretation of results, and finalized the manuscript. A. Aniskin contributed to structural and civil engineering interpretation of river system impacts, supported technical analysis, and assisted in manuscript revision and improvement. B. Botantayeva contributed to transport infrastructure and environmental impact assessment, supported data analysis, and assisted in manuscript editing.

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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
^oC	Degree Celsius
BI	Biotic index
BOD_5	Biochemical oxygen demand over five days
Ca^{2+}	Calcium ion
Cd	Cadmium
Cl^-	Chloride
cm	Centimeter
COD	Dichromate oxidizability
Cu	Copper
Fe	Iron
HCO_3^-	Hydrocarbonate
K^+	Potassium ion
km	Kilometer
km^2	Square kilometer
L	Liter
m	Meter
meq/L	Milliequivalent per liter
Mg^{2+}	Magnesium ion
mg/L	Milligram per liter
mg/kg	Milligram per kilogram
Mn	Manganese
MPC	Maximum permissible concentration
Na^+	Sodium ion
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
O_2	Oxygen
pH	Hydrogen ion concentration
PO_4^{3-}	Phosphate
QC	Quality class
SO_4^{2-}	Sulfate
SPSS	Statistical package for the social sciences
Zn	Zinc

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REVIEW ARTICLE

A bibliometric and systematic analysis of consumer behavior toward green consumption in the digital age

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ABSTRACT

Environmental pressures and the need to preserve natural resources have increasingly encouraged societies to reconsider current consumption patterns. In this context, responsible consumption has gained growing attention among researchers and practitioners, as it plays a crucial role in promoting more sustainable lifestyles and reducing environmental impacts. Nonetheless, consumer participation in environmentally friendly consumption is inconsistent and shaped by multiple social, psychological, and contextual elements, a situation that has been further intensified by the swift digital transformation of consumer settings since 2020. Understanding how consumer behavior shapes responsible consumption in this evolving digital context therefore represents an important and insufficiently addressed research challenge. The objectives of this study were to examine the relationship between consumer behavior and green consumption through a combined bibliometric and systematic literature review, with a specific focus on the 2020–2025 period. In contrast to earlier bibliometric reviews that either encompass wider time frames without distinguishing the post-pandemic digital transition or utilize both methods separately, this study integrates them by focusing on digital transformation as the core of the analysis. A two-stage methodological approach was adopted, guided by the preferred reporting Items for systematic reviews and meta-analyses protocol. First, a bibliometric analysis was conducted on 143 articles retrieved from the Scopus database, analyzed using VOSviewer to explore publication trends, co-authorship networks, and keyword co-occurrence structures. In the second phase, a thematic analysis was performed on 31 chosen articles utilizing qualitative data analysis software-12 to pinpoint significant research themes, theoretical Framework, and emerging viewpoints. The findings reveal a significant increase in academic interest in green consumption, particularly from 2023 onward, driven in part by post-pandemic shifts and the growing influence of digital platforms. Three bibliometric clusters structure the field: green marketing and advertising strategies, institutional and governmental drivers of sustainable consumption, and psychological and behavioral determinants anchored in the theory of planned behavior. The comprehensive examination additionally indicates that digital platforms are still insufficiently theorized as mediating mechanisms, and that an ongoing intention–behavior gap continues to pose challenge both theory and practice. The study proposes an integrative conceptual framework synthesizing these findings. Key limitations include reliance on the Scopus database, restriction to English-language publications, and the temporal boundary of the dataset.

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INTRODUCTION

In a context marked by the intensification of environmental challenges, largely associated with economic models based on rapid growth, consumer behavior has become a key determinant of long-term environmental sustainability (Kamolteeravit *et al.,* 2026; Han, 2021; Tanner and Wölfing Kast, 2003; Trong Nguyen *et al*., 2023). In fact, there is a rising awareness among both consumers and businesses about the significance of conserving natural resources and safeguarding the environment, along with the environmental effects linked to products and consumption behaviors (Naalchi Kashi, 2019; Young *et al.,* 2010). In response to this context, green consumption has been widely recognized as a key lever for promoting long-term environmental sustainability (Aagerup and Nilsson, 2016; Akehurst *et al.,* 2012: Cam *et al.,* 2025; Peattie, 2001) Green consumption refers to the use of products and services that satisfy consumers' needs while minimizing negative environmental impacts and preserving natural resources, thereby ensuring that future generations can meet their own needs without compromise (Bharti and Suneja, 2024; Bian, 2020). Throughout this study, the terms green consumption, sustainable consumption, and responsible consumption are used with distinct but related meanings. Green consumption mainly pertains to the environmental aspect of purchasing choices; sustainable consumption covers a more extensive socioeconomic range; and responsible consumption focuses on the ethical and social elements of consumer decisions (White *et al*., 2019). These distinctions are maintained consistently across the analysis. However, despite the growing importance attributed to green, responsible and environmentally preserving consumption, consumers' engagement in sustainable consumption behaviors remains complex and far from automatic (Aagerup and Nilsson, 2016; Acharya, 2019). Current studies indicate that green consumption behavior is influenced by various interconnected factors, such as social influence, habitual consumption patterns, environmental awareness, education, product attributes, and personal dimensions including self-identity and self-concept. (Trong Nguyen *et al*., 2023; White *et al*., 2019). As an illustration, Bharti and Suneja (2024) performed a systematic review encompassing 207 articles on green consumption spanning 1993 to 2023. Their findings indicate that the research in this domain is largely governed by the theory of planned behavior (TPB), concentrates predominantly on young, educated, and urban consumers in developed countries, and does not extend its analysis to the role of digital platforms or to the structural shifts in consumption behavior induced by the post-2020 context. Similarly, Korkmaz and Altan, (2023) reviewed sustainable consumer behavior in the industry 4.0 context over a ten-year period using the Web of Science database, finding a steady increase in publications from 2021 onward, yet without isolating the specific behavioral shifts of the post-pandemic period or examining digital platforms as mediating mechanisms in green consumption behavior. This current study intends to address these gaps concurrently by emphasizing the 2020–2025 timeframe, framing digital transformation as a central analytical perspective, and merging bibliometric mapping with systematic content analysis to yield cross-validated theoretical insights. The dual methodological design is theoretically grounded in the complementarity between quantitative mapping of intellectual structures and qualitative interpretation of thematic content, as recommended by (Donthu *et al*., 2021; Zupic and Čater, 2015). Relevant peer-reviewed articles were obtained from the Scopus database, which is well-known for its comprehensive coverage of high-quality scientific publications. After a rigorous screening and refinement process guided by the preferred reporting Items for systematic reviews and meta-analyses (PRISMA) protocol, a total of

143 articles were retained for the bibliometric analysis. To enhance the comprehension of the field, a comprehensive systematic analysis was performed on a selection of 31 selected articles. This combined approach enabled the identification of dominant theoretical frameworks, major research themes, existing theoretical gaps and future research directions in the study of green consumption and consumer behavior. Consequently, this research aims to tackle the subsequent study questions: 1) How has the study of green consumption and consumer behavior progressed during the 2020–2025 timeframe, and what influence has digital transformation had on this development? 2) What does the geographical and authorial distribution of publications reveal about the global structure of knowledge production in this field? 3) What thematic clusters and keyword co-occurrence patterns structure the intellectual landscape of green consumption research, and how do these reflect theoretical concentrations and gaps? 4) Which theoretical frameworks dominate empirical studies of green consumption behavior, and what tensions or underexplored perspectives can be identified? 5) What future research paths, especially those that interact with digital platforms, cross-cultural contexts, and emerging methodological approaches, are most critically required to enhance the discipline? This study makes three key contributions to literature. First, it delivers a time-sensitive synthesis of research on green consumption spanning the years 2020 to 2025, a recent period characterized by rapid digital transformation that has not been thoroughly analyzed in previous bibliometric reviews. Second, it develops an integrative conceptual perspective that highlights the role of digital environments alongside altruistic and egoistic value orientations as underlying mechanisms shaping sustainable consumption behavior. Third, by combining bibliometric mapping with thematic content analysis within the PRISMA framework, the study offers a complementary analytical perspective that links the structural evolution of the field with its underlying thematic developments. Collectively, these contributions offer researchers, practitioners, and policymakers a clearer perspective on the development of green consumption amid the growing digitalization of consumption ecosystems. This study aims to deepen the understanding of the interrelationship between consumer behavior and green consumption. To achieve this objective, the study employs a literature review methodology that integrates bibliometric analysis with a systematic content analysis of current research on green consumption. This study was conducted in Université Sidi Mohamed Ben Abdellah, Fez, Morocco in 2025.

METHODOLOGY

To achieve the objectives of this study, a hybrid review design was adopted combining bibliometric analysis with a systematic literature review, as such combined approaches are increasingly recommended to balance analytical breadth with conceptual depth (Donthu *et al*., 2021; Snyder, 2019; Zupic and Čater, 2015). The bibliometric element facilitated a quantitative analysis of publication trends, significant contributors, and the co-occurrence patterns of keywords that organize the literature (Donthu *et al*., 2021; Van Eck and Waltman, 2010). while the systematic review allowed a deeper examination of theoretical frameworks, empirical findings, and emerging research directions (Cuéllar-Rojas *et al*., 2022; Marzi *et al*., 2025; Paul and Criado, 2020; Tranfield *et al*., 2003). The bibliographic dataset was compiled in March 2025 from the Scopus database, selected for its broad multidisciplinary coverage, metadata reliability, and widespread use in management and marketing research (Baas *et al*., 2020; Donthu *et al*., 2021; Mongeon and Paul-Hus, 2016). Furthermore, this decision maintained analytical consistency, limiting the search to one database could lead to a selection

bias due to the restriction of the search to a single database, which should be considered when evaluating the broader applicability of the results (Chadegani *et al*., 2013; Mongeon and Paul-Hus, 2016). The search was conducted in the TITLE-ABS-KEY fields using the following query: TITLE-ABS-KEY ("green consumption" OR "green marketing") AND ("consumer behavior" OR "purchase behavior" OR "consumer engagement" OR "customer experience") AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"cp")) AND LIMIT-TO(LANGUAGE, "English"). Broader sustainability-related terms were excluded to avoid conceptual dilution (Page *et al.,* 2021; Tranfield *et al.,* 2003) and inclusion and exclusion criteria were established in advance to ensure transparency throughout the selection process (Liberati *et al.,* 2009; Page *et al.,* 2021), as summarized in Table 1.

The designated period (2020–2025) was selected to reflect the latest progress in green consumption studies, notably the rising integration of digital technologies in consumption contexts. The study selection followed the PRISMA framework. The preliminary search produced 1,543 records, which were subsequently deduplicated and evaluated through a multi-stage process that considered titles, abstracts, and keywords, leading to the retention of 143 publications retained for bibliometric analysis. A purposive subset of 31 articles was then selected for in-depth systematic analysis based on thematic relevance, theoretical and empirical richness, and adequate textual depth for qualitative coding (Castleberry and Nolen, 2018; Paul and Criado, 2020; Snyder, 2019). The 143 publications were analyzed using VOSviewer (version 1.6.20), with author keywords as the unit of analysis, a minimum occurrence threshold of five keywords (Van Eck and Waltman, 2010; van Eck and Waltman, 2017) and a normalization procedure applied to harmonize similar terms and consolidate closely related concepts (Donthu *et al*., 2021; Zupic and Čater, 2015). The bibliometrix package in R complemented this analysis with author-level productivity and co-authorship indicators (Aria and Cuccurullo, 2017). The 31 chosen articles were subsequently examined using systematic thematic coding within qualitative data analysis software (NVivo)-12, organized around five dimensions: research methodologies, theoretical frameworks, empirical findings, research perspectives, and managerial implications. The coding methodology predominantly utilized deductive logic, yet it also facilitated the emergence of new themes via iterative recoding. This method revealed consistent patterns, such as the role of digital platforms as mediating mechanisms, the effects of altruistic and egoistic values, challenges like price sensitivity and greenwashing, and the enduring intention–behavior gap. Several rounds of review were conducted within the research team to ensure analytical consistency and reduce interpretive subjectivity. The bibliometric analysis provided the structural mapping of the field while the systematic review enabled deeper theoretical interpretation, and Fig. 1 presents the complete study selection process following the PRISMA logic. In accordance with the two-stage review framework outlined previously, the findings are displayed in two complementary sections. The first part reports the bibliometric findings, including publication trends, influential contributors, and thematic structures identified through keyword co-occurrence analysis. The subsequent section outlines the findings from the systematic content analysis, emphasizing methodological patterns, theoretical frameworks, empirical results, and new research avenues in the domain of green consumption and consumer behavior (Paul and Criado, 2020; Webster and Watson, 2002).

Table 1: Inclusion and exclusion criteria

Criterion	Description
Topic relevance	The publication had to explicitly address green consumption, green marketing, or a closely related sustainability-oriented consumption issue in connection with consumer behavior.
Consumer focus	The study had to include a meaningful behavioral dimension such as consumer behavior, purchase behavior, consumer engagement, or customer experience.
Database source	Only publications indexed in Scopus were considered.
Language	Only English-language publications were retained.
Time window	Only studies published between 2020 and 2025 were included.
Document type	Only journal articles and conference papers were retained.
Initial screening basis	Relevance was assessed through titles, abstracts, and keywords.
Exclusion for weak fit	Publications were excluded if they addressed sustainability or environmental issues without a direct and explicit link to consumer behavior and green consumption.
Exclusion for insufficient depth	Studies lacking sufficient conceptual, empirical, or analytical substance for bibliometric or thematic interpretation were excluded from the in-depth review stage.

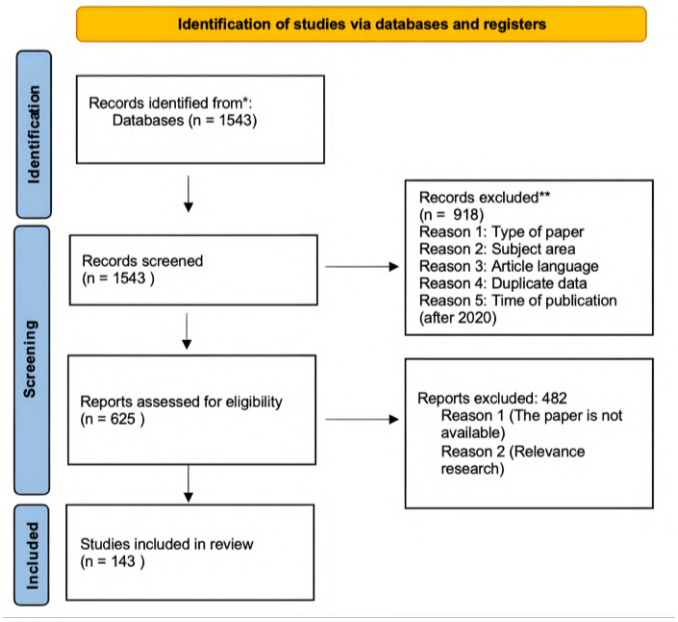

Fig. 1: The literature review process, following the Prisma diagram

Annual publications

Fig. 2 shows a gradual increase in the number of publications since 2020, with a marked peak observed between 2023 and 2024. This upward trend aligns with recent bibliometric studies that indicate a notable increase in research focused on green consumption and green marketing following the COVID-19 pandemic (Agarwal and Dubey, 2024; Bharti and Suneja, 2024). The pandemic has been identified as a structural turning point that reshaped consumer priorities toward sustainability concerns (He and Harris, 2020; Sheth, 2020), which may explain the growing academic attention devoted to green and sustainable consumption in recent years (Donthu and Gustafsson, 2020; Sajid *et al*., 2022; Sun *et al*., 2021). Throughout this timeframe, consumers embraced distinct purchasing habits, including panic buying, and demonstrated increased reliance on digital tools and online shopping platforms. These changes contributed to strengthening awareness of environmental issues and to reconfiguring consumption patterns, fostering growing interest in green, responsible

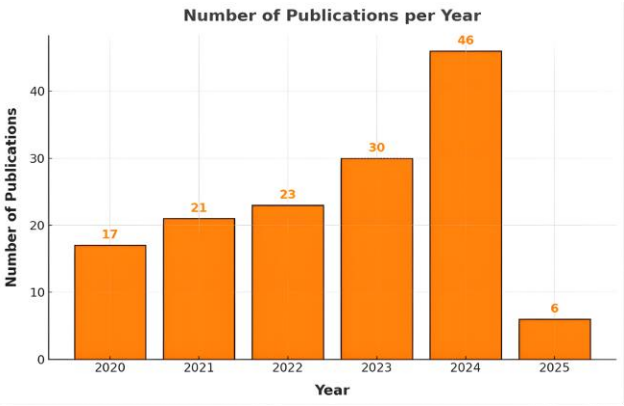

Fig. 2: Annual publications

and sustainable consumption practices (Sajid *et al.*, 2022; Sun *et al.*, 2021). In this context, the emergence of digitalization seems to serve as both a promoter of responsible consumption and a catalyst for new environmental issues. Indeed, the intensive and insufficiently regulated use of digital technologies may also lead to an increase in carbon footprint (Belkhir and Elmeligi, 2018; George and Schillebeeckx, 2022), which may partly explain the heightened scientific interest in consumer behavior and green consumption observed in the post-pandemic period.

Most productive authors

Fig. 3 presents the most productive authors contributing to research on green consumption and consumer behavior (Li *et al.*, 2020) appears as the most prolific author with five publications, followed by (Wang *et al.*, 2022) with four publications (Hu *et al.*, 2024; Shen and Chen, 2020; Wei *et al.*, 2024; Witek, 2020) each contributed three publications, while (Chang *et al.*, 2021; Gu *et al.*, 2022; Han *et al.*, 2020; Witek and Kuźniar, 2024) each contributed two publications. The findings suggest that research output is primarily focused among a small group of essential contributors, indicating the existence of prominent scholars who are actively promoting this area of research. Such a pattern is typical of developing research areas, where a relatively small group of authors contributes significantly to knowledge production. This concentration also reflects the progressive structuring of the field around emerging research leaders.

Co-authorship network

Fig. 4 illustrates the co-authorship network of the most productive authors identified in the dataset. The findings indicate a somewhat disjointed collaboration framework, primarily consisting of small research groups that have minimal interactions with one another. A total of 10 authors met the minimum threshold of two publications, forming several small clusters rather than large, highly connected networks. The most connected group brings together (Su and Li, 2024; Wang *et al.*, 2023; Zhou et al., 2022; Wang et al., 2022), suggesting the presence of a small but active collaboration core, while (Witek and Kuźniar, 2021 and 2024) appear to collaborate closely as a separate pair. Overall, the network indicates that collaboration in this area is still quite fragmented, with the majority of partnerships occurring within small research teams instead of through extensive international collaborations. This type of structure is often observed in developing research areas, where collaboration networks are still gradually taking shape. The prevalence of small and somewhat secluded groups implies that increased international and cross-institutional cooperation could further bolster the development and integration of research pertaining to green consumption.

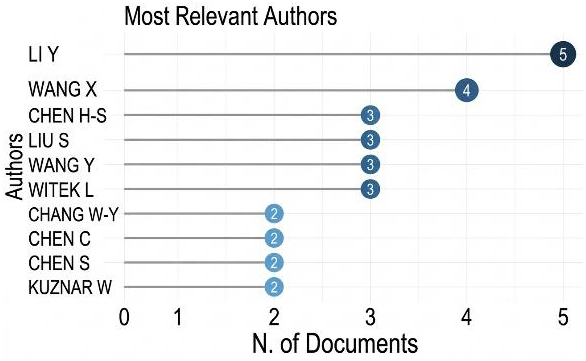

Fig. 3: Most productive authors

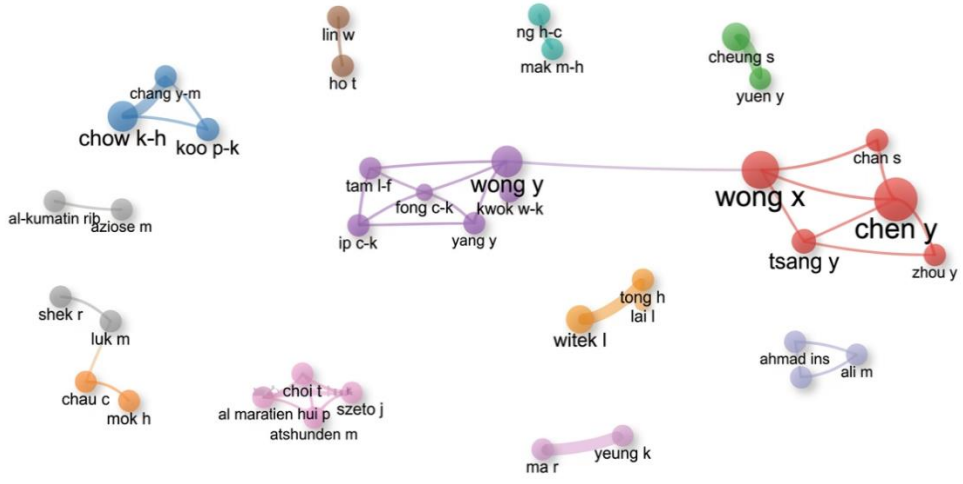

Fig. 4: Co-authorship network

Publications per country

Fig. 5 presents the geographical distribution of countries contributing to research on green consumption and consumer behavior across the 143 analyzed articles, representing 44 countries in total. A strong dominance of China can be observed with 36 articles, representing approximately 25% of the corpus, followed by India (10 articles), Vietnam (8 articles), and Poland and Indonesia (7 articles each). Asian countries collectively make up nearly 55% of the corpus, while European countries account for approximately 21%, with Poland, Portugal, and Italy standing out as the leading contributors from Europe. This distribution suggests that research on green consumption is particularly active in Asian countries, where rapid economic development and growing environmental concerns have stimulated academic interest in sustainable consumption, a pattern consistent with previous bibliometric studies (Bharti and Suneja, 2024; Haba *et al*., 2023). Collaboration patterns remain largely nationally oriented, indicating that international research partnerships are still relatively limited despite the global relevance of the topic, while the limited representation of other regions highlights potential geographical imbalances in literature. These discoveries pave the way for future studies, especially by promoting research in underrepresented areas like Africa and Latin America, to expand the geographical breadth of the discipline and gain a deeper understanding of context-specific factors influencing green consumption behavior.

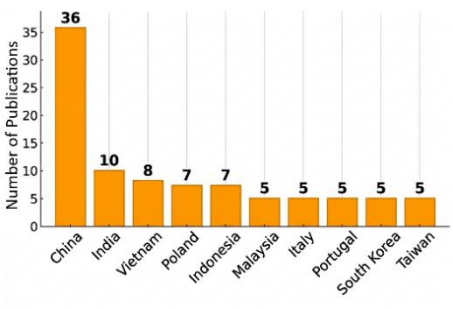

Fig. 5: Publications per country

Keywords clusters

Keyword co-occurrence analysis constitutes a fundamental analytical step in bibliometric research. This approach allows the identification of the main research domains as well as the interconnections between these domains, thereby contributing to the structuring of the conceptual framework of the field under study (Marlina *et al*., 2024; Waltman *et al*., 2010; Zupic and Čater, 2015). In the present study, keyword co-occurrence analysis was conducted using VOSviewer, applying a minimum co-occurrence threshold of two occurrences per keyword, which resulted in a final set of keywords grouped into three distinct clusters. Before the mapping process, terms that were semantically redundant and methodologically non-informative terms including human, humans, consumers, and consumers were manually excluded following a data cleaning procedure to enhance the conceptual clarity of the network. Clusters were then identified using the association strength normalization method implemented in Vos viewer (Van Eck and Waltman, 2010). As depicted in Fig. 6 and elaborated in Table 2, these three clusters form the intellectual basis of research concerning green consumption and consumer behavior across distinct yet interconnected thematic dimensions. Together, these clusters provide insights into Research Question 3 by revealing the main thematic concentrations and underexplored areas of the field. The red cluster mainly revolves around concepts associated with green marketing, purchase intention, perception, consumer behavior, and advertising. It emphasizes the essential function of marketing strategies in motivating and steering consumers towards adopting more sustainable consumption practices (Ahmed *et al*., 2023; Ali, 2021; Bagheri, 2014). More specifically, the expansion of digital marketing has intensified this process. By leveraging storytelling techniques, customized communication; interactive digital platforms, organizations increasingly function as channels for raising environmental awareness, communicating ethical positioning; influencing responsible consumption choices (Alkhatib *et al*., 2023; Dube *et al*., 2023; Kannan and Li, 2017; Rosário and Dias, 2025). The rising prevalence of keywords associated with digital marketing within this cluster indicates a heightened focus on digitalization as a catalyst for driver of green consumption in the post-2020 period, directly addressing Research Question 1 regarding the influence of digital transformation on the development of this research domain. Additionally, the presence of keywords such as "public attitude" and "environmental knowledge" further highlights the role of socio-cultural and cognitive influences in shaping green consumption behaviors. Public discourse and perceived social norms, as discussed by Carrington *et al*. (2010); Sheth (2020); Thøgersen (2006), may either encourage or constrain sustainable purchasing decisions. This indicates that green marketing efforts ought not to depend exclusively on

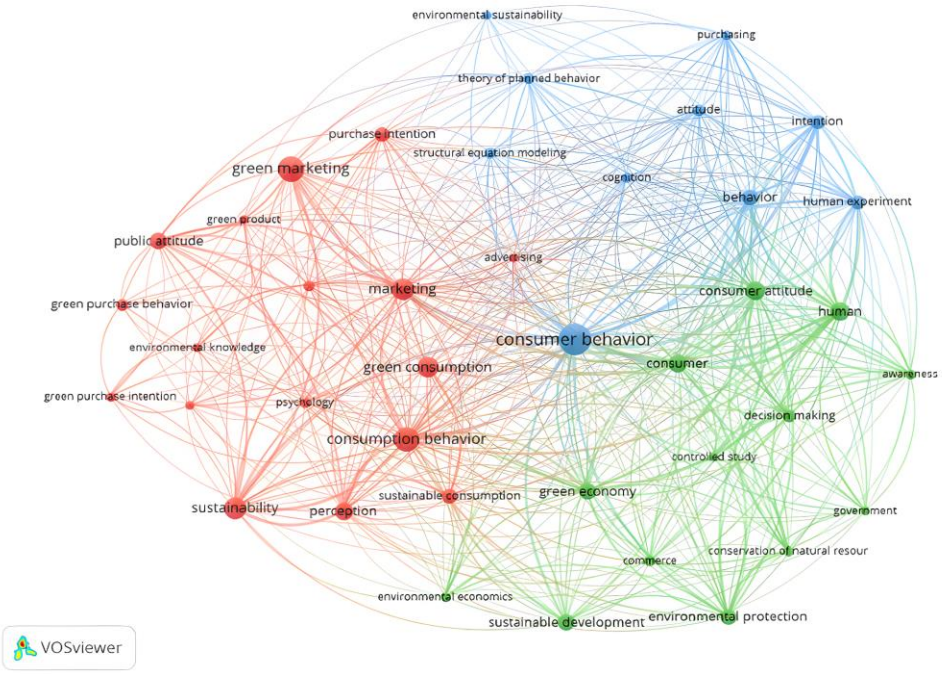

Fig. 6: Keyword co-occurrence network

Table 2: Keyword cluster

Red	Green	Blue
Green marketing	Sustainability	Consumer behavior
Purchase intention	Green consumption	Decision making
Advertising	Perception	Attitude
Green product	Government	Human experiment
Public attitude	Consumer attitude	Controlled study
Marketing	Environmental knowledge	Purchasing
Green purchase behavior	Sustainable consumption	TPB

persuasion at the individual level, but should also consider wider collective norms and shared environmental values. The green cluster encompasses themes related to sustainable development, environmental protection, green economy, government, the human dimension, decision-making. This cluster highlights the significance of public authorities and societal actors in influencing consumer behavior and promoting the establishment of sustainable and responsible consumption patterns (Kagan *et al*., 2003; Stern, 2000; Yang *et al*., 2023). It implies that consumer behavior transcends the individual level, extending to a more extensive collective participation that involves numerous stakeholders. This perspective aligns with institutional and stakeholder approaches, which underline the role of governance structures, regulatory frameworks; societal actors in shaping sustainable consumption behaviors (Stern, 2000; Yang *et al*., 2022; Ye *et al*., 2025). The blue cluster establishes the theoretical foundation of green consumption and consumer behavior. It includes themes related to intention, the TPB, attitude, cognition, and behavior. The literature indicates that the TPB identifies behavioral intention as the primary factor influencing consumer behavior (Ajzen, 1991; Kalafatis *et al*., 1999; Paul *et al*.,

2016). This intention depends on three essential factors: attitude, subjective norms, and perceived behavioral control. Attitudes are shaped by cognitive and affective evaluations; subjective norms reflect perceived social pressure from reference groups; and perceived behavioral control refers to the individual's belief in their capacity to perform the behavior (Ajzen, 1991; Akhtar and Mohd Suki, 2022; Wu and Chen, 2014). A temporal reading of the VOSviewer overlay visualization provides additional insights into the evolution of research themes within the field. The results indicate that keywords associated with the blue cluster, particularly the TPB and behavioral intention, align with the most well-established research foundations, with relevant studies emerging earlier in the study timeframe. In contrast, keywords belonging to the red cluster, such as digital marketing and interactive platforms, reflect more recent research directions that have gained increasing attention in recent years. This temporal configuration indicates that the field has progressively shifted from an initial emphasis on psychological and behavioral explanations of green consumption toward more contextualized approaches incorporate the influence of digital environments. This evolution reflects the growing importance of digital technologies in shaping consumption practices and the increasing interest of researchers in understanding how digital environments may influence sustainable consumption behavior (Agarwal and Dubey, 2024). Furthermore, the three clusters recognized in this study demonstrate notable parallels with the thematic structures found in earlier bibliometric studies concerning green consumption, which also underscore the essential function of TPB-oriented behavioral models alongside the rising significance of marketing perspectives (Agarwal and Dubey, 2024; Bharti and Suneja, 2024). However, the identification of a distinct cluster centered on governance and institutional dimensions, including themes such as government, sustainable development, and green economy, represents an additional structural insight. This pattern, which was not as prominently highlighted in earlier evaluations, may signify the rising attention given to sustainability governance and the growing awareness of the role that public actors play in influencing sustainable consumption dynamics.

Content analysis

To conduct the systematic content analysis, 31 articles were selected from the 143 publications included in the bibliometric review for the systematic content analysis. These articles were meticulously selected by omitting studies that did not directly pertain to both consumer behavior and green consumption. These articles were subjected to an in-depth manual analysis. To support and structure the analysis, NVivo 12, a qualitative data analysis software recognized for its capacity to organize and systematically analyze textual data, was also employed to identify patterns, relationships; thematic structures within the literature (AlYahmady and Al Abri, 2013; Brandão, 2015; Kraiwanit *et al*., 2023). Using NVivo, three main outputs were generated: word clusters, clusters of the most frequently used terms, and research perspectives. These outputs were utilized not solely for descriptive visualization but also to facilitate the identification of prevailing research themes, conceptual relationships, and emerging research directions. Subsequently, a comprehensive analysis of the chosen articles was performed to decipher these patterns and to pinpoint the primary theoretical frameworks utilized in the literature, facilitating a more analytical interpretation of emerging research perspectives.

Word cloud

To generate the word cloud, the full texts of the 31 selected articles were analyzed using a word frequency query configured to extract the 500 most frequent terms, with a minimum word length of five characters applied to exclude short and non-informative words, thereby enhancing the conceptual relevance of the analysis. The word

cloud was utilized as a means of exploratory analysis to identify key concepts and assist in the subsequent thematic interpretation rather than as a standalone analytical approach. It should be noted that word frequency reflects the relative prominence of themes within the corpus rather than theoretical importance per se. Fig. 7 highlights the predominance of the terms "green," "products," and "consumer," thereby affirming the significant impact of environmental product attributes in shaping consumer purchasing behavior. Previous studies have indicated that eco-labels and sustainable product features increase consumer trust and influence purchase intention (Aagerup and Nilsson, 2016; Alamsyah *et al*., 2021; Sh. Ahmad *et al*., 2022). Additionally, terms such as "marketing," "environment," "attitude," "brand," and "knowledge" underscore the strategic role of coordinated marketing efforts in strengthening consumer awareness and shaping pro-environmental attitudes, ultimately encouraging more responsible consumption behaviors (Amin and Tarun, 2021; Joshi and Rahman, 2015; Leonidou *et al*., 2011).

Theoretical frameworks mobilized by authors

The systematic review enabled the identification of the different theoretical frameworks mobilized in literature. An in-depth reading of the selected articles revealed that the TPB appears to be the most frequently used theoretical framework. This outcome aligns completely with the results of the bibliometric analysis. Additional theoretical viewpoints were also utilized, showcasing a variety of methods associated with rational decision-making, subjective norms, adaptation processes, the desire to explore new knowledge, social influence, and stakeholder engagemen. Table 3 summarizes the main theoretical frameworks identified in the reviewed studies and confirms that green consumption and consumer behavior are influenced by a network of interconnected mechanisms and factors that may influence purchasing and consumption decisions.



Fig. 7: Word cloud

Table 3: Theoretical frameworks mobilized in publications

Theory	Main contribution	Authors
Theory of planned behavior (TPB)	The intention to engage in green consumption and behave in an environmentally responsible way is based on three key mechanisms: subjective norms, attitudes toward green consumption, and perceived behavioral control.	(Fontes *et al.,* 2021; Jayasingh *et al.,* 2021; Nekmahmud and Fekete-Farkas, 2020; Riskos *et al.,* 2021; Susanty *et al.,* 2021; Zubair *et al.,* 2020)
Brand affect theory	Brand Affect Theory suggests that consumers develop positive feelings such as satisfaction and pleasure toward a brand, which increases their likelihood of purchase, particularly when the brand is perceived as socially responsible.	(Chen *et al.,* 2020)
Awe theory	Awe Theory refers to feelings of wonder and perceived vastness in response to stimulus. In the context of green consumption, awe encourages individuals to act in a more environmentally responsible and sustainability-oriented way, reduces egocentric attitudes toward the environment; promotes the adoption of new and sustainable consumption models.	(Sun *et al.,* 2021)
Signaling theory	Signaling Theory suggests that associating tangible signals with products, such as green labels and certifications, reduces information asymmetry and strengthens consumers' intention to engage in responsible consumption.	(Ha, 2022; Lopes *et al.,* 2024a)
Norm activation model (NAM)	The NAM suggests that consumers are more likely to engage in environmentally responsible consumption when they are aware of environmental consequences and feel personally responsible for protecting the environment.	(Barbaritano and Savelli, 2021; Joo *et al.,* 2022)
Prospect theory	Prospect Theory suggests that in the context of green consumption, consumers evaluate the potential gains and losses associated with green products and tend to give greater importance to perceived losses than to expected benefits. These perceived losses may include higher prices or uncertainty about product credibility, which may reduce green consumption intentions.	(Zubair *et al.,* 2020)
Theory of consumption values and altruistic-egoistic values	The Theory of Consumption Values and altruistic–egoistic values suggests that green consumption intentions are influenced by both altruistic values and egoistic values. Altruistic values reflect concern for others and the environment, whereas egoistic values are related to personal benefits and self-interest.	(Tan *et al.,* 2022)
Legitimacy theory	Legitimacy Theory suggests that organizations adopt socially and environmentally responsible practices to align with societal expectations, which strengthens corporate credibility and increases consumer trust in the brand	(Ha *et al.,* 2022)
Stakeholder theory	Stakeholder Theory suggests that organizations adopt social and environmentally responsible practices in response to the influence and expectations of stakeholders such as consumers, governments and non-governmental organizations.	(Witek and Kuźniar, 2021)
Resource-based view (RBV)	The RBV suggests that internal organizational resources, such as environmental capabilities, sustainable organizational practices and employee training, enable firms to adopt responsible practices and develop competitive advantage in green markets.	(Shabbir *et al.,* 2020)
Generativity theory	Generativity Theory suggests that individuals engage in environmentally responsible consumption to preserve the environment for future generations.	(Shiel *et al.*, 2020)
Theory of reasoned action (TRA)	The TRA suggests that consumer behavior is determined by behavioral intention, which is influenced by two key factors: attitudes and subjective norms.	(Tran *et al.,* 2022)
ABC theory	ABC Theory highlights the role of external factors in promoting responsible consumption. It suggests that behavior is influenced by both individual attitudes and the external context.	(Chen *et al.*, 2023)

A more detailed analysis of these theoretical viewpoints indicates that green consumption behavior can be understood through three interrelated analytical frameworks: individual-level cognitive models (TPB, TRA, NAM), value-based and psychological approaches (Consumption values theory, awe theory, generativity theory), and organizational or institutional viewpoints (Stakeholder Theory, Legitimacy Theory, RBV). The variety of theoretical perspectives emphasizes the complex nature of green consumption and indicates the necessity for more comprehensive frameworks that integrate individual, social, and organizational determinants across contexts and over time periods globally in different cultural settings.

Research perspectives

To determine future research directions, the 31 chosen articles were analyzed with NVivo 12. In this regard, the discussion and conclusion sections of the articles were carefully examined; the different research perspectives were systematically coded. A hierarchical diagram was then generated to obtain a structured distribution of the identified research perspectives. To deepen the understanding of each perspective, an additional in-depth reading of the articles was conducted. For instance, a commonly recurring viewpoint was the recommendation to investigate new research inquiries. The hierarchical diagram obtained from Nvivo was subsequently refined through manual processing in Word to provide a more detailed and structured presentation of each research perspective (Fig. 8). The objective of this section is to open new avenues for future researchers and to encourage further investigation into green consumption and consumer behavior. These research perspectives are not intended as universal recommendations; rather, they are specifically derived from the gaps and future research directions explicitly identified in the analyzed articles through the NVivo coding process.

Conduct cross-cultural comparative studies

One of the research perspectives identified in the literature is the need to conduct cross-cultural comparative studies. The literature first suggests conducting studies across cultures and between developed and developing countries to identify the general applicability of green consumption and its variability depending on the context (Ha *et al*., 2022; Nekmahmud and Fekete-Farkas, 2020). Additional research indicates the necessity to enhance the comprehension of cultural influence, at both individual and collective levels (Fontes *et al*., 2021). The literature also calls for comparative analyses between Nordic and non-Nordic cultures to better understand how institutional mechanisms, the role of the state, regulatory contexts, and cultural norms shape green consumption and consumer behavior (Tan *et al*., 2022).

Expand sample size and diversity

An additional research perspective involves increasing both the sample size and the diversity of the populations being studied. This includes, first, comparisons between green consumers and non-green consumers by analyzing their attitudes toward the environment (IEA/OEA) and the different factors that may motivate their consumption behavior (Fontes *et al*., 2021; Lopes *et al*., 2024a; Shen and Chen, 2020). The literature also suggests the need to further investigate socio-demographic characteristics such as age, gender; income, as well as comparisons between different generations such as Generation X, Millennials; Generation Z (Balaskas *et al*., 2023; Barbaritano and Savelli, 2021; Bonera *et al*., 2020; Zubair *et al*., 2020). Future studies ought to concentrate on additional target demographics, including rural communities, which have been comparatively overlooked in existing literature (Nekmahmud and Fekete-Farkas, 2020). The objective of this research perspective is to deepen the understanding of the different mechanisms that may influence consumer behavior toward green consumption.

Test other moderator/mediator variables.

The literature indicates that additional variables might act as mediating or moderating variables in the connection between consumer behavior and green consumption. First, the mediating role of technology was identified, particularly through the design of digital platforms and digital features, which may influence altruistic or egoistic values and subsequently foster sustainable consumption (Tan *et al*., 2022). Socio-demographic characteristics may also moderate this relationship, including age, gender, financial situation, rural or urban location; level of education (Chen *et al*., 2020). The classification of a product may impact the likelihood of consumers engaging in environmentally friendly consumption

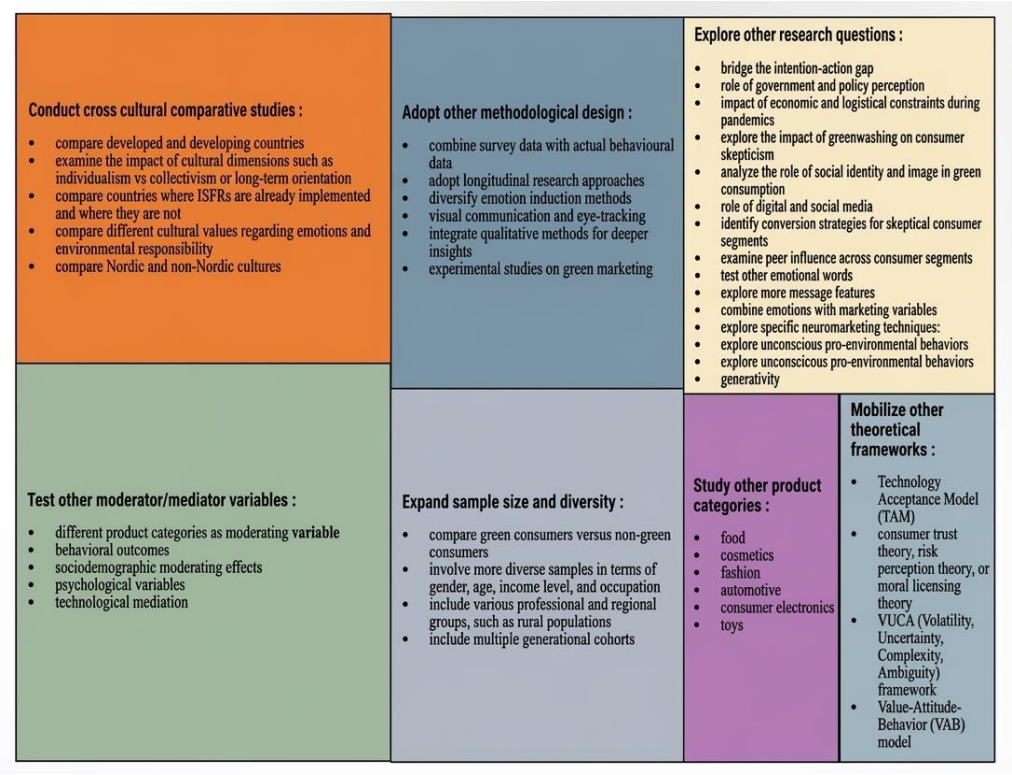

Fig. 8: Research perspectives

(Riskos *et al*., 2021). Behavioral outcomes may also act as moderating factors, such as willingness to pay more for green products, word-of-mouth, eco-literacy; environmental awareness. Finally, psychological variables such as social norms, altruism; moral obligation may also influence the relationship between consumer behavior and green consumption (Barbaritano and Savelli, 2021; Han *et al*., 2020; Shiel *et al*., 2020).

Adopt another methodological design

In relation to research methodology, the literature indicates that employing diverse methodological approaches can enrich the understanding of green consumption behavior. First, future research should rely on behavioral data to verify whether actual consumer behavior is aligned with the intentions declared in exploratory or survey-based studies (Dropulić and Krupka, 2020). Longitudinal studies are also recommended to observe how attitudes and intentions evolve over time, particularly in response to changes in marketing strategies, policy interventions; environmental education (Ha *et al.,* 2022; Lopes *et al*., 2024b). The literature also suggests conducting eye-tracking studies to visualize how eco-label designs may influence consumers' attitudes and behaviors (Riskos *et al*., 2021). Such methods can assist in determining which green advertising formats and visual components capture the highest levels of consumer attention and engagement. It is also important to highlight that most of the studies that relied on quantitative approaches were examined. This indicates the need for methodological diversification in future research to better understand consumer behavior toward green consumption.

Study other product categories

Product categories may also influence consumption patterns. Future research should therefore explore different categories of products such as food, cosmetics, fashion, toys, electronics; automobiles to better understand how green consumption behavior may vary across product types (Kaur *et al*., 2022; Witek and Kuźniar, 2021).

Explore other research questions

An additional significant research viewpoint is to delve into new research questions pertaining to green consumption and consumer behavior. First, future research should explore the role of digital technologies and social media (Ha *et al*., 2022; Han *et al*., 2020; Tan *et al*., 2022). Studies should analyze the influence of media messages, advertising campaigns; consumer reviews on green consumption behavior (Zubair *et al*., 2020). Future studies ought to investigate additional emotional expressions, including shame, disturbance, pride; hope, which may also influence green consumption. Furthermore, it is crucial to examine the impact of communication strategies and message framing, as well as operational marketing through the 7Ps (product, price, place, promotion, packaging, positioning; people) (Kaur *et al*., 2022). Attention should be given to product attributes such as packaging, pricing, brand reputation, sustainability labels. Future research should also investigate the role of greenwashing and misleading marketing messages in reducing consumer trust toward brands, as well as explore how firms can rebuild trust and credibility in green marketing practices (Bonera *et al*., 2020; Correia *et al*., 2023). Further studies ought to investigate the current disparity between intention and actual behavior, as well as pinpoint strategies that may contribute to bridging this gap (Nekmahmud and Fekete-Farkas, 2020). Finally, the literature highlights the need to integrate the concept of generativity by encouraging consumers to consider future generations through responsible consumption, rather than focusing only on current green purchase intentions. This perspective underscores that sustainable consumption is crucial not only for the protection of the current environment but also for the preservation of natural resources for future generations (Shiel *et al*., 2020).

Mobilize other theoretical frameworks

Another important research perspective is the mobilization of additional theoretical frameworks. As mentioned in the previous section, the TPB is the most frequently used theoretical framework in literature. To establish a more comprehensive theoretical basis, subsequent research ought to investigate additional theoretical frameworks, including the technology acceptance model (TAM), the volatility, uncertainty, complexity, ambiguity (VUCA) framework, the value–attitude–behavior (VAB) model, consumer trust theory, risk perception theory, and moral licensing theory (Han *et al*., 2020; Joo *et al*., 2022; Kaur *et al*., 2022).

Green consumption behavior: Integrative conceptual framework

Based on the findings obtained from both the bibliometric and systematic analyses, an integrative conceptual framework of green consumer behavior was developed and is presented in Fig. 9. The development of this framework was based on a two-stage derivation process. In the first stage, the bibliometric analysis informed the identification of the three main categories of independent variables. Specifically, the red cluster centered on green marketing, advertising, and digital marketing served as the empirical foundation for the dimension of marketing and informational factors dimension. The green cluster encompassing government, social norms, and stakeholder involvement grounded the social and institutional factors dimension. The blue cluster organized around the TPB, attitude, and behavioral intention contributed to the psychological factors dimension. In the second stage, the systematic content analysis of the 31 selected articles

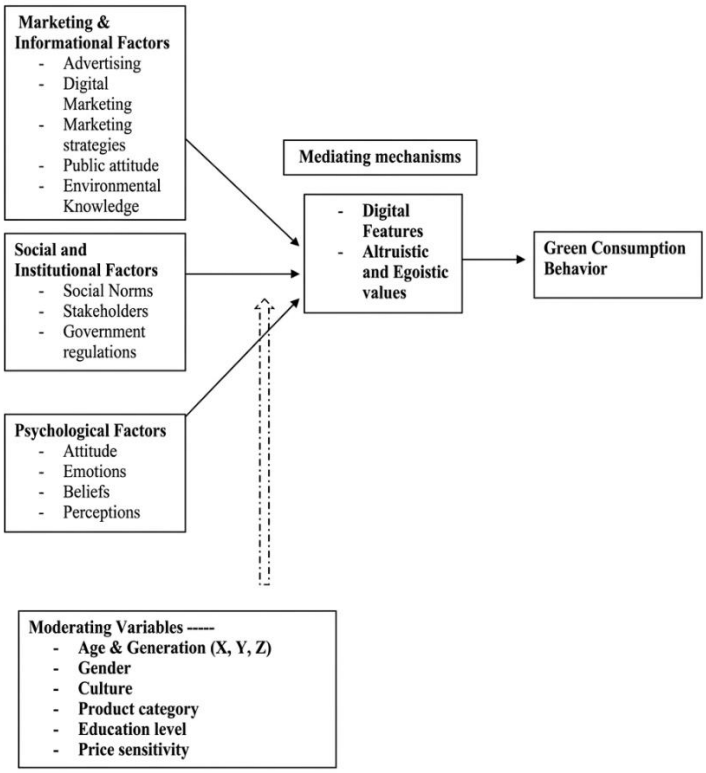

Fig. 9: Integrative framework of green consumption and consumer behavior

enabled the identification of the mediating and moderating mechanisms. The mediating role of digital features was highlighted in studies examining how digital environments shape consumers' altruistic and egoistic value orientations, which in turn influence green consumption behavior (Kumar *et al.,* 2016; Tan *et al*., 2022). The moderating influence of socio-demographic variables including age, gender, education, culture, product category, and price sensitivity was also consistently reported (Balaskas *et al*., 2023; Zubair *et al*., 2020). This framework is inherently conceptual and originates from a synthesis of established empirical findings rather than from the collection of original data. It therefore represents a theoretically grounded proposition intended to guide future empirical research rather than an empirically tested model. By integrating structural insights from bibliometric mapping with theoretical mechanisms highlighted in the systematic review, the framework provides a coherent synthesis of the main drivers, mediating processes, and boundary conditions shaping green consumption behavior, while simultaneously providing a well-organized basis for future research.

The results obtained from both the bibliometric and systematic analyses provide a deeper understanding of green consumption and highlight the mechanisms that may influence the relationship between consumer behavior and green consumption. The results demonstrate a rising interest in this research domain, especially in the literature analyzed from post-2020, in conjunction with the rapid growth of digital technologies, emphasizing the significance of green consumption research in both scientific and managerial contexts (Donthu and Gustafsson, 2020; Feng *et al*., 2025; Sheth, 2020). The

convergence between the bibliometric and systematic findings is particularly noteworthy. The three thematic clusters identified in the bibliometric analysis: marketing and informational factors, social and institutional factors, and psychological factors, are directly corroborated by the empirical themes emerging from the systematic review of 31 articles, confirming the internal consistency of the analytical framework. In addition to reviewing the existing literature, this research offers three significant contributions to the field of green consumption studies. First, it provides one of the first integrative reviews combining bibliometric mapping with systematic thematic synthesis in this field. Second, it highlights digital transformation as an emerging structural dimension influencing both the drivers and mechanisms of green consumption behavior. Third, it adds value by suggesting a comprehensive conceptual framework that links marketing, social, and psychological factors within a cohesive analytical structure. This convergence is also broadly consistent with findings from prior bibliometric reviews of green consumption, which similarly identify TPB-based behavioral frameworks and marketing strategies as dominant research themes (Agarwal and Dubey, 2024; Bharti and Suneja, 2024). However, the present study extends these findings by documenting the growing role of digital platforms and governance mechanisms as emerging research dimensions within the 2020–2025 research corpus analyzed in this study. The findings demonstrate that green consumption is affected by various mechanisms functioning at both individual and collective levels. Rather than representing isolated determinants, these factors appear to form an interconnected system of influences where marketing stimuli, social structures, and psychological drivers jointly shape sustainable consumption decisions. This integrative perspective contributes to theory development by suggesting that green consumption should be understood as a multi-level behavioral system where psychological intentions, institutional pressures, and digital infrastructures jointly shape sustainable consumption outcomes. Among the most important factors, socio-demographic characteristics such as age, gender, generational differences, education level, and geographical location appear to play a significant role, particularly when comparing different economic contexts (Balaskas *et al*., 2023; Zubair *et al*., 2020). The study indicates that marketing plays a crucial role in shaping consumer behavior. It appears that consumers are notably attuned to product-related indicators such as eco-labels and certifications, along with advertising messages and marketing tactics that encourage environmentally conscious consumption (Shabbir *et al*., 2020; Witek and Kuźniar, 2021). The dominance of the TPB across both the bibliometric clusters and the systematic review findings reflects its theoretical robustness in explaining intention-driven behaviors. As a framework that integrates attitude, subjective norms, and perceived behavioral control, TPB offers a thorough yet manageable framework for understanding the cognitive and social determinants of green purchase decisions. Nonetheless, its prevailing influence indicates a theoretical concentration that could restrict the field's ability to encompass the structural, emotional, and digital dimensions of green consumption behavior, highlighting the necessity to enhance TPB with emerging frameworks such as the TAM and VAB models. This also suggests that future theoretical development should move toward hybrid behavioral models integrating cognitive, technological, and contextual determinants to better capture the complexity of green consumption behavior in digital environments. Another significant observation pertains to the growing influence of digitalization. The systematic analysis confirms that digital features and platform design may function as mediating mechanisms in the relationship between consumer behavior and green consumption, operating through altruistic and egoistic value orientations (Kumar *et al*., 2016; Tan *et al*., 2022). These mechanisms contribute to

shaping consumers' perceptions and decision-making processes toward more responsible consumption patterns. These results indicate that digital environments ought to be regarded not just as communication channels but as behavioral infrastructures that can influence how consumers obtain sustainability information, evaluate environmental claims, and convert environmental concern into actual purchasing behavior. Furthermore, the literature highlights the existence of a significant gap between consumers' intentions and their actual behavior. This disparity can be attributed to various factors, such as a lack of trust in brands, apprehensions regarding greenwashing practices, and sensitivity to the pricing of eco-friendly products (Bonera *et al*., 2020; Correia *et al*., 2023; Gleim *et al*., 2013). This intention–behavior gap remains one of the key tensions highlighted in green consumption research. Overall, this study offers a comprehensive array of implications for scholars, managers, and governmental bodies.

Implications for researchers

This study, from a research perspective, delivers a well-organized synthesis of the current literature by introducing an integrative conceptual framework that underscores the primary patterns and interconnections among the various factors that influence the relationship between consumer behavior and green consumption. By linking bibliometric structures with systematic evidence, the study also identifies several theoretical gaps and research perspectives, including the need to conduct longitudinal studies and comparative research across different socio-demographic characteristics (Balaskas *et al*., 2023; Barbaritano and Savelli, 2021; Zeynalova and Namazova, 2022). Future research should also mobilize additional theoretical approaches such as the TAM and VAB; the VUCA framework (Joo *et al*., 2022; Kaur *et al*., 2022; Shen and Chen, 2020). Moreover, additional empirical investigation is required to examine the mediating influence of digital features alongside the altruistic and egoistic values identified in this study in explaining green consumption behavior.

Managerial implications

From a managerial standpoint, the results indicate that organizations ought to enhance their digital platforms and formulate effective storytelling strategies, while utilizing social media to bolster awareness and encourage green consumption practices (Joo *et al*., 2022; Zafar *et al*., 2021; Zou *et al*., 2021). Firms should also invest in environmental education through communication campaigns aimed at increasing consumer knowledge and strengthening environmental sensitivity. In addition, companies need to reinforce credibility and transparency by providing clear and reliable eco-labels and environmental information to reduce the negative effects of greenwashing and strengthen consumer trust (Alawadh *et al*., 2024; Han *et al*., 2020).

Policy implications

From a public policy perspective, the findings highlight the importance of promoting altruistic values and social responsibility to encourage sustainable consumption as a socially responsible behavior that contributes to protecting society and future generations (Alawadh *et al*., 2024; Ye *et al*., 2025; Zou et *al*., 2021). Public authorities ought to assume a significant role in addressing greenwashing by guaranteeing that environmental claims and marketing messages are credible and transparent (Correia *et al*., 2023; Riskos *et al*., 2021). Environmental education should be promoted from an early age by integrating sustainable consumption into school and university programs (Lopes *et al*., 2024b; Shiel *et al*., 2020). Ultimately, it is essential for public policies to strive towards minimizing inequalities in the availability of green products, making sustainable consumption more attainable for diverse demographic groups (Witek and Kuźniar, 2021).

CONCLUSION

The purpose of this study was to explore the relationship between green consumption and consumer behavior through a mixed literature review combining bibliometric and systematic approaches. The integration of these two approaches offers a thorough overview of the current literature and enhances the comprehension of the development within the research domain. Based on a dataset of 143 articles identified from the Scopus database between 2020 and 2025, a bibliometric analysis was first conducted, followed by an in-depth systematic review based on 31 selected articles drawn from the initial sample. The bibliometric analysis findings indicated an increasing interest in research related to green consumption, especially from 2023 onwards, and facilitated the identification of the leading contributors contributors in this domain while outlining the collaborative structures that define this research community. The geographical distribution of studies showed a strong dominance of Asian countries, particularly China, followed by India and Vietnam. The analysis of keyword co-occurrence has identified three primary clusters that organize the research domain: the first underscores the significance of marketing practices and strategies in shaping consumer behavior; the second emphasizes the role of governments, public policies, and stakeholders in promoting ethical and responsible consumption; and the third illustrates the theoretical foundations of the field, identifying the TPB as one of the most influential frameworks, showing that green consumption behavior mainly depends on attitudes, subjective norms, and perceived behavioral control. The convergence between both analytical approaches represents a significant methodological strength of this study, as the thematic clusters revealed through bibliometric mapping were directly corroborated by the empirical themes that arose from the systematic review, confirming the internal consistency of the findings and enhancing the validity of the proposed integrative conceptual framework. This study provides one of the first bibliometric syntheses of green consumption research specifically situated in the post-pandemic digital context, demonstrating that digital transformation has emerged as a structurally distinct analytical dimension reshaping both the drivers and the mediating mechanisms of sustainable consumption behavior. This finding plays a role in bridging a theoretical gap within the literature, given that only a limited number of studies clearly recognize digital platform design and digital marketing practices as crucial determinants of green consumption. The study also highlights the mediating role of digital features as well as altruistic and egoistic values in shaping the relationship between consumer behavior and green consumption. Subsequent studies should explore the impact of social media and digital advertising more thoroughly, including moderating factors like age, gender, generational differences, and education background, and utilize qualitative techniques to enhance the understanding of the motivations and challenges related to sustainable consumption behavior. Empirical validation of the integrative framework proposed remains a priority for future research. Despite these contributions, this study presents several limitations. The constraint of utilizing only one database may have caused a selection bias, likely leading to an underrepresentation of studies from non-English speaking contexts and reinforcing the geographical concentration observed in the corpus. The reliance on partial manual coding introduces a degree of interpretive subjectivity, and the integrative framework has not been empirically validated, meaning that the proposed relationships should be interpreted as theoretically grounded hypotheses rather than established causal mechanisms. Ultimately, the behavior of consumers towards green products is influenced by a multifaceted interplay of psychological, social, and contextual factors, which encompass beliefs, perceptions, social norms, cultural influences, educational

attainment, marketing strategies, and the involvement of governmental and institutional entities. As digital transformation continues to reshape consumption ecosystems, the capacity to theorize and empirically test the role of digital platforms as mediating mechanisms represents one of the most urgent and promising research frontiers in green consumption scholarship.

AUTHOR CONTRIBUTIONS

M. Soulami conceived the research idea, designed the study, conducted the bibliometric analysis, and prepared the manuscript draft. S. Benchekroun contributed to data collection and data cleaning and participated in bibliometric and systematic analyses. A. Galiulina contributed to the systematic literature review and thematic analysis. I. Sayarh contributed to the systematic literature review and thematic analysis. All authors contributed to the interpretation of the results and manuscript revision and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, 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
Covid-19	Coronavirus 2019
Fig.	Figure
NAM	Norm activation model
NVivo	Qualitative data analysis software
Prisma	Preferred reporting items for systematic reviews and meta-analyses
RBV	Resource-based view
SLR	Systematic literature review
TAM	Technology acceptance model
TPB	Theory of planned behavior
TRA	Theory of reasoned action
VAB	Value–attitude–behavior
VOS-viewer	Visualizing bibliometric networks software
VUCA	Volatility, uncertainty, complexity, ambiguity

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REVIEW ARTICLE

Artificial intelligence-driven financial technology for green finance and environmental sustainability

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ABSTRACT

Artificial intelligence has emerged as a transformative force reshaping financial technologies, green finance, and sustainability-oriented financial systems. Extensive studies focus on artificial intelligence-driven financial innovation, yet it remains fragmented across technological, financial, environmental, and governance dimensions. This fragmentation limits the comprehensive understanding of how financial technology facilitates sustainable financial transformations and ecological sustainability. The objectives of this study were to analyze the emerging relationship between artificial intelligence, financial technology, green finance, and environmental sustainability through a systematic review methodology and bibliometric and thematic analysis. The Scopus database was used as the primary source of data collection, and 78 peer-reviewed studies published between 2016 and 2025 were systematically analyzed using bibliometric mapping and thematic content analysis. Visualization of similarities viewer software was utilized to identify publication trends, influential authors, institutional collaborations, thematic clusters, citation networks, and emerging research streams within artificial intelligence-driven sustainable finance literature. Post-2020 data shows a sharp increase in literature targeting sustainable finance and environmental, social, and governance-oriented investment. This scholarly momentum is heavily fueled by advancements in artificial intelligence-based risk assessment, climate financial analytics, and green digital transformation initiatives. The analysis further identified several dominant thematic areas, including artificial intelligence-enabled financial inclusion, green investment analytics, environmental, social, and governance-driven financial decision-making, ethical governance, algorithmic transparency, sustainable digital banking systems, and environmentally responsible financial innovation. The results indicated that artificial intelligence-driven financial technology has significant potential to support environmental sustainability through green investment optimization, climate-risk modelling, resource-efficiency enhancement, sustainable capital allocation, and financial technology sustainability-oriented financial innovation. Despite this momentum, several critical barriers remain ethical governance deficits, data privacy concerns, a lack of algorithmic explainability, and regulatory fragmentation. Crucially, these issues are compounded by a lack of empirical evidence available from emerging and developing economies. This study contributes to the literature by providing an integrated sustainability-oriented framework linking artificial intelligence, financial technology, green finance, and environmental governance while identifying future research directions for sustainable digital finance ecosystems. Ultimately, this study serves as a strategic roadmap for aligning digital financial innovation with environmental sustainability goals and environmental, social, and governance-oriented development policies, offering valuable guidance for both market actors and policymakers.

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108	10	4

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INTRODUCTION

The advent of artificial intelligence (AI) has significantly transformed financial systems and accelerated the growth of the financial technology (Fintech) industry. Technologies such as machine learning (ML), predictive analytics, natural language processing, and automation have enhanced the speed and transparency of digital financial transactions. (Grout, 2021; Nguyen *et al*., 2023). AI-driven data analytics have revolutionized financial decision-making and intermediation by introducing sophisticated capabilities in credit scoring, fraud detection, compliance, and real-time risk management (Rasiwala and Kohl, 2021; Roy and Vasa, 2024). Recent studies further emphasize the strategic role of AI in enabling smart advisory platforms, financial automation, and adaptive digital banking models that support operational resilience and financial innovation (Ashrafi, 2023; Asif *et al*., 2024; Choi and Ngo-Ye, 2023). Beyond standalone applications, the convergence of AI, blockchain, and big data analytics has transformed risk management and ethical systems in traditional and Islamic banking, driving significant efficiency gains across both sectors (Syed *et al*., 2020; Hazar *et al*., 2023; Ghaemi Asl and Roubaud, 2024). At the same time, growing global concerns related to climate change, carbon emissions, biodiversity loss, resource shortages, and environmental management have heightened interest in research and institution-building focused on the potential for digital finance to facilitate environmentally sustainable economic change. Over the last few years, there has been a growing recognition that innovations in finance should support sustainable development goals (SDGs), climate finance strategies, and green economy transitions. Financial institutions are therefore aligning digital finance architecture with sustainability objectives by systematically adopting ESG principles, green finance (GF) practices, and environmentally sound policies (Carè *et al*., 2025; Ma *et al*., 2025; Alsaffarini and Awwad, 2026). Considering the above discussion, the advent of Fintech powered by AI stands out as a revolutionary tool that can be used to drive environmental sustainability through data-driven investment decisions, portfolio optimization, risk prediction, carbon emission tracking, and financial analysis regarding climate change. Applications of AI have been increasingly employed to help improve ESG reporting and governance, promote renewable energy financing, green bonds issuance, and transparency of sustainability reporting. Furthermore, the integration of AI with blockchain technology and big data analytics is enhancing the efficient tracking of environmental performance indicators, carbon emissions, and sustainable practices. Such a trend is indicative of a global trend that focuses on using technological innovation in addressing the issue of environmental damage, climate change finance, economic disparity, and financial exclusion alongside sustainable finance and environmental sustainability (Abdelhaq and Dwekat, 2024; Elhady and Shohieb, 2025). Despite the growing importance of AI-enabled sustainable finance, the existing body of literature remains fragmented across technological, financial, governance, and environmental sustainability dimensions. Current studies examine AI adoption, Fintech innovation, ESG integration, green finance, or sustainable finance individually, leading to a limited holistic understanding of their combined contributions to environmental sustainability outcomes. Furthermore, previous review studies have predominantly focused on technological adoption, operational efficiency, digital transformation, or financial inclusion, while comparatively limited attention has been directed toward the environmental consequences and sustainability implications of AI-driven Fintech systems (Puschmann *et al.,* 2020). Critical issues related to climate finance, carbon neutrality, environmental governance, ethical AI, algorithmic transparency, green financial innovation, and sustainability-oriented digital transformation also remain insufficiently synthesized within the

existing literature (Aldboush and Ferdous, 2023; Zarifis and Cheng, 2022; Awwad *et al*., 2026). Furthermore, previous bibliometric and review-oriented research often encounters conceptual vagueness concerning the definition of financial sustainability, which is often used interchangeably with financial inclusion, ESG integration, financial resilience, green finance, or sustainable finance. This lack of conceptual clarity limits the development of a coherent understanding of how AI-driven financial technologies contribute to measurable environmental sustainability outcomes, including carbon reduction, sustainable resource allocation, climate adaptation financing, and environmentally responsible investment behavior. Furthermore, notable geographical disparities exist within the literature, as empirical research is predominantly focused on developed economies, while emerging and developing markets are still afforded minimal academic scrutiny despite their growing dependence on digital financial transformation, climate finance mechanisms, and green investment initiatives (Alsaffarini and Awwad, 2026; Awwad and Salem 2025; Abdelhaq *et al*., 2026; Khan *et al*., 2025). Accordingly, this study seeks to address these gaps by conducting a comprehensive bibliometric and thematic review of the literature on AI-driven Fintech, green finance, ESG integration, and environmental sustainability. Using the Scopus database, the study systematically maps publication trends, influential contributors, institutional collaborations, thematic clusters, and emerging research directions within the field. In contrast to existing descriptive reviews, this study couples bibliometric mapping with thematic analysis to offer a sustainability-centered synthesis of the evolving interplay between AI, Fintech, green finance, and environmental sustainability. The study further contributes by clarifying the conceptual dimensions of sustainable digital finance and identifying future research opportunities related to climate-oriented financial innovation, ethical AI governance, ESG-driven technologies, renewable energy financing, and environmentally sustainable financial ecosystems. While prior literature relies heavily on descriptive reviews, this investigation advances the field by combining bibliometric mapping with a structured thematic analysis. This dual approach provides an integrative, sustainability-focused synthesis of how AI, Fintech, and green finance intersect with ecological objectives (Awwad and Awadallah Awwad, 2026; Salem *et al*., 2026). The interaction among these three dimensions is summarized in Fig. 1.

It is also possible to explore the linkages between AI, Fintech, and sustainability from the perspective of sustainable digital transformation. AI-driven technologies enable financial institutions to analyze vast, heterogeneous environmental and financial datasets, thereby optimizing sustainability-oriented decision-making and fostering environmentally responsible financial behavior. The existing literature reveals that AI-based technologies can support green finance operations, including carbon accounting, investment screening for sustainability, and ESG risk assessment (How *et al*., 2020; Babaei *et al*., 2023). Similarly, Ma *et al*. (2025) highlights the growing synergy between AI adoption and environmental, social, and governance integration, emphasizing the role of intelligent technologies in promoting ethical banking and environmentally sustainable financial ecosystems. From a governance perspective, the integration of AI into financial systems raises critical issues related to ethical responsibility, transparency, accountability, and environmental regulatory oversight. While AI offers transformative potential, its responsible deployment in the financial sector remains constrained by systemic challenges, including data privacy vulnerabilities, cybersecurity risks, algorithmic bias, and regulatory fragmentation (Aldboush and Ferdous, 2023). Scholars such as Zarifis and Cheng (2022) further emphasize that algorithmic explainability and ethical AI governance are essential for ensuring fairness, trust, transparency, and

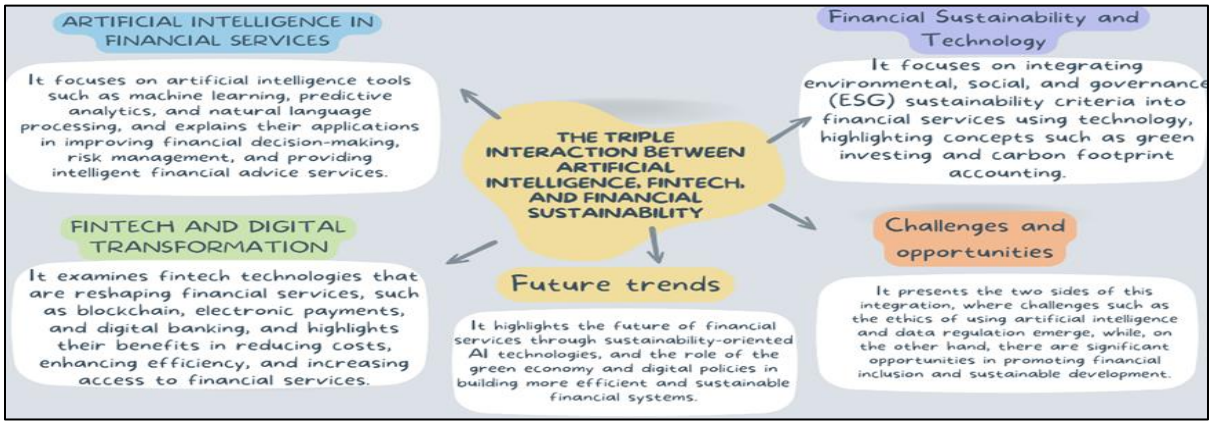

Fig. 1: The triple interaction between AI, Fintech, and environmental sustainability

environmental accountability in intelligent financial systems. Consequently, governance frameworks that balance technological innovation with environmental and ethical responsibility are increasingly important for the sustainable deployment of AI-driven financial technologies. In addition, consumer trust and behavioral acceptance remain key determinants of successful AI integration within sustainable digital finance ecosystems. Extensive studies underscore the pivotal roles of perceived usefulness, transparency, and trust in shaping consumer acceptance and long-term engagement with both AI-enabled banking services and sustainable financial platforms. Similarly, Al-Zaqeba *et al*. (2022) argue that behavioral acceptance is a critical enabler for AI-integrated Fintech adoption, particularly in developing economies undergoing rapid digital financial transformation. Theoretical discussions also highlight the growing importance of AI-powered regulatory technologies, including Supervisory Technology and Regulatory Technology, in supporting sustainable and resilient financial systems. According to Micheler and Whaley (2020), AI-driven regulatory tools optimize real-time surveillance, reduce systemic risks, and reinforce financial stability across digitalized financial systems. These technologies contribute not only to financial governance but also to sustainability-oriented regulatory compliance through enhanced monitoring of environmental, social, and governance practices and environmentally responsible financial activities. In spite of the growing academic focus, literature continues to be disjointed across the dimensions of technology, finance, governance, and environmental sustainability dimensions. Most studies examine AI adoption, Fintech innovation, ESG integration, or sustainable finance separately, while limited attention has been given to an integrated sustainability-oriented understanding of AI-driven Fintech and environmental sustainability outcomes. Conceptual ambiguity also persists regarding financial sustainability, which is often conflated with financial inclusion, ESG performance, financial resilience, green finance, or sustainable finance. Consequently, this study establishes a comprehensive conceptual framework that situates AI-driven Fintech as a multifaceted mechanism connecting digital financial innovation with environmental sustainability outcomes. As illustrated in Fig. 2, the framework explains how AI capabilities enhance sustainable financial ecosystems through intelligent risk assessment, environmental, social, and governance-oriented investment analytics, green finance optimization, operational efficiency, ethical governance, and sustainability-focused financial inclusion. Crucially, the proposed framework positions institutional governance and environmental regulation as vital boundary mechanisms

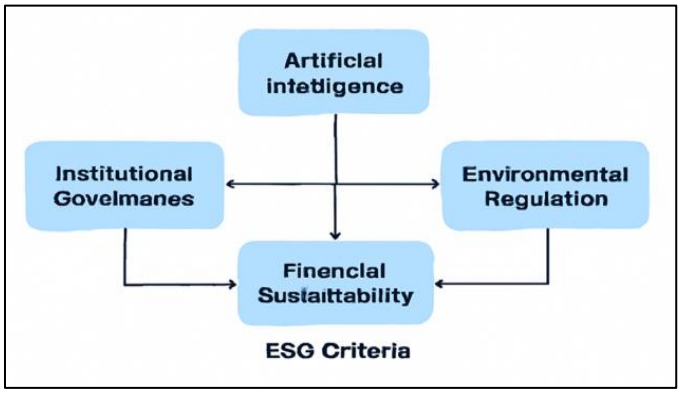

Fig. 2: Conceptual framework linking AI-driven Fintech, green finance, ESG integration, and environmental sustainability

conditions that amplify the sustainability and responsibility of digital finance architectures (Carè *et al*., 2025; Singh, 2024; Saura *et al.,* 2021; Umar *et al*., 2021; Tiwari *et al*., 2024; Salem *et al*., 2025). In this context, AI-enabled Fintech systems are not viewed merely as technological innovations, but as strategic instruments supporting environmentally sustainable financial transformation and long-term sustainability objectives. Methodologically, this investigation integrates bibliometric mapping with a structured thematic analysis to map the intersection of artificial intelligence, green finance, and ecological sustainability. In doing so, it clarifies the boundaries of the field and delineates future studies directions required to advance sustainable digital finance ecosystems (Brogi and Lagasio, 2024).

Environmental impact pathways of AI-driven FinTech in green finance

Beyond the conceptual framing of green finance and ESG integration, recent developments in AI-driven Fintech provide increasingly tangible environmental impact pathways that extend beyond financial optimization (Aldboush and Ferdous, 2023). In practice, AI-driven financial architectures generate quantifiable environmental impacts through a series of specialized operational mechanisms. First, advanced analytics and ML models enhance capital allocation efficiency by directing investments toward low-carbon and environmentally sustainable projects, thereby supporting the reduction of carbon-intensive economic activities (Salem *et al*., 2026). Second, digital financial infrastructures reduce reliance on paper-based and resource-intensive processes, contributing to improved energy efficiency within financial operations and related service ecosystems. Third, AI-powered ESG analytics enhance environmental risk profiling and oversight, allowing financial institutions to divest from environmentally detrimental activities. Fourth, data-driven decision-making supports more efficient resource allocation and encourages investment in circular economy initiatives, thereby reducing waste and improving resource utilization. Finally, predictive AI models strengthen climate risk assessment capabilities by allowing financial institutions and firms to better anticipate and adapt to environmental and climate-related risks. Collectively, these mechanisms demonstrate that AI-driven Fintech is not just a financial tool, but as a catalyst for environmental progress that translates sustainability discourse into measurable environmental performance (Ma *et al*. 2025). The aims of this study are to analyze the emerging relationship between artificial intelligence, financial technology, green finance, and environmental sustainability through a systematic review methodology and bibliometric and thematic analysis. This review study was

conducted globally using Scopus-indexed peer-reviewed studies published between 2016 and 2025, ensuring comprehensive scholarly coverage and robustness.

METHODOLOGY

AI-driven Fintech contributes to green finance, environmental, social, and governance integration, and environmental sustainability. The unit of analysis is peer-reviewed journal articles addressing AI-enabled financial innovation, sustainable finance, digital financial services, green finance, environmental sustainability, and governance-related dimensions of Fintech. Selecting journal articles as the primary unit of analysis ensures the integration of peer-validated data. This is critical for accurately delineating the intellectual framework, tracking thematic advancements, and evaluating the ecological sustainability alignment within the digital finance domain (Nguyen *et al*., 2023; Lăzăroiu *et al*., 2024). relevance to the recent expansion of AI, Fintech, environmental, social, and governance, and green finance research (Carè *et al.,* 2025), due to their relevance, citation impact, and frequent use in bibliometric and systematic review studies (Brogi and Lagasio, 2024; Ma *et al*., 2025). The search matrix was structured to isolate research spanning AI, Fintech, green finance, ESG sustainability, intentionally excluding purely technical or traditional financial studies devoid of environmental context. The concept of AI-driven sustainable finance refers to the application of AI techniques, including ML, predictive analytics, natural language processing, and intelligent automation, within Fintech systems to support green finance, ESG decision-making, climate-risk assessment, and environmental sustainability outcomes (Rahman *et al*., 2024; Singh, 2024). Accordingly, the search terms used in Scopus were: "AI", "ML", "Fintech", "digital finance", "green finance", "environmental sustainability", "environmental, social, and governance", and "sustainable finance", combined using Boolean operators. The search was applied to the TITLE-ABS-KEY fields as follows:

TITLE-ABS-KEY ("AI" OR "ML" OR "Artificial Intelligence")
AND TITLE-ABS-KEY ("Fintech" OR "Digital finance")
AND TITLE-ABS-KEY ("GF" OR "ESG" OR "Environmental sustainability" OR "Sustainable finance").

The initial search resulted in 1,032 documents, indicating the rapid growth of research in AI-enabled sustainable financial systems (Lăzăroiu *et al*., 2024; Ma *et al*., 2025). Following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, the study selection process was executed across five sequential stages: initial identification, duplicate removal, title and abstract screening, full-text eligibility assessment, and final inclusion. Studies included if they addressed AI-driven Fintech, green finance, ESG integration, sustainable finance, or environmental sustainability outcomes. Studies were excluded if they lacked sustainability relevance, were not peer-reviewed journal articles, or were not written in English. To maintain methodological consistency, the screening process adhered strictly to predefined inclusion and exclusion criteria. The publication period was restricted to 2016–2025, and only peer-reviewed journal articles were included, while non-journal publications were excluded. The analysis was limited to English-language studies to ensure consistency in interpretation (Brogi and Lagasio, 2024). Unlike several previous studies, this review did not restrict inclusion to open-access publications to reduce selection bias and improve representativeness. The systematic screening and duplicate elimination process yielded a final dataset of 78 studies, which were subjected to bibliometric and thematic evaluation. The selection process is summarized in Fig. 3 using a PRISMA-based framework. To ensure

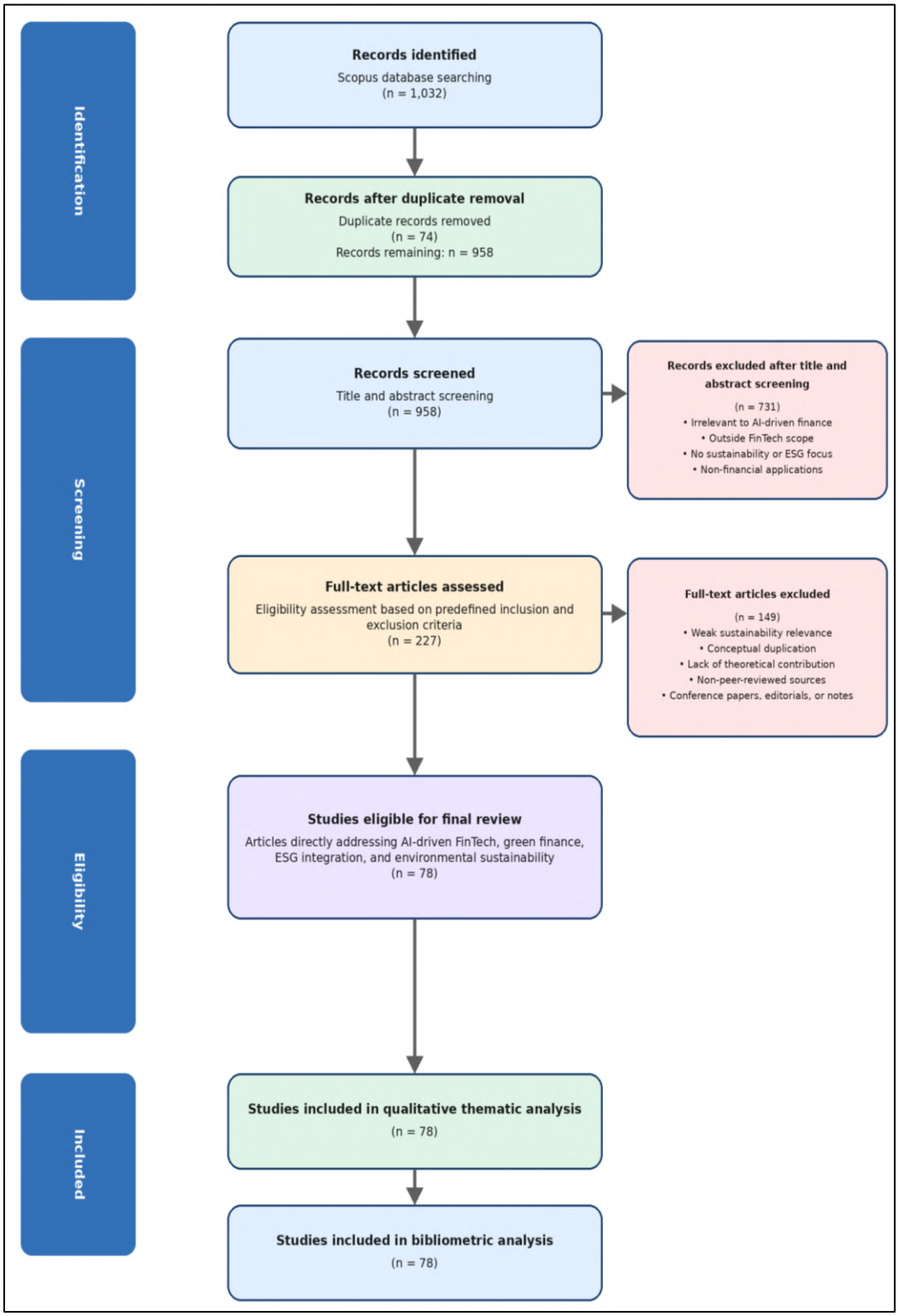

Fig. 3: PRISMA-based article selection process

methodological rigor and transparency, duplicate records were handled through a two-stage process. First, automated duplicate detection was conducted using reference management software based on title, author, year, and source matching. Second, a manual verification process was applied to confirm accuracy and avoid unintended exclusion of relevant studies. The screening process was conducted independently by two reviewers to reduce selection bias. Any discrepancies arising during the title, abstract, or full-text screening stages were systematically resolved through collaborative discussion and consensus. In cases where consensus could not be reached, a third reviewer was consulted to make the final decision. Furthermore, a structured quality assessment of the included studies was conducted to evaluate methodological clarity, relevance, and contribution to the research objectives. To ensure selection reliability, two reviewers independently screened each study and cross-referenced their assessments for consistency. The analytical framework is grounded in sustainable digital finance and responsible AI governance. AI-driven sustainable finance is conceptualized through five categories: AI technologies, Fintech transformation, ESG integration, governance and ethics, and environmental sustainability outcomes (Cui, 2025). While these core categories anchored the initial coding phase, an iterative thematic analysis was utilized to abstract higher-order themes. This systematized framework is illustrated comprehensively in Table 1. The 78 identified studies that directly addressed AI-driven Fintech, sustainable finance, ESG integration, governance issues, or environmental sustainability are presented in Table 2. The selected literature displays dual thematic architecture; whereas all included studies map onto AI-enabled financial innovation or digital transformation, a specialized sub-corpus isolates the dimensions of green finance, ESG integration, regulatory risk, privacy, or responsible AI dimensions. The classification Table 2 was used to support the thematic synthesis and improve the transparency of the literature mapping process.

The bibliometric analysis was conducted using visualization of similarities viewer (VOSviewer) software version 1.6.20 due to its extensive application in mapping scientific knowledge structures, co-occurrence relationships, citation networks, and thematic evolution in multidisciplinary research domains (Bazeliuk *et al*., 2023; Zada *et al*., 2024; Xu *et al*., 2023). To map the structural boundaries of the field, bibliometric metrics were leveraged to evaluate macro-level trends—such as publication velocity, high-impact outlets, and transnational co-authorship networks—alongside micro-level thematic keyword clustering within the sustainable digital finance domain. Full counting procedures and association-strength normalization were applied to improve network visualization accuracy and reduce structural fragmentation within the bibliometric maps. Furthermore, a systematic keyword standardization protocol was implemented. By applying thesaurus-based cleaning techniques to consolidate variant forms of equivalent terms, this step minimized semantic noise and optimized the accuracy of the co-occurrence analysis. Similar concepts such as “AI” and “ML” were standardized where appropriate, while institutional name variations were manually refined to minimize affiliation inconsistencies and improve bibliometric reliability. In addition to bibliometric mapping, thematic content analysis was employed to provide qualitative interpretation of the conceptual and environmental sustainability dimensions of AI-driven Fintech research (Moro Visconti, 2024; Ma *et al*., 2025). The coding process involved three iterative stages. First, the selected studies were systematically reviewed to identify recurring concepts related to AI technologies, Fintech applications, ESG integration, green finance, environmental sustainability, governance, ethics, financial inclusion, climate-risk management, and regulatory technologies.

Table 1: The analytical framework to guide the thematic content analysis

No.	Categories	Sub-categories	Specification
1	AI technologies	ML; natural language processing (NLP); predictive analytics; intelligent automation	All AI tools and computational techniques used to support financial decision-making, automation, risk assessment, and intelligent financial analytics.
2	Fintech transformation	Digital banking; blockchain; robo-advisory; smart payments	All digital financial applications through which AI reshapes financial services, operational models, customer interaction, and financial innovation.
3	Sustainability and ESG	ESG integration; green finance; climate finance	All sustainability-oriented finance dimensions linking digital financial innovation with ESG performance, green investment, and sustainable finance practices.
4	Governance and ethics	Ethical AI; transparency; privacy; Regulatory Technology (RegTech); risk governance	All governance factors affecting responsible AI adoption, algorithmic accountability, data protection, cybersecurity, and regulatory compliance.
5	Environmental sustainability outcomes	Carbon reduction; green investment; climate-risk modeling; resource efficiency	All environmental outcomes or sustainability mechanisms through which AI-driven Fintech may contribute to green financial transformation.

Table 2: Classification of reviewed studies in AI-driven sustainable finance research

No.	Country / Region	AI focus	ESG / green finance	Governance dimension	Unit of analysis	Sources
1	United Kingdom	√		√	Consumers / users	Grout *et al.* (2021)
2	Tunisia	√	√	√	Reviewed literature	Nefla *et al.* (2025)
3	United Kingdom	√		√	Banking / financial institutions	Singh *et al.* (2024)
4	South Africa	√			Banking / financial institutions	Coetzee *et al.* (2018)
5	Russian Federation	√			Fintech firms / Small and medium enterprises (SMEs)	Mayorov *et al.* (2020)
6	Spain	√		√	Consumers / users	Zarco *et al.* (2024)
7	Russian Federation	√			Consumers / users	Artemenko *et al.* (2021)
8	Italy	√	√		Reviewed literature	Trotta *et al.* (2024)
9	Montenegro	√		√	Banking / financial institutions	Vučinić *et al.* (2022)
10	Spain	√			Consumers / users	Flavián *et al.* (2022)
11	Italy	√		√	Consumers / users	Grassi *et al.* (2024)
12	Portugal; Spain	√			Consumers / users	Gonçalves *et al.* (2023)
13	South Africa	√		√	Reviewed literature	Mhlanga *et al.* (2020)
14	Chile; China	√	√	√	Consumers / users	Zada *et al.* (2024)
15	United Arab Emirates; Mexico	√	√	√	Consumers / users	Rafiuddin *et al.* (2023)
16	United Kingdom; Greece	√			Financial markets / assets	Sermpinis *et al.* (2016)
17	Slovakia; Romania	√		√	Reviewed literature	Kliestik *et al.* (2024)
18	Iran; France	√			Financial markets / assets	Ghaemi Asl *et al.* (2024)
19	Bangladesh	√		√	Consumers / users	Ashrafi *et al.* (2023)
20	United Kingdom; Viet Nam	√	√	√	Financial markets / assets	Huynh *et al.* (2020)
21	South Korea	√			Consumers / users	Lee *et al.* (2022)
22	Pakistan	√		√	Reviewed literature	Asif *et al.* (2024)
23	Saudi Arabia	√		√	Consumers / users	Alkadi *et al.* (2025)
24	Portugal	√		√	Consumers / users	Costa *et al.* (2024)
25	Bahrain	√	√	√	Reviewed literature	Rabbani *et al.* (2022)
26	Nigeria	√			Consumers / users	Olayiwola *et al.* (2024)
27	United States; Belgium	√			Consumers / users	Demertzis *et al.* (2018)
28	United States	√			Consumers / users	Choi *et al.* (2023)
29	Spain	√			Fintech firms / SMEs	Méndez-Suárez *et al.* (2019)

30	Kosovo	√			Banking / financial institutions	Miftari *et al.* (2024)
31	Turkey; Cyprus	√		√	Consumers / users	Rjoub *et al.* (2023)
32	India	√		√	Banking / financial institutions	Rasiwala *et al.* (2021)
33	United Kingdom	√		√	Reviewed literature	Micheler *et al.* (2020)
34	Bangladesh; Australia	√	√		Reviewed literature	Rahman *et al.* (2024)
35	Ukraine	√		√	Banking / financial institutions	Bazeliuk *et al.* (2023)
36	United Kingdom; Cyprus	√		√	Consumers / users	Zarifis and Cheng, (2022)
37	Latvia	√			Consumers / users	Mavlutova *et al.* (2021)
38	United Kingdom; Saudi Arabia	√	√	√	Consumers / users	Khan *et al.* (2023)
39	Jordan	√	√		Consumers / users	Al-Zaqeba *et al.* (2022)
40	Lebanon; Jordan	√		√	Financial markets / assets	El Khoury *et al.* (2023)
41	Norway	√		√	Consumers / users	Loutfi *et al.* (2022)
42	United States; Hong Kong	√		√	Fintech firms / SMEs	Xu *et al.* (2023)
43	Australia; Singapore	√		√	Consumers / users	How *et al.* (2020)
44	United Kingdom; Spain	√			Financial markets / assets	Abakah *et al.* (2022)
45	United States; New Zealand	√			Consumers / users	Figueiredo *et al.* (2023)
46	Malaysia; Pakistan	√	√	√	Consumers / users	Aw *et al.* (2024)
47	Portugal; Spain	√			Consumers / users	Saura *et al.* (2021)
48	Italy	√		√	Reviewed literature	Brogi *et al.* (2024)
49	United Kingdom; Vietnam	√		√	Financial sector / Fintech ecosystem	Nguyen *et al.* (2023)
50	Bahrain; India	√		√	Consumers / users	Savitha *et al.* (2022)
51	Sweden	√			Reviewed literature	Zhu *et al.* (2024)
52	Russian Federation	√	√		Financial markets / assets	Kazachenok *et al.* (2023)
53	United States; Australia	√	√	√	Fintech firms / SMEs	Karim *et al.* (2024)
54	Italy	√		√	Reviewed literature	Grassi *et al.* (2022)
55	Poland; Italy	√	√	√	Reviewed literature	Secinaro *et al.* (2025)
56	Netherlands; Romania	√	√	√	Reviewed literature	Carè *et al.* (2025)
57	Jordan	√	√		Reviewed literature	Alrawashdeh *et al.* (2022)
58	Bangladesh; Hungary	√		√	Reviewed literature	Roy *et al.* (2024)
59	Jordan	√		√	Reviewed literature	Aldboush *et al.* (2023)
60	New Zealand; Germany	√	√	√	Banking / financial institutions	Ma *et al.* (2025)
61	Turkey	√	√		Banking / financial institutions	Hazar *et al.* (2023)
62	Saudi Arabia; Bahrain	√			Fintech firms / SMEs	Syed *et al.* (2020)
63	Italy	√		√	Financial markets / assets	Moro Visconti *et al.* (2024)
64	United Kingdom	√			Fintech firms / SMEs	Cubric *et al.* (2024)
65	Jordan	√	√	√	Consumers / users	Khaddam *et al.* (2024)
66	United Kingdom; Poland	√	√	√	Reviewed literature	Roszkowska *et al.* (2021)
67	Austria; Finland	√	√	√	Consumers / users	Naveed *et al.* (2017)
68	Poland	√	√		Consumers / users	Waliszewski *et al.* (2020)
69	Saudi Arabia; India	√		√	Consumers / users	Tiwari *et al.* (2024)
70	Netherlands; Germany	√			Consumers / users	Boot *et al.* (2021)
71	Russian Federation; Kazakhstan	√			Reviewed literature	Patashkova *et al.* (2021)

72	Italy	√		√	Consumers / users	Babaei *et al.* (2023)
73	Hungary	√		√	Consumers / users	Abu Daqar *et al.* (2020)
74	United States	√		√	Financial markets / assets	Giri *et al.* (2025)
75	Poland	√		√	Reviewed literature	Gąsiorkiewicz *et al.* (2020)
76	United Kingdom; Australia	√	√		Reviewed literature	Lăzăroiu *et al.* (2024)
77	United Arab Emirates	√		√	Reviewed literature	Ghandour *et al.* (2021)

Second, the preliminary codes were systematically categorized based on conceptual proximity and sustainability relevance, establishing the foundation for higher-order thematic abstraction. Third, the identified themes were refined and validated through iterative comparison across the dataset to ensure analytical consistency and alignment with the research objectives. The thematic analysis identified several dominant streams, including AI-driven financial inclusion, ESG-oriented digital finance, green investment analytics, ethical governance and algorithmic transparency, AI-enabled risk management, sustainable digital banking systems, and climate and environmental sustainability in financial ecosystems. To complement the qualitative insights, a systematic thematic frequency analysis was integrated to quantify the prevalence of core research streams and isolate the primary dimensions characterizing the final dataset. The analysis examined the frequency of sustainability-oriented themes related to AI-driven financial innovation, ESG integration, green finance, governance dimensions, environmental sustainability, climate-risk modelling, and sustainable digital banking systems. By grounding the qualitative synthesis in these quantitative frequencies, this mapping isolated the dominant research domains while safeguarding the overall interpretive rigor of the study. The distribution of the major thematic dimensions identified in the reviewed literature is presented in Table 3, while the broader thematic structure derived from the analysis is illustrated in Fig. 4. Ultimately, this dual-layered methodological framework leverages bibliometric mapping alongside rigorous content analysis to deliver a comprehensive, mixed-methods evaluation of the thematic trajectory and structural development defining AI-enabled sustainable finance research. This combined methodology enhances the credibility of the review by linking publication patterns, knowledge networks, institutional partnerships, and thematic interpretation within a unified sustainability-oriented conceptual framework (Donthu *et al*., 2021; Zupic and Čater, 2015; Snyder, 2019; Aria and Cuccurullo, 2017). Accordingly, this methodological framework provides a comprehensive foundation for examining how AI-driven Fintech contributes to green finance development, ESG integration, and environmentally sustainable financial transformation while identifying future research directions within sustainable digital finance ecosystems. The results of the bibliometric and thematic analyses indicate a swift advancement in research at the convergence of AI, Fintech, green finance, ESG integration, and environmental sustainability (Kwong *et al*., 2023; Roy and Vasa, 2025; Kozar and Wodnicka, 2024; Zournatzidou, 2025; Dar *et al*., 2024). The findings indicate that AI-driven financial innovation has emerged as a multidisciplinary research domain characterized by growing academic attention, increasing institutional collaboration, and expanding sustainability-oriented applications within digital financial ecosystems. In alignment with the structural guidelines of the journal, the findings transcend isolated descriptive statistics; instead, they are critically contextualized within the

Table 3: Major thematic dimensions identified in AI-driven sustainable finance literature

No.	Thematic dimensions	Green finance	ESG integration	Governance	Environmental sustainability	Number of articles
1	AI-driven financial innovation	√	√	√		52
2	ESG-oriented digital finance		√	√	√	41
3	Green investment analytics	√	√		√	37
4	Ethical AI and transparency		√	√		34
5	Climate-risk modeling	√	√		√	29
6	Sustainable digital banking	√	√	√	√	27
7	Financial inclusion		√		√	24
8	AI-enabled risk management	√	√	√		22

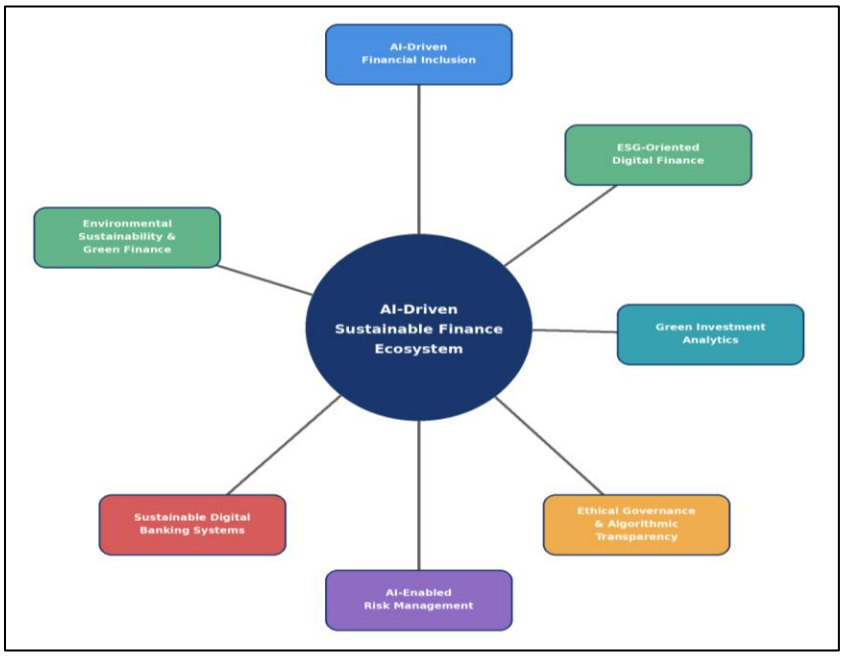

Fig. 4: Major thematic clusters in AI-driven Fintech and environmental sustainability research

broader conceptual and practical evolution of sustainable digital finance. Accordingly, the following subsections integrate bibliometric evidence with thematic interpretation to explain how AI-driven Fintech contributes to green finance development, ESG-oriented decision-making, environmental governance, and sustainable financial transformation.

Publication trends and research growth

The temporal distribution of publications demonstrates a substantial increase in scholarly interest in AI-driven Fintech and sustainable finance research between 2016 and 2025. As illustrated in Fig. 5, annual publication velocity remained relatively constrained during the initial phase of the study period, underscoring that the nexus of AI, Fintech, and ecological sustainability had not yet solidified into a distinct academic field. However, after 2020, the number of publications increased markedly, reflecting the acceleration of digital transformation initiatives, the global expansion of ESG-oriented investment strategies, and the growing use of AI-enabled financial services. Ultimately, this accelerating trend indicates that AI-driven sustainable finance has transitioned from a localized, technology-centric niche into a robust, interdisciplinary domain that

integrates corporate governance, financial economics, environmental sustainability, and digital innovation. The observed growth is consistent with previous studies emphasizing the increasing convergence between digital financial innovation, sustainable finance, and ESG transformation (Nguyen *et al*., 2023; Lăzăroiu *et al*., 2024; Ma *et al*., 2025; Fotova Čiković *et al*., 2025). It also reflects the increasing relevance of AI-enabled financial technologies in supporting climate-related financial analysis, green investment decisions, financial resilience, and SDGs.

Citation structure and influential authors

Citation analysis provides insight into the intellectual foundations shaping AI-driven sustainable finance research. As illustrated in Fig. 6, the citation network reveals that a core cluster of seminal authors and foundational studies has shaped the conceptual development of this field. These contributions are mainly concentrated around AI governance, financial innovation, intelligent risk assessment, ESG analytics, sustainability reporting, and digital financial transformation. The structural topology of the citation network reveals a dual dynamic: a specialized core of high-impact literature anchor the field's foundational paradigms, while a heterogeneous network of cited authors drives its interdisciplinary diffusion. The citation pattern further reveals that the literature is moving beyond operational applications of AI in finance toward broader sustainability-oriented concerns. Recent highly cited contributions increasingly emphasize ethical AI governance, algorithmic transparency, ESG integration, digital banking transformation, and green financial innovation. This transition indicates that the field is maturing beyond a narrow optimization of technological efficiency toward a more holistic integration of sustainability, corporate accountability, and environmental stewardship. Such findings support the argument that AI-driven Fintech should not be viewed only as a financial automation tool, but also as a potential mechanism for advancing sustainable and environmentally responsible financial systems (Brogi and Lagasio, 2024; Singh, 2024).

Knowledge network and conceptual structure

The co-occurrence network analysis provides a clearer understanding of the conceptual structure of AI-driven Fintech and environmental sustainability research. Fig. 7 illustrates the relationships among the dominant keywords extracted from the selected Scopus publications. In this network topology, the dimensions of the nodes are proportional to conceptual prominence, whereas the density of the edges signifies the relative strength of the thematic associations among terms. The network identifies Fintech, AI, ML, blockchain, and Digital Transformation as central conceptual hubs within the knowledge structure. At the same time, sustainability-related terms such as ESG, GF, financial inclusion, risk management, and Sustainable Finance appear increasingly connected with AI-related concepts. This indicates that sustainability concerns are no longer peripheral in Fintech research but are becoming integrated into the core conceptual vocabulary of the field. The network structure demonstrates that AI-driven Fintech research is evolving through the interaction of technological innovation, governance frameworks, financial inclusion, environmental sustainability, and green investment practices. Ultimately, these results underscore the value of a mixed-methods design; the resulting network topology acts as an empirical anchor that visually substantiates the literature's shift toward sustainable digital finance.

Keyword co-occurrence and emerging themes

Keyword frequency analysis further confirms the thematic evolution of the field toward sustainability-oriented financial innovation. As shown in Fig. 8, Fintech and AI represent the dominant terms within the reviewed literature, followed by ML, digital transformation,

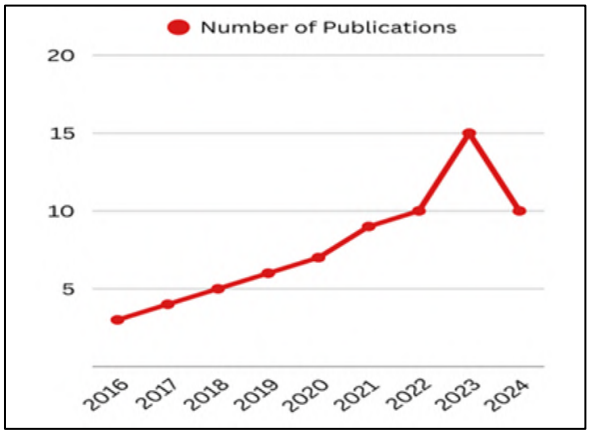

Fig. 5: Annual publication trends in AI-driven Fintech, green finance, and environmental sustainability research (2016-2025)

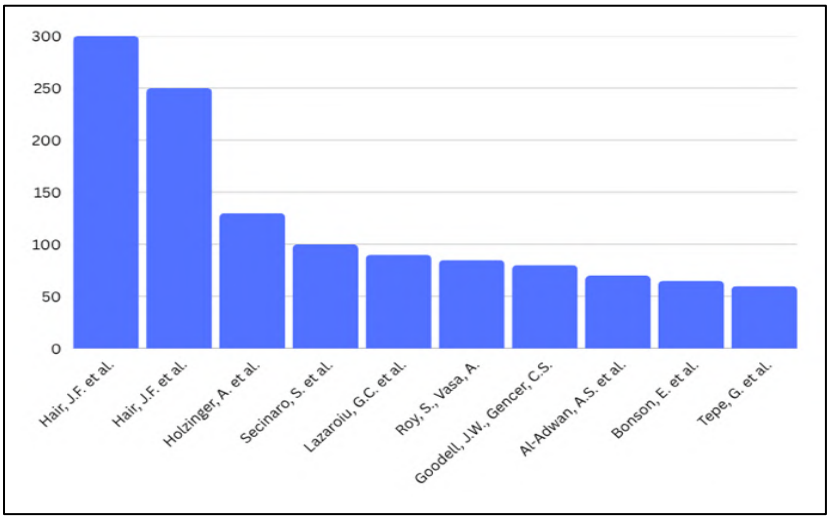

Fig. 6: Most influential authors in AI-driven Fintech and sustainability research

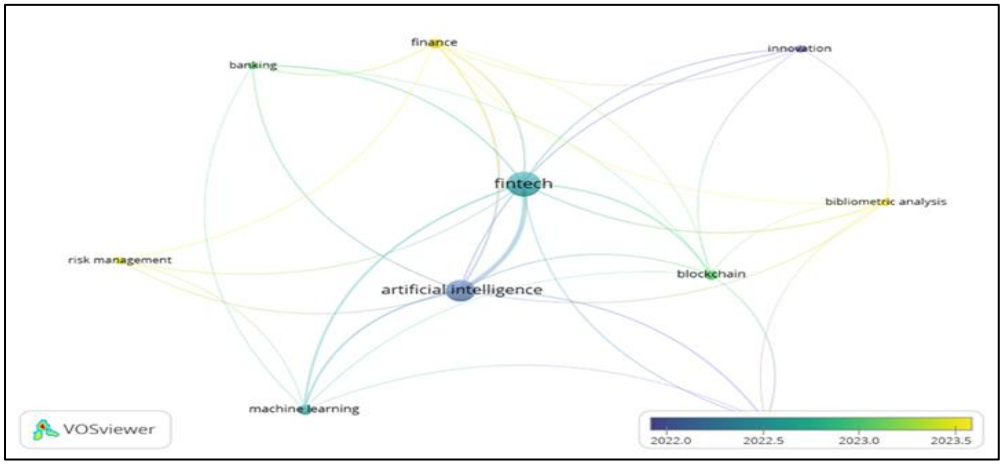

Fig. 7: Knowledge network of AI-driven Fintech and environmental sustainability research

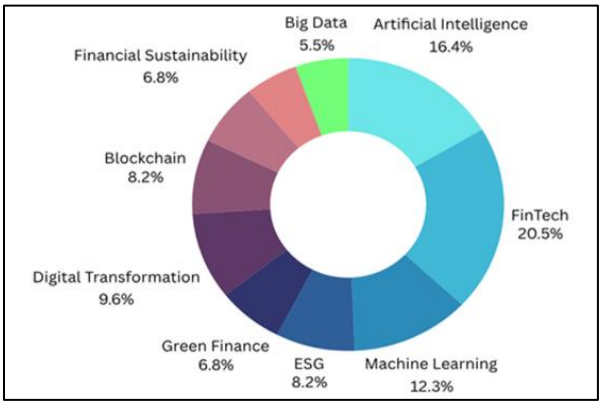

Fig. 8: Most frequent keywords in AI-driven Fintech and environmental sustainability research

blockchain, ESG, sustainable Finance, and Risk Management. Predictably, the keyword landscape exhibits a heavy density of AI and Fintech terminology—a feature that validates the precision of the initial retrieval strategy in isolating the nexus of intelligent systems and digital finance. However, the increasing presence of ESG, green finance, and sustainable finance keywords indicates a growing academic recognition of the sustainability implications of AI-driven financial systems. The keyword structure suggests that the literature is gradually shifting from a purely technological orientation toward a broader sustainability agenda. Earlier studies often focused on efficiency, automation, credit scoring, robo-advisory services, and fraud detection. More recent studies increasingly examine ESG analytics, climate-risk assessment, green investment optimization, ethical governance, and environmentally responsible financial innovation. Ultimately, this evolutionary trajectory aligns with a changing global paradigm, where financial intermediaries face intensifying pressure to dual-track their strategic priorities—marrying digital transformation with ecological responsibility and global sustainability frameworks (Lăzăroiu *et al*., 2024; Ma *et al*., 2025).

Geographic distribution of research contributions

The geographic distribution of publications demonstrates notable disparities in global research productivity. As illustrated in Fig. 9, developed economies, particularly the United States, the United Kingdom, and China, dominate research contributions in AI-driven sustainable finance. The prevalence of this dominance can be attributed to enhanced digital infrastructure, more sophisticated financial markets, higher levels of investment in AI technologies, and more established ESG regulatory frameworks. Emerging economies such as India, Turkey, Bahrain, Saudi Arabia, Jordan, and the United Arab Emirates also appear in the dataset, but their contribution remains comparatively limited. This geographic imbalance has important implications for the development of theory and practice. Since emerging and frontier economies often face distinct institutional conditions, digital infrastructure constraints, financial inclusion challenges, and sustainability priorities, the limited representation of these contexts restricts the generalizability of current knowledge. The geographic underrepresentation of developing economies is particularly critical, given that AI-driven financial innovations possess significant potential to alleviate financial exclusion, optimize sustainability-oriented investments, and catalyze green finance transformation within these vulnerable markets (Abdelhaq and Dwekat, 2024; Abdeljawad *et al*., 2025, Khoffash and Awwad, 2024, Awwad *et al*., 2024). Therefore, future research should pay greater attention to context-specific evidence from developing economies and frontier markets.

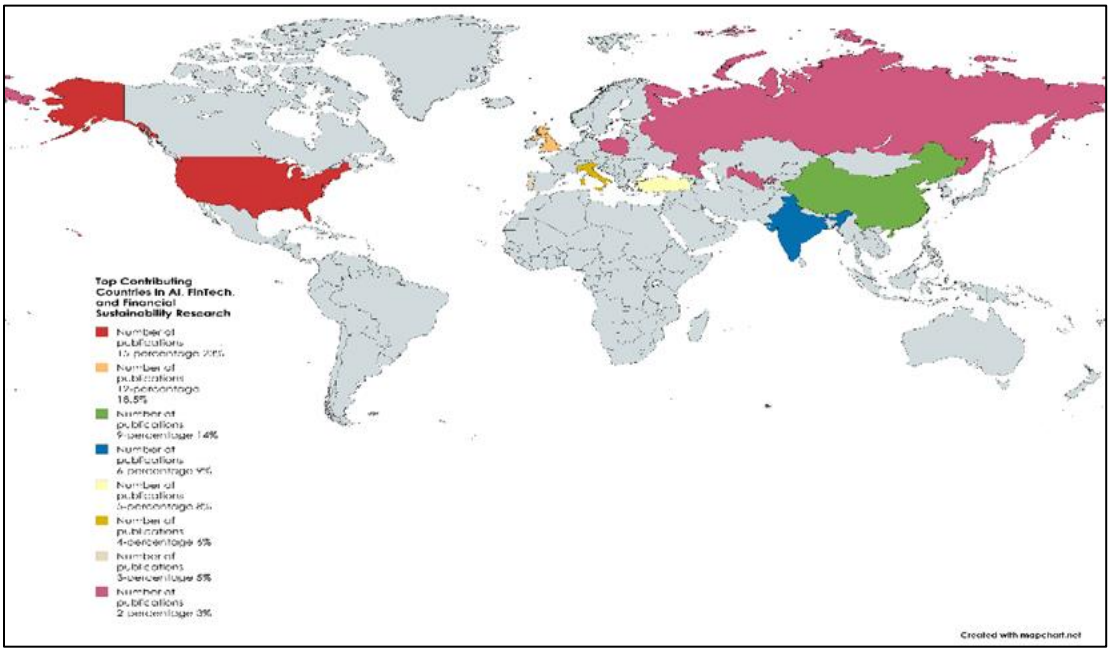

Fig. 9: Geographic distribution of research contributions in AI-driven Fintech and environmental sustainability

Institutional collaboration and bibliographic coupling

The analysis of bibliographic coupling indicates a growing collaboration among institutions within research networks focused on AI-driven sustainable finance research networks. Fig. 10 demonstrates that the field is shaped by interconnected institutional clusters involving universities, business schools, financial research centers, and sustainability-oriented research groups. The presence of these institutional linkages signifies that AI-driven Fintech research has transformed into a collaborative, cross-disciplinary area that bridges finance, data science, governance, sustainability, and environmental management. The presence of strong institutional clusters suggests that research collaboration is becoming increasingly globalized, although concentration remains stronger in developed academic ecosystems. This trend aligns with the global publication distribution, highlighting the persistent geographic disparities in knowledge production within the AI-driven sustainable finance remains uneven. Nevertheless, the emergence of collaborative clusters across countries and institutions indicates a growing opportunity for cross-regional research, particularly in areas related to ESG integration, climate finance, sustainable banking, and responsible AI governance.

Leading journals and publication outlets

Table 4 presents the leading journals contributing to AI-driven Fintech and environmental sustainability research. The findings indicate that the reviewed studies are distributed across journals specializing in international finance, Fintech, sustainability, digital innovation, banking, and environmental management. The prominence of outlets such as Research in International Business and Finance, Finance Research Letters, Sustainability, and related interdisciplinary journals confirm the multidisciplinary nature of the field. An analysis of the target journals reveals a significant paradigm shift, indicating that ecological and social sustainability dimensions are no longer peripheral but are now deeply anchored in mainstream

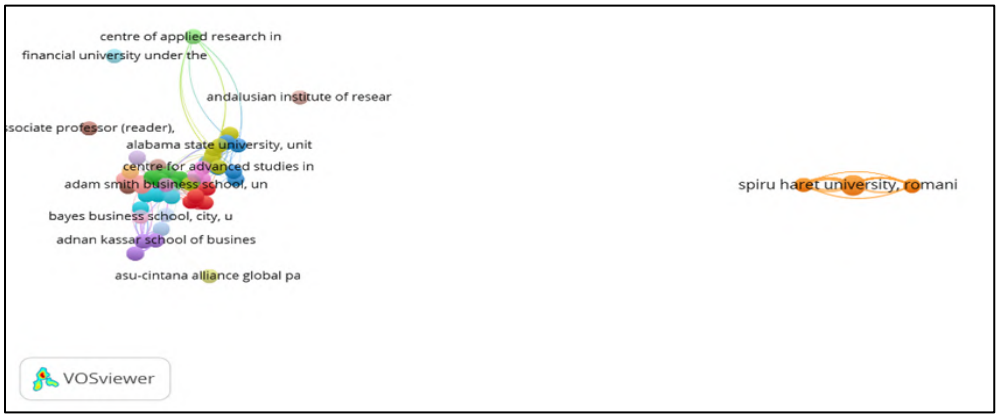

Fig. 10: Bibliographic coupling of research institutions in AI-driven sustainable finance research

Table 4: Leading journals in AI-driven Fintech and environmental sustainability research

Rank	Journal name
1	Research in International Business and Finance
2	Finance Research Letters
3	Sustainability
4	International Journal of Financial Studies

Fintech scholarship. Although many journals remain finance-oriented, the growing presence of sustainability and environmental management journals suggests that AI-driven Fintech is gaining relevance beyond traditional financial studies. This finding is particularly important for the current study because it confirms the suitability of positioning AI-driven Fintech within the environmental sustainability and green finance discourse, rather than treating it merely as a technological or banking innovation topic.

AI and Fintech transformation

The thematic content analysis underscores the role of AI as a cornerstone of Fintech innovation, driving structural transformations across the sector. The reviewed literature emphasizes the role of AI in enabling automation, predictive analytics, intelligent decision-making, customer personalization, credit scoring, fraud detection, and digital banking performance (Nguyen *et al*., 2023; Ma *et al*., 2025). AI-enabled financial systems enhance operational efficiency, bolster risk detection capabilities, improve service responsiveness, and facilitate real-time financial decision-making (Ghandour, 2021; Costa *et al*., 2024; Roszkowska, 2021; Rjoub *et al*., 2023). These results underscore a profound transformation in traditional financial intermediation, demonstrating how AI-enabled fintech is restructuring legacy banking models. Digital platforms supported by AI technologies are increasingly capable of processing large volumes of structured and unstructured data, identifying behavioral patterns, assessing risks, and delivering personalized financial services. Prior literature confirms that these technologies have catalyzed the development of highly scalable, adaptive, and resilient digital financial ecosystems (Coetzee, 2018; Demertzis *et al*., 2018; Cubric and Li, 2024; El Khoury *et al*., 2023; Boot *et al*., 2021). However, the results also suggest that technological transformation alone is insufficient unless AI-enabled financial innovation is aligned with broader sustainability, governance, and environmental objectives, while fostering transparency, resilience, accountability, and inclusive stakeholder participation.

Financial inclusion and sustainable development

Financial inclusion emerged as one of the dominant sustainability-oriented themes in the reviewed literature. AI-driven financial systems minimize transactional overhead, broaden digital footprints, optimize alternative credit-scoring frameworks, and foster financial inclusion among traditionally underserved populations (Carè *et al*., 2025; Naveed *et al*., 2017; Miftari *et al*., 2024). These functions are particularly relevant in emerging and developing economies where traditional banking infrastructure may be limited and where large segments of the population remain excluded from formal financial services. The reviewed studies indicate that AI applications such as intelligent customer segmentation, automated risk assessment, mobile financial services, and digital lending platforms can support broader financial inclusion and contribute to SDG-oriented development objectives (Abu Daqar *et al*., 2020; Al-Zaqeba *et al*., 2022; Mhlanga, 2020; Rahman *et al*., 2024). Concurrently, the net sustainability impact of AI-driven financial inclusion hinges on whether expanded digital access translates into responsible financial behavior, equitable lending practices, and tangible social and ecological benefits. Therefore, financial inclusion should be interpreted not only as access to financial services, but also as a pathway toward inclusive and sustainable development.

ESG integration and green finance

A rapidly expanding body of literature focuses on the role of AI in supporting ESG integration and environmentally sustainable financial practices. The findings show that AI-driven systems can improve sustainability reporting, ESG analytics, green investment screening, and climate-risk modelling (Lăzăroiu *et al*., 2024; Singh, 2024). These capabilities are increasingly important because financial institutions and investors require timely, accurate, and verifiable sustainability-related information to guide responsible investment decisions. The synthesized literature demonstrates that the convergence of blockchain technologies, intelligent financial architectures, and data-driven ESG frameworks can significantly enhance operational transparency, resource efficiency, and sustainable supply-chain finance (Rabbani, 2022; Patashkova *et al*., 2021; Gonçalves *et al*., 2023; Olayiwola *et al*., 2024). In this regard, AI-driven Fintech can strengthen green finance by improving the identification of sustainable investment opportunities, assessing environmental risks, and monitoring ESG performance. Nonetheless, the existing literature continues to offer limited empirical evidence that directly connects AI adoption with quantifiable environmental results. A thorough comparison of the studies reviewed also uncovers significant discrepancies in the conceptualization and assessment of environmental sustainability within AI-driven financial ecosystems. While several studies emphasize ESG integration, sustainability reporting, and green investment screening as indicators of sustainable financial transformation (Lăzăroiu *et al.,* 2024; Singh, 2024), relatively fewer studies provide direct empirical evidence regarding measurable environmental outcomes such as carbon-emission reduction, energy-efficiency improvement, pollution mitigation, or climate-adaptation performance. Crucially, the intellectual landscape suffers from a profound spatial imbalance; while developed economies with institutionalized digital infrastructure and mature ESG mandates dominate the literature, insights from emerging and developing economies remain highly fragmented and empirically underdeveloped (Carè *et al.,* 2025; Abdelhaq and Dwekat, 2024). This imbalance suggests that current knowledge remains more conceptually developed than empirically validated, particularly regarding the environmental effectiveness of AI-

enabled financial technologies within sustainability-oriented financial systems. However, literature still lacks sufficient empirical evidence linking these technological capabilities to measurable environmental outcomes such as carbon reduction or energy efficiency. In addition, a critical sustainability paradox emerges while AI systems are leveraged to optimize environmental efficiency, their underlying deployment relies on energy-intensive computational infrastructures—such as hyper-scale data centers and large language models—that directly exacerbate carbon emissions (Mayorov, 2020). This creates a critical need for a balanced perspective that considers both the environmental benefits of AI-enabled financial systems and their underlying energy footprint. Accordingly, future developments should prioritize "Green AI" approaches and energy-efficient digital finance infrastructures to ensure that technological advancement aligns with genuine environmental sustainability objectives (Rahman *et al*., 2024).

Ethical governance and regulatory challenges

Despite the substantial opportunities associated with AI-driven finance, ethical and governance-related concerns remain highly prominent. Data privacy risks, cybersecurity vulnerabilities, algorithmic bias, lack of explainability, and fragmented regulatory frameworks creates a complex matrix of operational and compliance barriers hindering responsible AI integration across financial architectures (Kazachenok *et al*., 2023; Kliestik *et al*., 2024; Khaddam and Alhanatleh, 2024). These challenges are particularly important because financial decisions based on opaque AI systems may affect credit access, investment allocation, risk pricing, and consumer protection. The literature therefore emphasizes the importance of ethical AI governance frameworks capable of ensuring transparency, accountability, fairness, and sustainability-oriented regulation within digital financial ecosystems (Mayorov, 2020; Abdelhaq *et al*., 2025a). Furthermore, scholars assert that the implementation of explainable AI (XAI), ethical auditing, responsible data governance, and adaptive regulatory frameworks are essential for reconciling innovation with consumer protection and environmental accountability (Brogi and Lagasio, 2024; Zarifis and Cheng, 2022). These findings suggest that the sustainability of AI-driven Fintech depends not only on technical capability but also on the governance structures that regulate its use. To move beyond a general discussion of ethical governance in AI-driven Fintech, it is essential to critically examine how key governance mechanisms are operationalized within real-world sustainable finance ecosystems. Explainable AI (XAI) constitutes a foundational pillar within this paradigm, enabling financial institutions to enhance the transparency of algorithmic decision-making by generating interpretable outputs for credit underwriting, ESG risk assessment, and portfolio asset allocation. This enhances trust among stakeholders and supports regulatory compliance by ensuring that model decisions can be understood, justified, and challenged when necessary (Abu Daqar *et al*., 2020; Al-Zaqeba *et al*., 2022; Mhlanga, 2020). In parallel, algorithmic auditing has surfaced as an effective governance tool for overseeing, assessing, and verifying AI systems used in financial services. Deploying dual internal and external auditing mechanisms enables financial intermediaries to systematically isolate algorithmic bias, verify lending fairness, and ensure strict compliance with socio-ecological and ethical standards. Such auditing mechanisms are increasingly integrated into risk management and compliance structures to strengthen accountability in AI-enabled financial ecosystems (Rahman *et al*., 2024). Furthermore, regulatory harmonization plays a critical role in ensuring the

consistent and responsible deployment of AI-driven financial technologies across jurisdictions. Given the cross-border nature of digital financial services, the alignment of regulatory frameworks is necessary to mitigate legal fragmentation, enhance supervisory efficiency, and promote standardized ESG disclosure and AI governance practices. Collectively, these mechanisms demonstrate that ethical governance in AI-driven Fintech is not merely a conceptual requirement, but an operational necessity embedded in explainability, auditing, and coordinated regulatory oversight within sustainable finance systems (Khan *et al*., 2025).

Environmental sustainability and green transformation

The findings demonstrate that AI-driven Fintech is increasingly institutionalized as a core mechanism for advancing sustainability objectives. Through advanced analytics, automated monitoring, and data-driven decision-making, AI can support climate-risk assessment, green investment optimization, carbon-related financial analysis, and sustainability-oriented financial innovation (Mertzanis, 2023). These functions hold significant importance for environmental sustainability since financial intermediaries play an indispensable role in mobilizing capital toward eco-friendly ventures while actively disincentivizing investment in carbon-intensive sectors. Nevertheless, the reviewed literature remains more conceptually developed than empirically validated in relation to environmental sustainability outcomes) (Elhady and Shohieb, 2025). Many studies discuss the potential of AI to support sustainable finance, but fewer provide direct empirical evidence on how AI-driven Fintech affects environmental indicators. This constraint is pivotal for the future advancement of the discipline and holds particular significance for journals focused on environmental management. Future research should therefore examine how AI-enabled financial systems influence measurable sustainability outcomes, including green investment performance, emissions reduction, climate-risk mitigation, and resource efficiency (Pavlidis, 2025). Despite the growing theoretical consensus that AI-driven Fintech can support environmental sustainability, empirical validation of these claims remains limited (Khan *et al*., 2025). The majority of current studies predominantly emphasize the conceptual connections between AI technologies and sustainability results, especially in domains like ESG integration, optimization of green investments, and analytics related to climate risk (Abu Daqar *et al*., 2020). However, there is still a lack of robust empirical evidence based on measurable environmental performance indicators, such as carbon emission reduction, energy efficiency improvements, and quantifiable climate mitigation outcomes. This indicates a clear gap between the theoretical expectations of AI-enabled sustainable finance and its actual environmental impacts in practice. Consequently, forthcoming studies ought to emphasize empirical, longitudinal, and data-driven methodologies to evaluate the actual environmental performance effects of AI-driven financial technologies (Ghandour, 2021). In addition to its enabling role in sustainable finance, AI systems are associated with significant computational and energy demands, particularly in large-scale data processing and model training. This introduces an important consideration regarding the net environmental impact of AI technologies. Furthermore, while AI aids in promoting sustainable financial choices, the energy it consumes and the infrastructure it necessitates might diminish these environmental advantages. Therefore, a balanced evaluation of AI-driven Fintech should consider both its sustainability-enhancing capabilities and its

underlying environmental footprint (Miftari *et al*., 2024).

Research gaps and future directions

The results reveal several important research gaps. First, empirical evidence remains concentrated in developed economies, while emerging and frontier markets remain comparatively underrepresented (Abdelhaq and Dwekat, 2024; Abdeljawad *et al*., 2025). Second, numerous studies emphasize the technological or financial advantages of AI-driven Fintech, while a smaller number investigate its implications for environmental performance. Third, longitudinal and interdisciplinary research remains limited, particularly in relation to the long-term sustainability effects of AI-enabled financial systems (Miftari *et al*., 2024; Aw *et al*., 2024). Accordingly, future research should develop more context-sensitive, empirical, and interdisciplinary approaches. Comparative studies across developed and developing markets can enhance the comprehension of how institutional quality, regulatory capacity, digital infrastructure, and sustainability policies influence AI-driven sustainable finance. In addition, future studies should integrate environmental performance indicators into Fintech research to assess whether AI-driven financial innovation contributes to green finance transformation and environmental sustainability.

Integrated discussion

Overall, the findings indicate that AI-driven Fintech is evolving into a sustainability-oriented financial ecosystem; however, the literature remains fragmented across technological, financial, governance, and environmental dimensions, limiting the development of unified theoretical and empirical frameworks (Mertzanis, 2023; Pavlidis, 2025). From a critical empirical standpoint, the foundation of evidence backing the environmental efficacy of AI-driven Fintech is predominantly theoretical rather than empirically substantiated. While existing studies frequently assume positive sustainability outcomes, there is still limited robust empirical evidence directly linking AI-based financial applications to measurable environmental impacts. This constraint is especially apparent in developing economies, where disjointed ESG reporting frameworks and data limitations obstruct dependable empirical validation (Abu Daqar *et al.,* 2020; Elhady and Shohieb, 2025). Moreover, the translation of AI-driven financial analytics into real-world environmental performance outcomes remains insufficiently examined. Although AI systems increasingly influence investment decisions and ESG risk assessments, their actual contribution to long-term sustainability outcomes requires further investigation through longitudinal and cross-country empirical approaches (Abdelhaq and Dwekat, 2024; Abdeljawad *et al.,* 2025). In addition, governance and ethical aspects are crucial for the successful implementation of AI-driven sustainable finance. The absence of cohesive regulatory structures, coupled with algorithmic bias, a deficiency in transparency, and unequal access to AI-enhanced financial systems, continues to challenge fairness and accountability (Elhady and Shohieb, 2025; Pavlidis, 2025). From an implementation perspective, AI-driven sustainable finance adoption is influenced by organizational readiness, managerial capability, technical integration complexity, scalability limitations, interoperability challenges, cybersecurity risks, and weak data governance structures (Abu Daqar *et al*., 2020). Ultimately, securing the long-term sustainability of AI-enabled fintech remains contingent upon optimizing infrastructure energy-efficiency, integrating supportive technologies, and developing standardized sustainability metrics alongside advanced digital human capital. Future research

should therefore adopt more empirically grounded approaches that evaluate both the opportunities and risks associated with AI-driven sustainable finance systems.

Theoretical implications

From a theoretical perspective, this study contributes by integrating AI, Fintech, ESG integration, green finance, and environmental sustainability within a unified conceptual framework. Unlike previous studies that examined these dimensions separately, the current study demonstrates their interconnected role in shaping sustainable digital finance ecosystems and highlights the multidimensional role of AI in enabling environmentally responsible financial transformation. The findings further extend knowledge by positioning AI-driven Fintech not merely as a technological innovation mechanism, but as a sustainability-enabling infrastructure supporting green investment analytics, climate-risk assessment, ESG-oriented decision-making, and environmentally sustainable financial inclusion. Crucially, this study offers a valuable framework by exposing the nascent thematic clusters and structural intellectual topographies that govern the evolutionary trajectory of the sustainable digital finance paradigm. Furthermore, it highlights the need for future interdisciplinary research integrating sustainability science, digital finance, governance studies, and environmental economics to better understand long-term environmental and climate implications of AI-driven financial systems (Khan *et al*., 2025).

Practical and managerial implications

The findings provide several practical implications for financial institutions, Fintech firms, and digital banking practitioners. Ultimately, the data reveals that the deployment of intelligent financial systems transcends basic automation; it systematically refines operational efficiency, operationalizes advanced fraud mitigation, and structures a resilient framework for risk management and hyper-personalized customer engagement (Ghandour, 2021; Rahman *et al*., 2024). More importantly, financial institutions should increasingly integrate AI capabilities into sustainability-oriented financial practices, including ESG analytics, green investment evaluation, climate-risk modelling, and environmentally responsible financing strategies. AI-driven financial systems can also foster greater inclusivity in digital financial services by enhancing access for underrepresented communities and backing sustainable financial inclusion programs (Abu Daqar *et al*., 2020; Al-Zaqeba *et al*., 2022). Additionally, organizations should prioritize transparency, explainability, and ethical AI governance to strengthen consumer trust and ensure responsible digital transformation. Implementing explainable AI (XAI) frameworks, transparent data management practices, and ethical auditing systems may improve accountability and enhance stakeholder confidence in AI-driven financial services (Brogi and Lagasio, 2024; Zarifis and Cheng, 2022).

Policy and regulatory implications

The study also offers important implications for policymakers and regulatory authorities responsible for governing digital financial systems. Managing the rapid expansion of AI-enabled fintech demands robust regulatory architectures that equitably balance financial innovation against consumer safety, ethical governance, and socio-environmental sustainability. The findings indicate that policymakers should develop adaptive regulatory strategies addressing algorithmic transparency, cybersecurity risks, data privacy protection, and AI accountability within financial ecosystems (Mayorov, 2020; Abdelhaq *et al*.,

2025b). Regulatory institutions must also support sustainability-driven financial innovation by endorsing ESG disclosure standards, offering incentives for green finance, and fostering environmentally conscious digital financial practices. Moreover, governments and financial regulators—particularly in emerging economies—should strengthen digital infrastructure, financial literacy programs, and sustainability-oriented regulatory capacities to facilitate responsible AI adoption and inclusive financial transformation. Collaboration across jurisdictions and coordination of international governance could enhance the establishment of globally uniform standards for ethical and sustainable AI-driven finance (Boot *et al*., 2021; Coetzee, 2018, Awwad, 2022).

Future research directions

Several promising directions for future research emerge from this study. First, future empirical investigations should examine the direct environmental impacts of AI-driven Fintech systems using measurable sustainability indicators such as carbon reduction, energy efficiency, green investment performance, and climate-risk mitigation outcomes (Lăzăroiu *et al*., 2024; Singh, 2024). Second, addressing the empirical gap in emerging and frontier economies is crucial to understanding how institutional environments, regulatory quality, digital infrastructure, and socioeconomic dynamics shape the socio-environmental impacts of AI-driven financial systems (Abdelhaq and Dwekat, 2024; Abdeljawad *et al*., 2025). Third, future studies should explore the long-term ethical and societal implications of AI-driven finance, particularly regarding algorithmic fairness, consumer behaviour, financial inequality, and digital trust. Crucially, the long-term integrity of digital financial markets hinges on a strategic pivot toward explainable AI, formalized ethical auditing frameworks, and systemic governance mechanisms designed to anchor automated workflows within transparent and sustainable paradigms. Finally, future interdisciplinary research integrating environmental sustainability, AI governance, climate finance, ESG analytics, and digital innovation is essential for developing a deeper understanding of how AI-driven Fintech can contribute to achieving (SDGs) and promoting resilient, inclusive, and environmentally sustainable financial systems.

CONCLUSION

This study examined the interrelationships between AI, Fintech, sustainable finance, ESG integration, and environmental sustainability using a combined bibliometric and thematic content analysis approach. These results demonstrate that AI serves as a foundational driver in transitioning financial systems toward data-driven, sustainable, and digitally integrated decision-making architectures. Bibliometric results reveal a significant growth in scholarly attention to AI-driven sustainable finance, particularly after 2020, driven by the global expansion of ESG integration, green finance initiatives, and sustainable investment strategies. This evolution reflects a conceptual shift in literature, moving from technology-focused viewpoints to more cohesive frameworks that merge financial innovation with sustainability objectives. The thematic analysis demonstrates that AI-enabled financial technologies support sustainability through multiple channels, including green investment analytics, ESG risk assessment, climate-risk modeling, sustainable digital banking, and financial inclusion enhancement. However, the findings also highlight persistent challenges related to algorithmic bias, data privacy concerns, cybersecurity risks, lack of transparency, and fragmented regulatory structures, which may limit

the effectiveness and fairness of AI-driven financial systems. From a critical perspective, the current body of literature is predominantly characterized by conceptual and exploratory research, with scant empirical evidence demonstrating direct connections between AI-driven Fintech applications and measurable environmental outcomes such as carbon emission reduction, renewable energy financing, and enhancements in resource efficiency. This limitation is particularly evident in emerging economies, where data availability and ESG measurement infrastructures remain underdeveloped. In addition, an increasingly important yet underexplored dimension is the environmental footprint of AI systems themselves. The significant computational requirements, energy consumption, and infrastructure intensity associated with large-scale AI applications present serious concerns regarding their net sustainability impact, thus creating a crucial paradox between facilitating environmental solutions and generating further environmental pressures. Accordingly, forthcoming studies ought to emphasize empirical, longitudinal, and lifecycle-based approaches that simultaneously evaluate the environmental advantages and ecological expenses associated with AI-driven financial systems. Such approaches are essential to develop a more balanced, evidence-based, and policy-relevant understanding of sustainable digital finance. Overall, this study asserts that AI-driven Fintech ought to be perceived not just as a technological innovation, but as a multifaceted transformation reshaping financial systems, governance structures, and pathways to sustainability. Strengthening empirical validation, improving methodological rigor, and integrating environmental impact assessments remain essential for advancing both academic discourse and practical policy development in this evolving field.

AUTHOR CONTRIBUTIONS

R. BinSaddig was responsible for conducting the bibliographic search, selecting the relevant studies, organizing and screening the literature, contributing to thematic coding, preparing the initial manuscript draft, and revising the manuscript during the review process. B.S. Awwad was responsible for conceptualizing the study, designing the research framework and methodology, supervising the bibliometric and thematic analyses, interpreting the findings, synthesizing the manuscript, and critically reviewing and revising the final manuscript version. A. Zakaria Salem was responsible for supporting the data analysis process, reviewing the bibliometric mapping and thematic classification, validating the analytical interpretation, and reviewing and editing the manuscript for intellectual and academic consistency.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors confirm that all ethical considerations related to plagiarism, research misconduct, data fabrication or falsification, duplicate publication or submission, and redundancy have been fully observed throughout the preparation and submission of this study.

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☑ Negative AI Statement

The authors confirm that no AI tools or services were used in the writing, analysis, interpretation, or preparation of this manuscript.

ABBREVIATIONS

AI	AI
ESG	Environmental, social, and governance
Fintech	Financial technology
GF	Green finance
ML	Machine learning
NLP	Natural language processing
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
RegTech	Regulatory technology
SDGs	Sustainable development goals
SMEs	Small and medium enterprises
VOSviewer	Visualization of similarities viewer
XAI	Explainable AI

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