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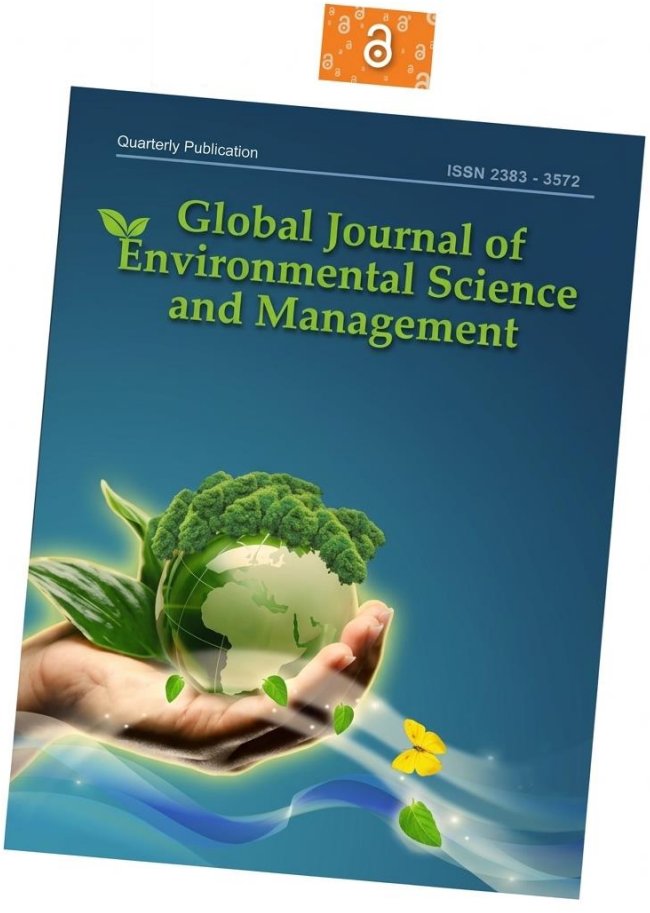

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ORIGINAL RESEARCH PAPER

Simultaneous removal of heavy metals from aqueous solutions by pineapple crown and avocado peel hydrogel composites

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ABSTRACT

BACKGROUND AND OBJECTIVES: Heavy metal contamination from industrial wastewater remains a global concern. Biomass waste still contains active compounds that can be processed into useful materials. The study aimed to resolve both challenges by synthesizing composite hydrogels derived from pineapple crowns and avocado peels, facilitating the concurrent adsorption of lead, cadmium, and copper from aqueous solutions.

METHODS: Composite hydrogels were synthesized using free radical polymerization using pineapple crown biochar and avocado peel biochar as grafting substrates. The material was characterized using F*ourier transform infrared spectroscopy*, *scanning electron microscopy-energy dispersive x-ray spectroscopy*, *Brunauer-Emmett-Teller, and hardness testing* to determine its physicochemical properties. The process of adsorption utilizes a batch system in a solution that contains lead, cadmium, and copper ions at the same time, with a potential of 4 to 6 and a temperature set at 26 degrees Celsius, operating at a speed of 125 revolutions per minute for a total time of 300 minutes. *The adsorption kinetics were assessed utilizing both the pseudo-first-order and pseudo-second-order models, with the model fit determined by the* coefficient of determination value and the correlation.

FINDINGS: Both hydrogels demonstrated mesoporous structures with high specific surface areas (square meters per gram) of 767.61 for pineapple crown composite hydrogel and 802.41 for avocado peel composite hydrogel, along with rich functional groups such as hydroxyl, carboxyl, alkyl, nitrile, and carbonyl groups that facilitate chemisorption. *The composite hydrogel made from avocado peel demonstrated the greatest adsorption capacity (measured in milligrams per gram), recording values of* 0.56 for lead, 0.43 for cadmium, and 0.41 for copper. These results were better than the performance of the pineapple crown composite hydrogel. Adsorption kinetics were well described by the pseudo-second-order model, with coefficient of determination values from 0.91 to 0.98 for composite hydrogel.

CONCLUSION: The performance of avocado peel composite hydrogels has improved compared to that of pineapple crown composite hydrogels, which is due to better porous accessibility and the presence of functional groups. These outcomes validate the significance of selecting biomass and the parameters of synthesis. Although the resulting adsorption capacity is lower than developed adsorbents, this study *offers benefits related to sustainability, affordability, and the availability of local raw materials, rendering it very* promising for sustainable wastewater treatment.

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INTRODUCTION

Biomass waste from agriculture and the food processing industry has become an increasingly serious environmental problem, particularly in tropical countries with high fruit production. Biomass is composed of 40–45 percent (%) lignocellulosic compounds, which include 25–35% cellulose, 15–30% hemicellulose, approximately 10% lignin, and approximately 10% inorganic components (Rico-García *et al.,* 2020). In Indonesia, pineapple is a leading horticultural commodity; in Aceh Province alone, the production of pineapple and avocado reached 214,372 quintals (21,437.2 tons) and 857,944 quintals (85,794.4 tons), respectively, in 2023. Despite its significant content of structural polysaccharides and bioactive compounds, avocado peel, which makes up about 15–20% of the fresh fruit's weight, is similarly treated as waste during processing (García-Vargas *et al.,* 2020; Ahmad and Danish, 2022; Bangar *et al.,* 2022). The magnitude of this problem is amplified by the rapid increase in fruit production. Over the last two decades (2000–2022), pineapple production in Indonesia has grown at an average rate of 13.42% per year, with an even higher growth rate of 23.85% per year in the most recent five-year period. As a result of this expansion, biomass waste is generated that accounts for about 10–25% of the total mass of the fruit, which encompasses crowns, peels, cores, and stems (Pereira *et al.*, 2021; Fouda-Mbanga and Tywabi-Ngeva, 2022; Sarangi *et al.*, 2022). Pineapple crown biomass typically contains about 56% cellulose, 16.8% hemicellulose, and 13.1% lignin (Faria *et al*., 2020; Mamani *et al*., 2020; Bernardes *et al*., 2023), whereas avocado peel contains 12.1–27.6% cellulose, 11.5–25.3% hemicellulose, and 4.4–35.3% lignin (Palma *et al*., 2016; Páramos *et al*., 2020; Ahmad and Danish, 2022; Bangar *et al*., 2022). This composition reveals a considerable density of hydroxyl groups and various reactive functional groups, notably a high level of oxygen content, thereby making both biomasses exceptionally well-suited for application as precursors for lignocellulosic adsorbents, such as biochar and hydrogel composites. These functional groups are critical for generating surface reactivity during pyrolysis, enhancing the development of porous biochar structures, and enabling efficient grafting within the hydrogel matrix. These features can markedly enhance the ability of the resulting composites to engage in chemical interactions by binding heavy metal ions through mechanisms such as complexation and ion exchange. Simultaneously with the rising accumulation of biomass, the pollution of aquatic systems by heavy metals persists as a critical issue for environmental integrity and public health. Among various types of heavy metals, lead [Pb(II)], cadmium [Cd(II)], and copper [Cu(II)] are among the most problematic because they are non-biodegradable, accumulate in aquatic organisms, and pose serious toxic impacts on both humans and ecosystems (Reshmy *et al*., 2021; Saran *et al*., 2021; Alraddadi *et al*., 2023). Chronic exposure to these metals is associated with neurological disorders, kidney damage, hypertension, carcinogenesis, and reproductive dysfunction. At the ecosystem level, the presence of heavy metals damages the structure and function of aquatic food webs, thus inhibiting energy flow and ultimately reducing biodiversity levels. Numerous human activities, such as mining, electroplating, the battery and pigment sectors, along with intensive agricultural methods, serve as significant contributors to the levels of Pb, Cd, and Cu found in industrial effluents. Therefore, to reduce the concentration of heavy metals before they are discharged into the environment, effective, efficient, and sustainable wastewater treatment technologies are needed. Chemical precipitation, coagulation-flocculation, ion exchange, membrane filtration, electrochemical processes, and bioremediation are some of the physical, chemical, and biological processes commonly used to remove heavy metals from wastewater. Despite their advantages, all of these methods are still subject to various constraints, including the production of secondary sludge, significant

reagent or energy usage, and a limited range of hydrogen potential (pH) in which they can operate effectively (Alraddadi *et al*., 2023). One of the best, most adaptable, and least expensive ways to get rid of heavy metals from solutions is through adsorption. Conventional adsorbents such as activated carbon, zeolites, and ion exchange resins perform well in absorbing heavy metals, but they are expensive and difficult to regenerate. Consequently, the focus should be on creating biosorbent materials from renewable biomass that excel in absorbing heavy metals, characterized by excellent performance, cost-effectiveness, and eco-friendliness. Hydrogels are three-dimensional cross-linked polymers that can absorb water well. Due to its modifiable chemical nature, high swelling capacity, and excellent mass transfer characteristics, hydrogel continues to be a potential adsorbent matrix for removing heavy metals (Zhao *et al*., 2023; Zhu *et al*., 2023). Hydrogels can provide a very large binding site for metal ions by incorporating hydrophilic groups such as carboxylic acid (–COOH), hydroxyl (–OH), amine (NH_2), and sulfonic acid (SO_3H) into the matrix. Conversely, the growing three-dimensional network improves ion diffusion into the material's interior (Curvello *et al*., 2019; Rahmanihanzaki and Hemmati, 2022). In this case, biochar produced through pyrolysis of lignocellulosic biomass has a highly porous structure with a large specific surface area and diverse surface chemistry. On the other hand, nanocellulose derived from agricultural residues has a high aspect ratio, high mechanical strength, and high density of hydroxyl groups. Consequently, the inclusion of biochar and nanocellulose within a hydrogel matrix is an advantageous approach for the development of high-performance biosorbents. Biomass-based hydrogel composites for heavy metal adsorption have been studied in previous research. These include cellulose hydrogels produced from agricultural waste combined with zeolite for extracting Cu(II) (Lunardi *et al*., 2024); cellulose/poly(glycerol tartrate) nanocomposite hydrogels for extracting Pb(II), Cd(II), and Cu(II) (Mohammadbagheri *et al*., 2024); porous graphene-based composite hydrogels for extracting Pb(II) and Cd(II) (Zhang *et al*., 2023); and sodium alginate/coffee waste composite hydrogels for extracting Pb(II) (Alraddadi *et al*., 2023). Hydrogels composed of lignin and produced from a mixture of biochar demonstrate strong capabilities in the absorption of various metals and dyes (Wu *et al*., 2021; Du *et al*., 2023; Zhang *et al*., 2023; Zhao *et al*., 2023). Based on the literature review conducted, no research reports are to be identified that discuss the synthesis or application of hydrogel composites derived from pineapple crown and avocado peel biomass for the simultaneous removal of Pb(II), Cd(II), and Cu(II) from aqueous solutions. This study aims to fill the existing research gap by showcasing an innovative biosorbent system that utilizes underutilized agricultural waste. This approach offers a sustainable and effective means of adsorbing multiple metal ions. The combination of polyacrylamide (PAM) hydrogel with biochar, nanocellulose, and nanolignin, all derived from agricultural waste, has the potential to enhance adsorption capacity, improve mechanical stability, and promote environmental sustainability. Theoretical and comparative studies into hydrogel materials reveal that PAM has a considerable ability to absorb water and is straightforward to process (Gujjala *et al*., 2022). Research on composite hydrogels is still being conducted utilizing various types of raw materials. This study aims to synthesize, characterize, and evaluate the adsorption kinetics and capacity of composite hydrogels derived from pineapple crown and avocado peel for the simultaneous removal of Pb(II), Cd(II), and Cu(II) from aqueous solutions, with emphasis on the influence of biomass composition and synthesis conditions on adsorption performance. The primary aim of this study is to analyze the adsorption kinetics under a fixed initial concentration to determine the initial performance of the material. Adsorption isotherms and thermodynamic parameters will be

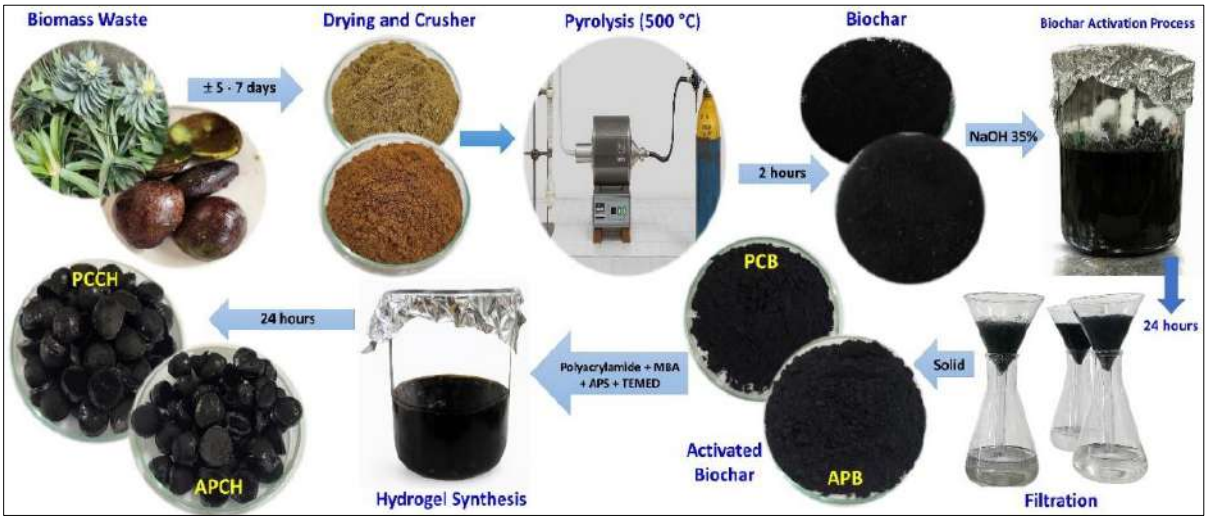


Fig. 1: The stages of the process of hydrogel composite synthesis from biomass waste

addressed in subsequent studies. This study was conducted at the Research Laboratory of the Department of Chemical Engineering, Faculty of Engineering, Syiah Kuala University, Banda Aceh, Indonesia, in 2025.

MATERIALS AND METHODS

The research materials consisted of pineapple crown and avocado peel, sodium hydroxide (NaOH, 35%, Merck), PAM (Sigma-Aldrich), N,N'-methylenebisacrylamide (MBA, Sigma-Aldrich), ammonium persulfate (APS, Merck), tetramethylethylenediamine (TEMED, Sigma-Aldrich), nitric acid (HNO_3 65%, Merck), lead(II) nitrate ($Pb(NO_3)_2$, Merck), cadmium(II) nitrate tetrahydrate ($Cd(NO_3)_2{\cdot}4H_2O$, Merck), copper(II) sulfate pentahydrate ($CuSO_4{\cdot}5H_2O$, Merck), and distilled water.

Composite hydrogel preparation

The pineapple crown and avocado peel waste collected earlier were cleaned and washed until free of dirt, then dried in the sun for 5–7 days. The biomass was then dried in an oven at 80 degrees Celsius (°C) for 1 hour (h) to reduce its moisture content and then ground to a particle size of 100 mesh. The biomass powder was pyrolyzed at 500 °C for 2 h in a tubular furnace (Nabertherm high-temperature lifting (LHT) 02/17, with a bottom loading (LB) system) under a continuous nitrogen flow of 100 milliliters per minute (mL/min) and a heating rate of 10°C/min. The conditions for pyrolysis operation were established based on prior literature and empirical optimization aimed at enhancing pore development and the generation of oxygen-containing functional groups (for instance, –OH, –COOH) on the biochar surface, which effectively bind heavy metals in aqueous solutions. The biochar was then chemically activated using a 35% NaOH solution at a solid-liquid ratio of 1:3 weight per volume (w/v) for 24 h at room temperature. Subsequently, it was rinsed with distilled water until a neutral pH was achieved and then dried in an oven at 105°C for 1 h. Three grams of activated biochar from pineapple crowns (PCB) and avocado peels (APB) were each placed in a glass beaker, followed by the addition of 40 g of 10% w/w PAM solution, which was already filled with distilled water as a solvent. The mixture was then stirred using a magnetic stirrer (Cimarec, Thermolyze) at a speed of 600 rpm for 15 minutes at room temperature. Subsequently, 0.1% MBA (relative to the weight of PAM) was incorporated as a crosslinker. The polymerization process begins by adding 0.1 grams of ammonium persulfate (APS) and 0.05

milliliters (mL) of tetramethylethylenediamine (TEMED), which are equivalent to 0.1% by weight and 0.05% by weight, respectively, relative to the PAM weight basis. After thoroughly mixing, the solution mixture is shaped and allowed to sit for 12 to 24 hours at room temperature to guarantee complete polymerization. Subsequently, the hydrogel underwent drying in an oven set at 40–60°C for a period of 12–24 hours to ensure that structural stabilization was achieved before proceeding with further characterization and adsorption testing. These polymerization parameters were selected to optimize network density and pore structure, which influence the swelling behavior and diffusion of metal ions during adsorption. The phases involved in the synthesis process of hydrogel composites derived from biomass waste are illustrated in Fig. 1.

Physicochemical characterization

The identification of functional groups, particularly organic acids, was conducted using Fourier transform infrared spectroscopy (FTIR); Nicolet iS10, thermo scientific, over a wavenumber range of 4000 to 500/centimeter (cm). The specific surface area and pore characteristics were determined with the Brunauer, Emmett, and Teller (BET) analysis (Micromeritics ASAP 2020). The microstructure morphology and elemental composition were analyzed using scanning electron microscopy combined with energy dispersive spectroscopy (SEM–EDS); Hitachi SU3500) at an accelerating voltage of 15 kilovolts (kV), and the elemental composition was expressed as weight percent (wt%). The mechanical hardness of the hydrogel samples was evaluated using a Shore A durometer (Model SHR-A-GOLD, SR. No. 17958) under controlled conditions. Measurements were conducted at room temperature (22.1 °C) and relative humidity of 53.2%, in accordance with standard indentation intervals of 1 and 15 seconds. This approach facilitates a uniform evaluation of the structural durability of hydrogels when subjected to mild compression, which is pertinent to batch adsorption scenarios.

Adsorption process

To prepare the initial solutions of Pb(II), Cd(II), and Cu(II), 0.226 g of $Pb(NO_3)_2$, 0.344 g of $Cd(NO_3)_2{\cdot}4H_2O$, and 0.451 g of $CuSO_4{\cdot}5H_2O$ were combined in 1 L of distilled water until a homogeneous solution was achieved. To prevent precipitation and ensure ionic stability, especially for Pb(II) and Cu(II), 1 mL of concentrated nitric acid (HNO_3, 65%) was added to the stock solution to maintain the pH below 2. The initial concentrations of Pb(II), Cd(II), and Cu(II) were 141.51, 125.66, and 114.94 mg/L, respectively. The adsorption procedure was conducted utilizing 5 grams each for PCCH and APCH and 20 grams of both PCB and APB. The samples were placed separately in a batch reactor containing 100 milliliters of stock metal solution. The amount of adsorbent was determined based on initial optimization, considering the differences in water content, porosity, and surface area distribution between the hydrogel and biochar. Even though the masses of the dsorbents vary, the comparison of adsorption performance was conducted based on normalized capacity (mg/g), with plans for additional tests to explore kinetics under mass-balanced conditions. The pH of the solution used was maintained in the range of 4–6, which was controlled using a dilute NaOH solution. The pH was periodically monitored and adjusted to remain within the desired range using dilute NaOH, to prevent drift caused by hydrolysis or ion exchange. This pH range was determined to limit the potential for metal hydroxide precipitation and to sustain the ionic forms of Pb(II), Cd(II), and Cu(II), while simultaneously enhancing the electrostatic attraction between the metal ions and the adsorbent surface. A portable digital pH meter (ATC, waterproof model) was used for periodic monitoring of pH to ensure solution stability throughout the adsorption process, thereby minimizing variability in metal uptake due to pH fluctuations. The adsorption experiment

was conducted in a batch system at 26 °C using an orbital shaker (Edmund Buhler SM 25) operated at a speed of 125 rpm for 300 minutes. Observations conducted at various time intervals (5, 15, 30, 60, 120, 180, and 300 minutes) to analyze the adsorption kinetics. At each observation point, the adsorbent was separated from the filtrate using vacuum filtration lined with Whatman No. 42 filter paper (pore size 2.5 µm). The stability of the hydrogel was preserved throughout the filtration process, with no signs of disintegration or particle breakthrough detected, thereby reducing the likelihood of interference in atomic absorption spectroscopy (AAS) measurements. The filtration was then analyzed to determine the residual metal concentrations using AAS.

Adsorption capacities and adsorption kinetics

The removal of heavy metal ions by the adsorbent is expressed as a percentage removal (%R), and the number of ions adsorbed per unit weight of adsorbent at equilibrium is expressed as adsorption capacity (qe), in milligram per gram (mg/g), and was calculated the removal efficiency using Eq. 1 (Kumar *et al*., 2023): and calculates the adsorption capacity at equilibrium using Eq. 2 (Kumar *et al*., 2023).

$$\%(R) = \frac{(C_o - C_e)}{C_0}\ x\ 100 \quad (1)$$

$$q_e = \frac{(C_o - C_e)\,V}{m} \quad (2)$$

Where: C_o (mg/L) is the initial metal ion concentration in the solution, Ce (mg/L) is the equilibrium concentration after adsorption, V is the volume of the solution in liters (L), and m (g) is the adsorbent mass. All adsorption experiments were carried out in triplicate, and the results are shown as the mean along with standard deviation to ensure statistical reliability. Significant differences between adsorbents were assessed using one-way ANOVA with a significant level of $p < 0.05$. To investigate the adsorption mechanism and rate-controlling steps, the experimental kinetic data were fitted using pseudo-first order (PFO) using Eq. 3 (Godiya *et al*., 2019; Wang *et al*., 2020) and pseudo-second-order (PSO) models using Eq. 4 (Shaban *et al*., 2018; Weber and Quicker, 2018; Zhang *et al*., 2020; Pasgar *et al*., 2022):

$$log\ (q_e - q_t) = log\ q_e \frac{k_1}{2.303}\,t \quad (3)$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (4)$$

Where: k_1 is the PFO rate constant, in per minute (/min), and k_2 is the PSO rate constant, in grams per milligram per minute (g/mg/min). The kinetic parameters (k_1, k_2, and qe) were obtained from linear regression fitting using OriginPro 2025 software, and the coefficient of determination (R^2) was used to assess the goodness of fit of each model.

RESULTS AND DISCUSSION

Physicochemical characterization

The FTIR spectra of PCCH and APCH, shown in Fig. 2, indicates the absorption bands at 3348/cm (PCCH) and 3346/cm (APCH), indicating O–H stretching vibrations. The findings obtained are in agreement with prior studies which suggest that hydroxyl and amide groups found in hydrogels can act as active sites that facilitate interactions in the adsorption mechanism of heavy metal ions through hydrogen bonding and complexation, thus enhancing the adsorption capabilities of composite hydrogel materials (Zhao *et al*., 2025b). Strong bands at 1657/cm for PCCH and 1610–1608/cm for APCH are attributed to the amide C=O group and/or $–COO^-$, indicating the contribution of activated biochar within the matrix. The transition to lower wavenumber bands in APCH aligns with prior studies indicating that the incorporation of biochar into the hydrogel network can modify bonding via enhanced chemical interactions (Chame *et al*., 2025). The band around 1453–1454/cm indicates C–H bending vibrations from aliphatic components and

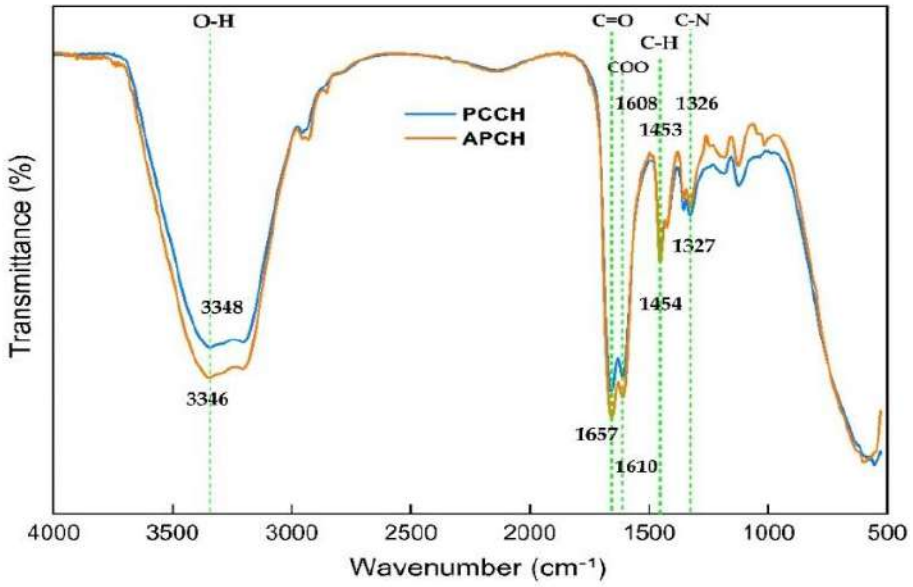


Fig. 2: FTIR spectra of the hidrogel composit samples

symmetrical carboxylate groups, and the band at 1326–1327/cm is related to C–N vibrations, confirming the successful polymerization of polyacrylamide as well as the presence of functional groups relevant for metal ion adsorption. This finding aligns with the study by (Zhang *et al*., 2024), who used FTIR to demonstrate the relationship between functional groups in hydrogels and the adsorption capacity of metal ions Pb(II), Cd(II), and Cu(II). The fingerprint region (1200–500/cm), which exhibits a combination of C–O–C, C–O, and lignin aromatic ring vibrations, indicates that the biochar functional groups are still active after pyrolysis and integration into the hydrogel, consistent with the report by (Siryk *et al*., 2024), stating that biochar-hydrogel composites retain active groups for the adsorption interaction of various pollutants. In summary, the FTIR spectrum illustrated in Fig. 2, corroborates the incorporation of pineapple crown biochar and avocado peel into the polyacrylamide hydrogel matrix, leading to a composite material characterized by multiple active functional groups (–OH/–NH, –COOH/–COO^-, –$CONH_2$, and C–N). These clusters effectively provide sites for adsorption mechanisms such as complexation, ion exchange, and electrostatic bonding, which are crucial for the hydrogel's ability to adsorb Pb(II), Cd(II), and Cu(II) ions. This finding is consistent with recent international literature indicating that hydrogel-biochar composites have a porous three-dimensional structure with functional groups that support the efficiency of heavy metal removal from aqueous solutions (Siryk *et al*., 2024).

Surface morphology observation through SEM images (Fig. 3a) shows that PCB has a highly porous surface structure with irregular cavities formed by pyrolysis at 500°C and NaOH base activation. This surface structure architecture featuring open and interconnected pores signifies an efficient pore development process, in agreement with scholarly reports that assert biochar has a significantly porous structure that facilitates the adsorption of contaminants from water solutions, attributed to its large surface area and well-connected porosity. Conversely, APB in Fig. 3b exhibits finer and denser pores, reflecting the inherent lignocellulosic nature of avocado peel, which tends to produce carbon structures with more micropores. When both biochars were

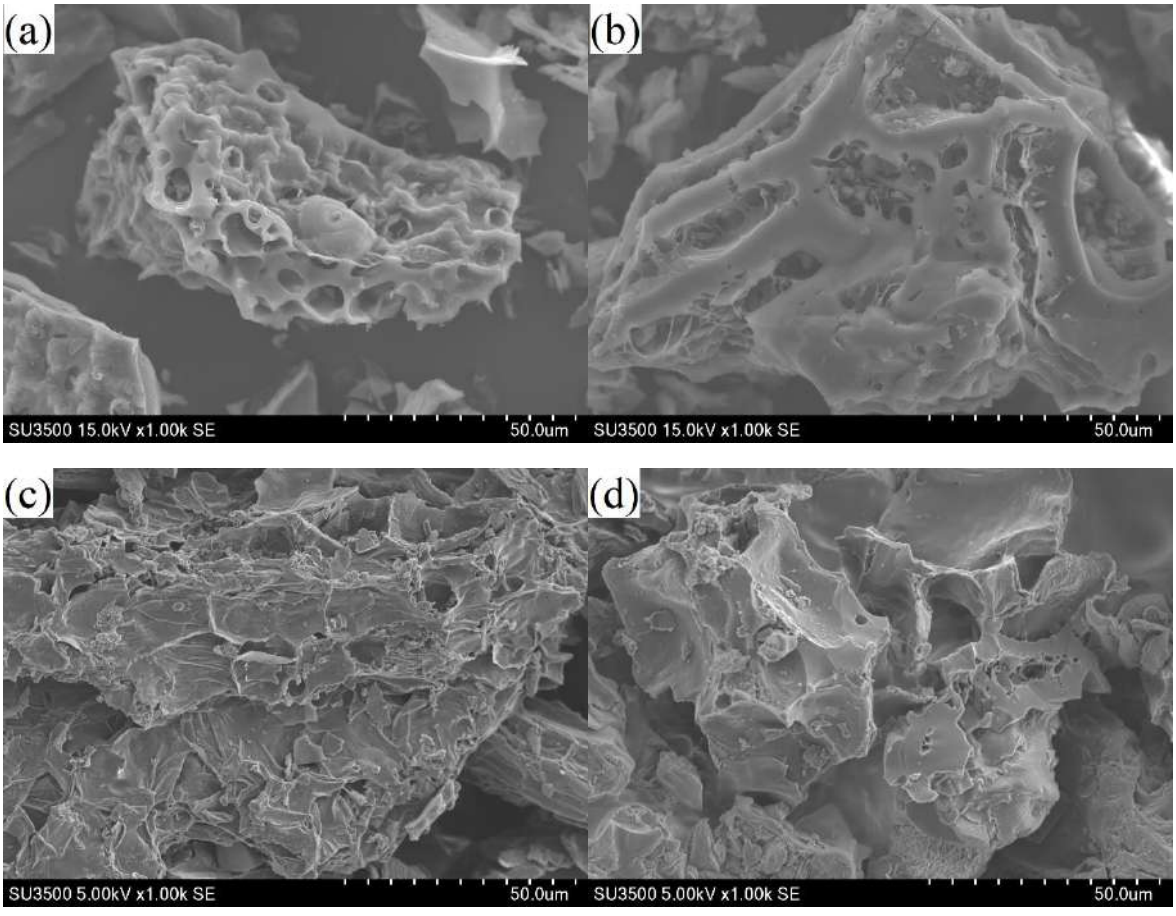


Fig. 3: SEM images of the (a) PCB; (b) APB; (c) PCCH; and (d) APCH

incorporated into the polyacrylamide hydrogel matrix, the macroporous characteristics were maintained, as seen in the PCCH (Fig. 3c) and APCH (Fig. 3d) composites. The composite surface displays a fairly uniform three-dimensional hydrogel network, wherein biochar particles are uniformly integrated into the matrix, lacking a distinct interfacial boundary between the biochar and the polymer. This indicates a high degree of compatibility and good interfacial adhesion between the activated biochar and the polymer network formed by PAM–MBA, which is consistent with previously reported characteristics of biochar–hydrogel composites, where the three-dimensional hydrogel framework supports the uniform dispersion of biochar filler particles while maintaining the material's structural integrity. Furthermore, the small fissures and voids that were still apparent on the PCCH and APCH suggest that the initial porosity of the biochar was preserved throughout the polymerization process, thereby offering a broad and sufficient diffusion route for metal ion infiltration during the adsorption process. This finding aligns with literature reports indicating that biochar within a hydrogel matrix retains its internal pores, contributing to increased adsorption capacity and efficient contaminant diffusion rates.

Further EDS analysis (Fig. 4) further supports the SEM results by showing the dominance of carbon and oxygen elements in all samples, reflecting the successful biomass carbonization process. In

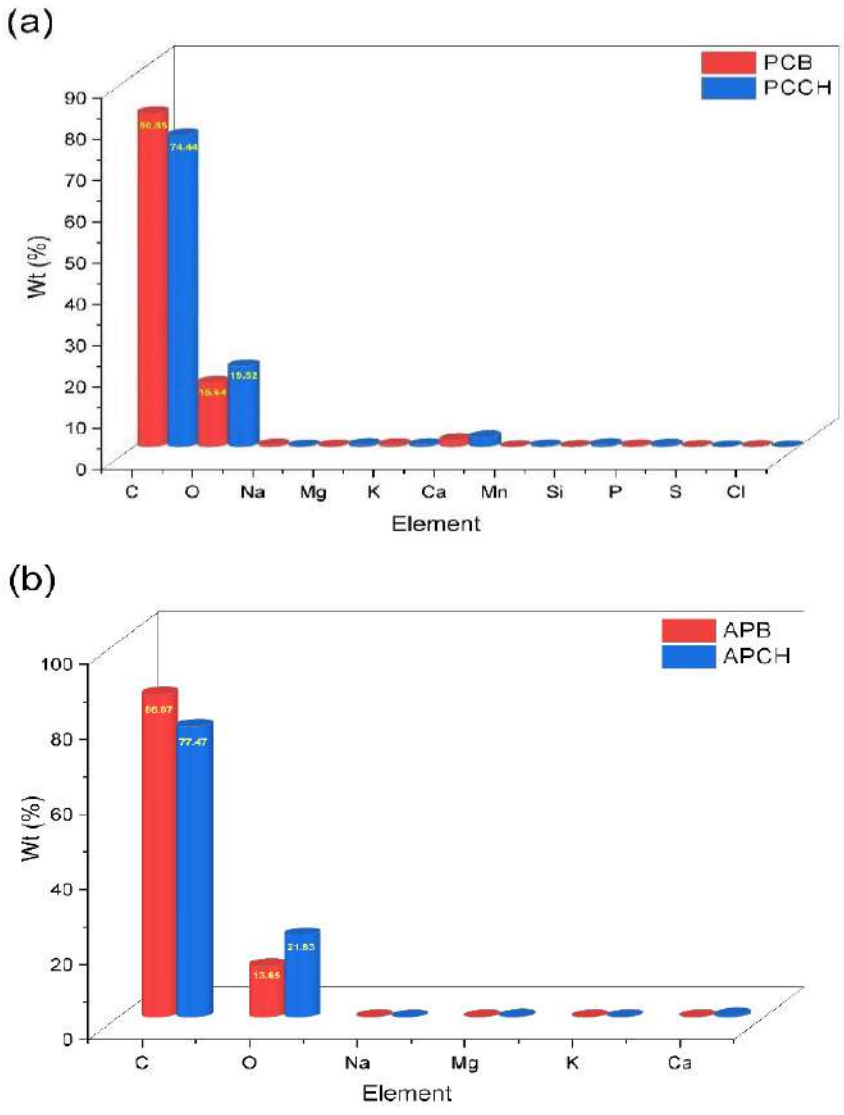


Fig. 4: EDS analysis of (a) PCB-PCCH and (b) APB-APBC

PCB,the carbon content reaches 80.85 wt% and oxygen 15.64 wt%, while APB shows a higher carbon content of 86.07 wt% and oxygen 13.65 wt%. The inclusion of biochar in the hydrogel leads to a decrease in carbon (C) proportion and an increase in oxygen (O) in PCCH (C: 74.44 wt%, O: 19.52 wt%) and APCH (C: 77.47 wt%, O: 21.83 wt%), reflecting the contribution of carbonyl and amide groups from polyacrylamide within the composite. This increase in oxygen content is consistent with the formation of a hydrogel network rich in polar sites such as –OH, –COOH, and $–CONH_2$, as confirmed by FTIR and SEM morphology analysis, supporting the integration of biochar material, which enhances the distribution of active functional groups on the adsorbent surface, which play a role in the metal ion adsorption mechanism. Moreover, the detection of mineral components like sodium (Na), potassium (K), calcium (Ca), and silicon (Si) in minor quantities within biochar and composites suggests that the inherent mineral remnants of

Table 1: Surface area parameters of the samples

Parameter	PCB	PCCH	APB	APCH
Surface area (m^2/g)	893.666	767.607	679.547	802.41
BET slope (1/g)	69.173	2.683	47.349	2.570
BET intercept (1/g)	-172.972	1.853	-129.145	1.770
Correlation Coefficient	0.988	0.995	0.987	0.996

biomass continue to exist even after the activation process. These minerals can function as supplementary active sites within the process of metal ion interaction or adjust the surface characteristics of biochar, as outlined in the biochar composite analysis for wastewater treatment, which underscores the importance of mineral residues in improving contaminant adsorption (Zhao *et al*., 2025b). Overall, the integration of SEM-EDS results indicates that the pyrolysis process and NaOH activation have successfully formed porous biochar with surface characteristics preserved after hydrogel composite formation. The hybrid structure, characterized by its porous morphology and reinforced by a flexible hydrogel network, demonstrates a significant adsorption capacity. Furthermore, the chemical composition discloses the presence of active functional groups and supporting minerals that could potentially enhance interactions with Pb(II), Cd(II), and Cu(II). These physicochemical properties confirm that PCCH and APCH are highly suitable adsorbent composites for multi-component heavy metal removal applications in the aqueous phase, aligning with recent research trends demonstrating the superiority of biochar-hydrogel composites in heavy metal-contaminated water treatment.

According to the results of the BET analysis (Table 1), it is evident that biochar and hydrogel composites exhibit a considerable specific surface area. This feature demonstrates its ability as a heavy metal adsorbent. PCB has the highest surface area of 893.67 square meters per gram (m^2/g), while APB has a slightly lower value of 679.55 m^2/g. The pyrolysis combined with chemical activation produced a porous carbon structure characterized by a well-developed micro-mesoporous network in both biochars. These findings are consistent with previous studies, which stated that biochar has a large surface area and a porous structure effective for heavy metal adsorption (Meetam *et al*., 2024; Zhao *et al*., 2025a). The hydrogel composite integrated with biochar into the polyacrylamide hydrogel matrix resulted in changes in the surface area characteristics of the hydrogel composite. In the PCCH, the surface area decreased from 893.67 m^2/g to 767.61 m^2/g. This occurrence is attributed to the penetration of polymer chains into specific biochar pores, leading to the obstruction of some of these pores by a hydrogel network. However, this decrease is not significant, so most of the PCB pore structure is still preserved in the composite, allowing for effective diffusion and adsorption of metal ions. Similar changes were also reported in biochar–hydrogel composite studies, where hydrogel integration tended to partially close the biochar pores but still maintained a high surface area that contributed to high adsorption capacity. Simultaneously, APCH achieved a significant surface area of 679.55 m^2/g, which increased to 802.41 m^2/g after the hydrogel composite was formed. This growth signifies that the hydrogel polymerization process effectively improves the pore structure of APB, occurring via the establishment of an expanding (swelling) hydrogel network that generates additional voids between biochar aggregates. This phenomenon is attributed to the redistribution of biochar within the hydrogel matrix, which diminishes the agglomeration of biochar particles and thus

Table 2: Mechanical hardness (Shore A) of composite hydrogels

Sample	Reading (1 s/15 s)	Average	Std. Dev.	Hardness
PCCH	11/10, 9/9, 11/11, 9/9	10	±1	10
APCH	11/10, 9/9, 11/11, 10/10	10	±1	10

increasing the effective surface area. This condition aligns with the literature report stating that the interaction of hydrogels with biochar can produce a three-dimensional structure that expands the pore profile and increases the surface area of the composite material, thereby improving adsorption performance. The BET correlation coefficient values of 0.987–0.996 indicate that gas adsorption follows the model well, which suggests the stability of the pore structure and the suitability of the multilayer adsorption model for this material. The precision of the BET model in characterizing this surface adsorption phenomenon is crucial for elucidating the adsorption capacity of porous materials such as biochar and hydrogel composites. Overall, the BET results confirm that the porous nature of biochar is maintained after integration into the hydrogel composite. The alteration in surface area aligns with the SEM findings, which indicate that the pore structure remains accessible in both PCCH and APCH. Additionally, the FTIR results validate the incorporation of active functional groups into the hydrogel network. The combination of high surface area, pore accessibility, and the presence of polar functional groups makes this hydrogel composite highly promising for use as a multi-component adsorbent in removing Pb(II), Cd(II), and Cu(II) from aqueous solutions. Furthermore, the relative roles of the functional groups in chemisorption can be understood through FTIR shifts and kinetic modeling. Hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O) groups are the primary sites for metal ion binding via surface complexation and coordination, especially with Cd(II) and Pb(II), which show higher affinity for oxygen-containing groups. Amide groups (–$CONH_2$) introduced through PAM polymerization further enhance binding with Pb(II) through lone-pair electron interactions. This arrangement of functional group roles reinforces the selectivity pattern and adsorption behavior noted among the analyzed metals.

The robustness of hydrogel-based adsorbents significantly influences their operational stability, particularly when subjected to mechanical agitation and prolonged exposure to aqueous environments. In this study, the mechanical stability of PCCH and APCH was evaluated through the Shore A hardness testing, a method that reliably assesses a material's resistance to pressure, reflecting network strength and polymer chain interactions. Both PCCH and APCH exhibited a Shore A hardness value of 10, with a standard deviation of ±1, based on four sets of measurements (indentation intervals of 1 second and 15 seconds) conducted at room temperature (22.1°C) and 53.2% relative humidity (Table 2). Even though this value implies that the hydrogel is soft, it still conforms to the acceptable standards for semi-rigid adsorbent materials employed in batch systems. These consistent values indicate that both hydrogels have sufficient mechanical integrity to maintain their structure during the 300-minute adsorption process under 125 rpm stirring conditions. No deformation, damage, or collapse was noted in either hydrogel during or following the adsorption experiments, further confirming their durability under operational conditions. Although wet-dry cycling tests were not performed, the noted low variation and structural integrity suggest an indirect resistance to mild to moderate mechanical stress. The inclusion of 0.1% MBA as a crosslinker and the use of optimized APS and TEMED concentrations likely contributed to the formation of an effective polymer network, thereby reducing the risk of disintegration. This study did not encompass regeneration testing, yet the mechanical integrity

Table 3: Comparison of kinetic parameters for Pb(II), Cd(II), and Cu(II) adsorption onto different adsorbents based on PFO and PSO models

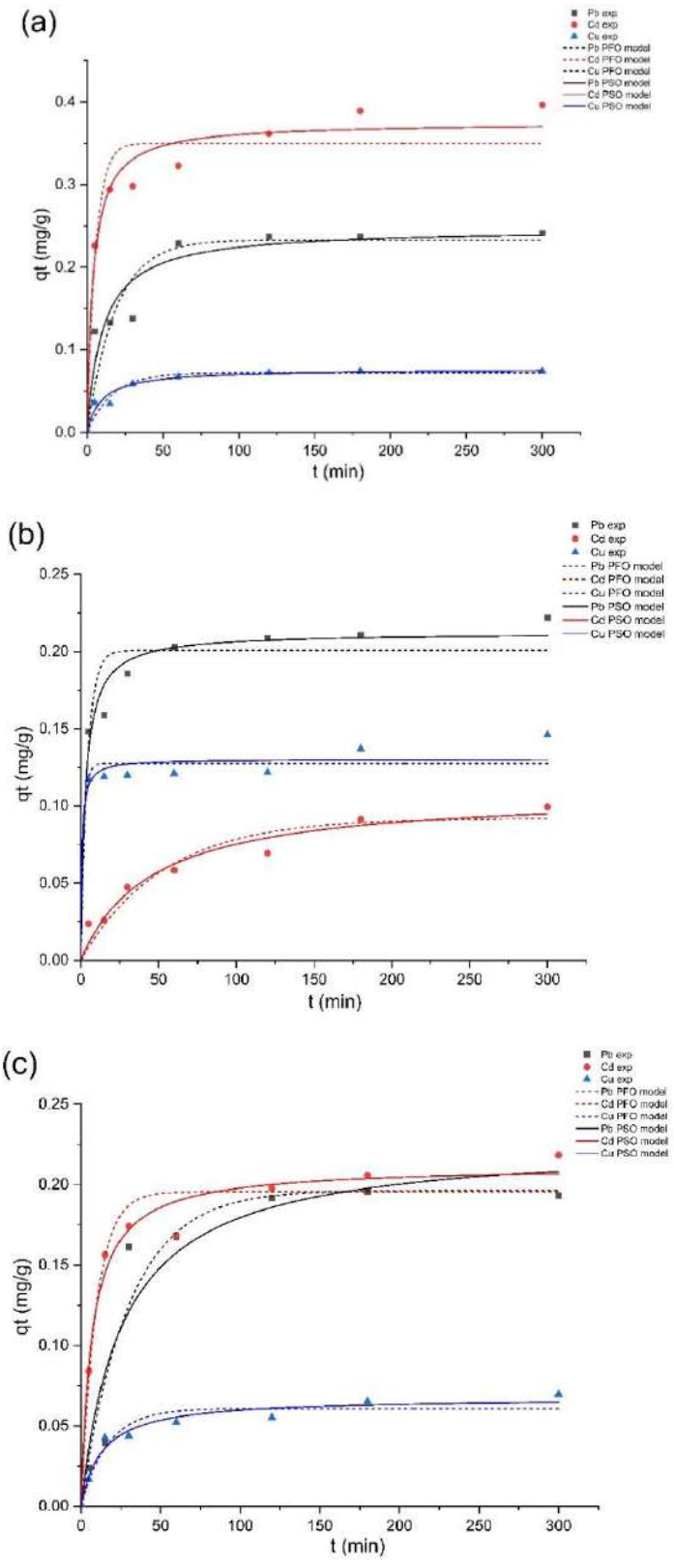
Adsorbent	Ion	q_e, exp (mg/g)	q_e, PFO (mg/g)	k_1 (/min)	R^2 (PFO)	q_e, PSO (mg/g)	k_2 (g/mg/min)	R^2 (PSO)
PCB	Pb(II)	0.24	0.23 ± 0.02	0.05 ± 0.02	0.86	0.25 ± 0.02	0.40 ± 0.17	0.91
	Cd(II)	0.36	0.35 ± 0.02	0.18 ± 0.05	0.93	0.37 ± 0.01	0.66 ± 0.18	0.97
	Cu(II)	0.07	0.07 ± 0.00	0.06 ± 0.02	0.92	0.08 ± 0.00	1.39 ± 0.02	0.95
APB	Pb(II)	0.20	0.20 ± 0.01	0.23 ± 0.06	0.94	0.21 ± 0.01	1.65 ± 0.42	0.98
	Cd(II)	0.10	0.09 ± 0.01	0.02 ± 0.00	0.93	0.11 ± 0.01	0.20 ± 0.07	0.96
	Cu(II)	0.13	0.13 ± 0.00	0.50 ± 0.21	0.96	0.13 ± 0.00	9.98 ± 7.16	0.96
PCCH	Pb(II)	0.23	0.23 ± 0.02	0.05 ± 0.02	0.94	0.23 ± 0.02	0.17 ± 0.08	0.92
	Cd(II)	0.22	0.35 ± 0.02	0.18 ± 0.05	0.96	0.21 ± 0.01	0.68 ± 0.15	0.98
	Cu(II)	0.07	0.07 ± 0.00	0.06 ± 0.02	0.93	0.07 ± 0.00	1.13 ± 0.31	0.97
APCH	Pb(II)	0.55	0.50 ± 0.03	0.03 ± 0.01	0.96	0.56 ± 0.03	0.07 ± 0.02	0.98
	Cd(II)	0.42	0.38 ± 0.02	0.03 ± 0.01	0.96	0.43 ± 0.02	0.10 ± 0.02	0.99
	Cu(II)	0.40	0.36 ± 0.01	0.04 ± 0.01	0.98	0.41 ± 0.01	0.13 ± 0.01	0.99

and chemical stability of the composite materials suggest promising potential for reuse. This finding is supported by the results of Shore A hardness and FTIR findings, which confirm the structural resistance and preservation of active functional groups after synthesis. Subsequent efforts will concentrate on assessing the adsorption-desorption cycle and its effects on the performance and integrity of the material.

Adsorption kinetics of Pb(II), Cd(II), and Cu(II)

The adsorption kinetics profile for all adsorbents (Table 3 and Fig. 5) was observed for 300 minutes. The results of the study reveal that the adsorption phenomenon unfolds in two phases: in the early minutes, the process of adsorption is quick, demonstrating that the active sites are open and available on the pore surface, enabling them to effectively bind heavy metals. The second stage is the phase toward equilibrium, which identifies the contribution of diffusion resistance (film or intraparticle) and the reduction in the number of remaining active sites. For all adsorbents and metal ions tested, the PSO model showed a better fit compared to PFO, as indicated by higher R^2 values and q_e values more comparable to the experimental equilibrium capacity. The model curve demonstrates that PSO (solid line) reliably delivers a more accurate representation of the experimental data compared to PFO (dashed line) for all adsorbents. According to the PSO model, the adsorption rate is chiefly influenced by chemisorption mechanisms that entail surface complexation between metal ions and functional groups that contain oxygen and nitrogen (–OH, –COOH/–COO^-, and –$CONH_2$). The relative impact of these factors varies according to the physicochemical properties of Pb(II), Cd(II), and Cu(II).

The results of kinetic modeling on PCB adsorbent (Table 3 and Fig. 5a) show that the metal ion adsorption process differs between the two models used. The PFO model provided lower conformity (R^2 = 0.86) with a q_e, PFO value of (0.23 ± 0.02 mg/g), which slightly deviated from the experimental equilibrium capacity. In contrast, the PSO model showed better conformity (R^2 = 0.91) and a q_e value (0.25 ± 0.02 mg/g) that was closer to q_e, exp. This implies that the adsorption mechanism for PCB aligns more closely with the PSO kinetics approach. Analysis of PSO parameters revealed that Cd(II) exhibited the highest adsorption rate and capacity, followed by


(a)
Pb exp
Cd exp
Cu exp
Pb PFO model
Cd PFO model
Cu PFO model
Pb PSO model
Cd PSO model
Cu PSO model
qt (mg/g)
t (min)
(b)
Pb exp
Cd exp
Cu exp
Pb PFO model
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qt (mg/g)
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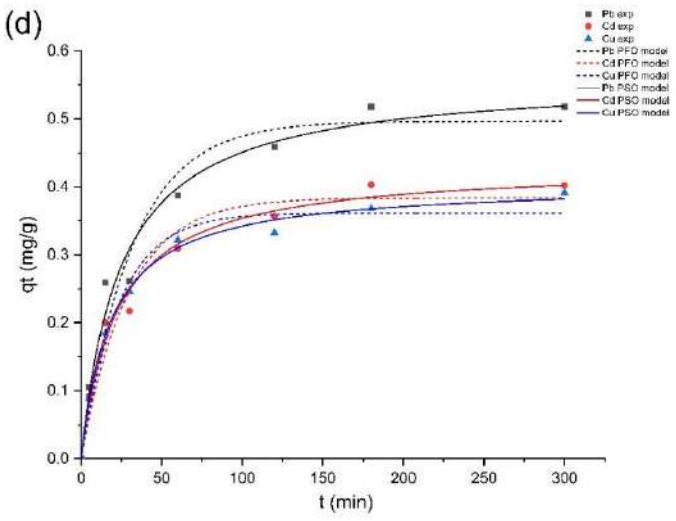

Fig. 5: Adsorption kinetics curve for (a) PCB; (b) APB; (c) PCCH and (d) APCH

Pb(II) and Cu(II), resulting in an affinity order of Cd(II) > Pb(II) > Cu(II). This selectivity pattern is governed by physicochemical factors such as ionic radius, hydration energy, and electronegativity. Cd(II) has a moderate ionic radius (0.97 Å) and lower hydration energy (–1,806 kJ/mol), allowing easier dehydration and stronger interaction with surface functional groups. Pb(II), with a slightly larger radius (1.19 Å) and higher polarizability, can still form stable surface complexes. In contrast, Cu(II) exhibits the highest electronegativity (1.90) and hydration energy (–2,010 kJ/mol), leading to stronger hydration shells that inhibit interaction with binding sites. These results are consistent with the principle that lower hydration enthalpy and moderate ionic size facilitate higher chemisorption efficiency. This trend also aligns with the hard and soft acids and bases (HSAB) theory, where Cd(II), as a borderline acid, forms stronger complexes with polar functional groups (e.g., –COOH, –OH) compared to Cu(II), a borderline-soft acid with stronger hydration effects. A kinetic curve illustrating a pronounced rise at the beginning (t < 30 min) followed by a plateau signifies a swift occupation of surface-active sites, subsequently constrained by diffusion to deeper or less accessible sites. Adsorbent APB showed high model suitability for both PFO and PSO models (R^2 > 0.93; Table 3 and Fig. 5b), indicating that the adsorption process was rapid and reached equilibrium quickly. Nonetheless, PSO consistently yielded a more precise representation, particularly for Pb(II), with an enhancement in R^2 from 0.94 to 0.98 and a qe value of PSO (0.21 ± 0.01 mg/g). Similar results were also observed for Cd(II), where PSO increased the R^2 value from 0.93 to 0.96 and the adsorption capacity q_e from 0.09 to 0.11 mg/g, further supporting the indication that the underlying mechanism involves surface complexation and/or ion exchange, as also reported for biochar systems based on fruit waste. Cu(II) on APB exhibits good kinetic characteristics for both PFO and PSO models with an R^2 value of 0.96; however, PSO yields a very high k_2 value (9.98 ± 7.16 g mg/min), but PSO produces a very high k_2 value (9.98 ± 7.16 g mg/min) with low final adsorption capacity (q_e ≈ 0.13 mg/g). This combination of high k_2 value and low capacity demonstrates the rapid uptake–early saturation phenomenon. This can be explained by the existence of a limited quantity of high-affinity sites that are swiftly occupied by Cu(II), but these sites quickly reach saturation due to their restricted number or accessibility. For Cu(II) on APB, PSO yielded an exceptionally high k_2 value (9.98 ± 7.16 g/mg/min) accompanied by a relatively low equilibrium capacity (q_e ≈ 0.13 mg/g). This

combination indicates a phenomenon of rapid uptake and early saturation, suggesting that a finite number of high-affinity sites are swiftly filled by Cu(II). However, these sites become saturated due to restricted accessibility and strong hydration effects. Similar kinetic behavior has been observed in biochar-based systems, where the adsorption of Cu(II) is restricted by factors related to speciation and hydration constraints (Hussin *et al*., 2022; Ma *et al*., 2024). The integration of biochar into the hydrogel matrix of PCCH significantly affects the adsorption capacity and kinetics of metal ions, as shown in Table 3 and Fig. 5c. Although the PFO model showed good agreement with the data, with R^2 values ranging from 0.93 to 0.96, the PSO model provided a higher fit, particularly for Cd(II) and Cu(II), with R^2 reaching 0.98. The PSO q_e values for PCCH declined relative to PCB; for example, Cd(II) decreased from 0.37 mg/g on PCB to 0.21 mg/g on PCCH. This reduction is ascribed to the partial obstruction of pores and the masking of high-energy adsorption sites by the polyacrylamide network, which is corroborated by BET analysis indicating a reduction in the specific surface area from PCB to PCCH. Although the decrease in adsorption capacity for PCCH suggests partial masking of active sites, the incorporation of hydrogel improves handling, structural integrity, and reusability under dynamic conditions, making it more applicable in real-world water treatment systems where mechanical robustness and ease of separation are essential. This decline in capacity implies that, while the composite was being formed, some pores and active sites of the biochar were likely obstructed or masked by the hydrogel polymer network. As a result, access to high-energy adsorption sites was diminished. The kinetic results show a decrease in the value of k_2 and a lower value in PCCH compared to PCB (Table 3). This result is shown for Cd(II), where the initial rate decreased from 0.090 g mg/min in PCB to 0.030 g mg/min in PCCH. This denotes increased diffusion resistance within the hydrogel matrix before ions reach the embedded biochar surface, resulting in a more gradual attainment of equilibrium. The mechanisms that regulate this system encompass a blend of resistances—including diffusion within the film, diffusion within the gel, and surface reactions. Collectively, these elements serve to decelerate the effective adsorption rate, even though the alignment with the PSO model is notably strong. These findings are consistent with reports on various biochar hydrogel composite systems, which confirm that increasing the complexity of transport pathways within the polymer matrix can reduce kinetic performance despite maintaining chemical adsorption characteristics as the dominant mechanism (Siryk *et al*., 2024; Tao *et al*., 2024). APCH exhibited the highest kinetic and adsorption capacity performance among all the tested adsorbents, as indicated in Table 3 and Fig. 5d. The PSO model provided a high degree of fit for all three metal ions (R^2 = 0.98–0.99), with q_e, PSO values of 0.56 ± 0.03 mg/g for Pb(II), 0.43 ± 0.02 mg/g for Cd(II), and 0.41 ± 0.01 mg/g for Cu(II). The BET analysis revealed that APCH surface area increased from 679.55 to 802.41 m^2/g, while PCCH decreased from 893.66 to 767.61 m^2/g, clearly illustrating that the polymerization process in APCH improved pore exposure rather than blocking it. This distinction serves as a crucial quantitative rationale for the enhanced performance of APCH. This change indicates better pore accessibility and improved dispersion of biochar within the polymer matrix. Furthermore, FTIR findings corroborated an elevated density of polar functional groups (–COOH, –OH, and $–CONH_2$), which promote surface complexation and chemisorption. Although the value of k_2 is in the low range (0.07–0.13 g/mg/min), remains competitive and relatively balanced for all ions (0.018–0.022 g/mg/min), indicating the availability of many easily accessible binding sites without significant transport resistance dominance. The combination of a high q_e value and a moderate k_2 signifies that the system is primarily characterized by chemical adsorption rather than rapid yet capacity-restricted absorption. The fundamental process of

adsorption analyzed in this study is controlled by surface complexation, supported by FTIR findings that reveal shifts in peaks corresponding to the–COOH, –OH, and –$CONH_2$ functional groups. These functional groups interact with metal ions, resulting in the formation of stable complexes. The high R^2 value (> 0.96) for the PSO kinetic model further confirms that chemisorption is the dominant rate-determining step. Electrostatic attraction also contributes to the rapid initial adsorption stage especially because negatively charged functional groups interact with positively charged Pb(II), Cd(II), and Cu(II) ions at pH 4–6. Ion exchange takes place by substituting hydrogen ions with metal ions within the functional groups, whereas pore diffusion plays a role in the subsequent phase of the kinetic profile, where the rate diminishes due to constraints in internal transport. This mechanism is consistent with earlier research on metal ion adsorption in hydrogel-biochar systems. The kinetic curve shows a rapid initial increase in rate, followed by a plateau at high capacity, reflecting an adsorption mechanism controlled by chemical interactions and the abundance of active sites. The findings are corroborated by BET and FTIR characteristics, demonstrating an enhancement in specific surface area and the density of polar functional groups (–COOH, –OH, –$CONH_2$) after hydrogel formation. The low k_2 value but high q_e reflects the characteristics of a system with many easily accessible adsorption sites, unlike systems with high but limited affinity sites, such as in the case of Cu(II)–APB. Recent literature on biochar-based hydrogel composites, including those from avocado peel, also supports the dominance of chemical or coordination binding mechanisms of metal ions to polar groups within the hydrogel network, where the PSO model provides a high fit because it can represent the complexity of surface reaction-based kinetics (Chwastowski and Staron, 2023; Ma *et al*., 2024). Furthermore, the pH range employed (4–6) not only confirmed that metal ions maintained in soluble cationic forms but also enhanced surface deprotonation of the functional groups (–COOH, –OH), favoring electrostatic interaction and surface complexation. The moderate ionic strength present in the medium, combined with the absence of strongly competing anions including phosphate or sulfate, also played a role in enhancing the selectivity and stability of the adsorption mechanism. Therefore, the performance of APCH scientifically reflects the synergistic efficiency between the enhancement of surface physicochemical properties and the hydrogel network polymer structure that supports optimal adsorption capacity and kinetics. The adsorption profile displays two separate phases: a rapid initial uptake phase associated with external (film) diffusion, followed by a slower phase nearing equilibrium, indicative of intraparticle diffusion. By maintaining a stirring speed of 125 rpm, the thickness of the boundary layer is reduced, which in turn enhances external mass transfer. The porous structure of biochar, combined with the interconnected network of the hydrogel, facilitates the internal diffusion of metal ions. The maintenance of a uniform particle size attained via grinding and sieving further helps to decrease mass transfer resistance. Consequently, the adsorption process sequentially involves both film diffusion and intraparticle diffusion. Adsorption equilibrium was observed for 300 minutes for all composite systems. This relatively long time can be attributed to the structural complexity of the hydrogel-biochar matrix, where metal ions require time to penetrate the inner pores and interact with the functional groups embedded within the hydrogel network. The prevailing chemisorption mechanism, characterized by its slower nature owing to distinct binding interactions, additionally plays a role in achieving equilibrium. To minimize the time required for adsorption in upcoming applications, approaches including enhancing biochar dosage and increasing biochar particle size, along with the implementation of agitation techniques (for instance, sonication), may be investigated to expedite mass transfer.

Overall, APCH is the most effective adsorbent due to its good increase in q_e for Pb(II), Cd(II), and Cu(II). This is demonstrated by the synergy between i) better biochar dispersion within the hydrogel, ii) increased pore accessibility/effective surface area, and iii) the addition of coordinating groups from polyacrylamide ($–CONH_2$) that enhance metal complexation. Conversely, in pineapple crowns, he development of PCCH appears to reduce capacity, particularly for Cd(II). This phenomenon can be most logically attributed to the effects of masking or partial pore blockage, as well as heightened transport resistance to the active sites of the embedded biochar. The PSO model for all systems (especially APCH and PCB for Cd) shows a good fit, confirming that adsorption involves chemisorption/complexation at oxygen-nitrogen groups, which is supported by the results of FTIR and SEM-EDS analysis. The results of the study reveal that hydrogel-biochar composites, especially APCH, exhibit an adsorption capacity for heavy metals Pb(II), Cd(II), and Cu(II) of 0.56 mg/g, 0.43 mg/g, and 0.41 mg/g, respectively. The enhanced fit of the PSO model, as evidenced by a higher R^2 value and a stronger correlation between calculated and experimental q_e values, demonstrates the dominance of the chemisorption mechanism. This implies that the step that determines the rate is characterized by electron-sharing interactions or combinations between metal ions and the polar functional groups present on the adsorbent surface. This finding is supported by the FTIR spectrum, which validates the direct involvement of the –COOH, –OH, and $–CONH_2$ groups in the ion binding process. The dependable model fit of PSO across a range of ions and adsorbents emphasizes the consistency of surface interaction behavior, implying that adsorption is determined by surface reaction kinetics instead of just physical attraction or external mass transfer limitations. The adsorption capacity of PCCH composite is 0.23 mg/g for Pb(II), 0.21 mg/g for Cd(II), and 0.07 mg/g for Cu(II). These values surpass those of PCB and APB, suggesting that the incorporation of biochar into the polyacrylamide hydrogel network significantly improves the performance of heavy metal adsorption. Although synthetic adsorbents made with advanced engineering like Biochar–hydroxyapatite composite (BHAp) or corn cob biochar have higher adsorption capacities, their performance is still within the range suitable for biomass waste-based materials (Su *et al*., 2025). Pineapple crowns and avocado peels, traditionally viewed as waste, can indeed be converted into valuable functional materials. The manufacturing process also doesn't require dangerous chemicals or expensive technology—just base activation and simple polymerization. The characterization results also show that the pore structure remains intact, functional groups such as –OH and –COOH remain active, and the material has outstanding stability for repeated use. The capacity of this material to simultaneously adsorb three different types of metals broadens its potential applications. In other words, although the adsorption capacity of this composite has not yet rivaled modified adsorbents, the approach used offers a balance between efficiency, sustainability, and ease of field application—a combination that is important and highly needed in the development of today's environmentally friendly technologies. It is essential to emphasize that every adsorption experiment carried out in this study was performed under constant initial concentrations in a ternary metal ion system, thereby restricts the applicability of isotherm modeling that depends on equilibrium data spanning various concentrations. Therefore, isotherm analysis was not performed. Future studies will incorporate multi-concentration designs to evaluate Langmuir, Freundlich, and Temkin isotherm parameters, which are essential for determining adsorption capacity, site heterogeneity, and interaction behavior in multi-metal systems

Adsorption Capacity Comparison with Literature

The comparison of q_e for APCH and PCCH with various biochar and hydrogel-based adsorbents

previously developed is presented in Table 4. A simultaneous system was utilized to observe the heavy metal adsorption process concerning three heavy metal ions, specifically Pb(II), Cd(II), and Cu(II). APCH showed the best performance with an adsorption capacity of 0.56 mg/g for Pb(II), 0.43 mg/g for Cd(II), and 0.41 mg/g for Cu(II), while PCCH showed a lower capacity, at 0.23, 0.21, and 0.07 mg/g for Pb(II), Cd(II), and Cu(II), respectively. The results substantiate that the incorporation of biochar within the hydrogel matrix not only sustains but also improves adsorption efficiency, attributed to the active functional groups such as –COOH, –OH, and $–CONH_2$, as confirmed by FTIR characterization. Although the adsorption capacity reported here is lower than highly engineered adsorbents like BHAp and commercial materials like activated carbon, the performance of APCH remains competitive when compared under similar multimetal conditions. APCH demonstrates favorable q_e values in comparison to other biomass-derived adsorbents, including corn cob biochar and COSAC, while also offering the benefits of a more straightforward and cost-effective synthesis. In simultaneous systems, competitive adsorption significantly reduces capacity, as observed for BHAp where Pb(II) uptake decreases from 311.16 mg/g to 220.08 mg/g (Liu *et al.*, 2023). This decrease is due to competition among metal ions for active sites, which is an inherent challenge in multimetal systems. This study reveals that APCH's capability to uphold a consistent adsorption ability for three metal ions concurrently indicates that the pore structure and the accessible active sites are proficient in managing multi-ion interactions. This result is supported by BET analysis, which shows that APCH experienced an increase in specific surface area to 802.41 m^2/g after biochar integration into the hydrogel. This enhancement broadens the diffusion routes and accessibility to active sites, thereby promoting adsorption efficiency in dynamic conditions. Additionally, the adsorption kinetics data following a PSO model with a coefficient of $R^2 > 0.96$ indicate that the adsorption mechanism is dominated by chemisorption, which is the chemical bonding between metal ions and polar groups within the hydrogel structure, rather than mere physical interaction. This study suggests significant advantages from the perspective of sustainability and applicability. The composite is formulated using plentiful and extremely inexpensive biomass waste, specifically avocado peels and pineapple crowns. The synthesis procedure is conducted via free radical polymerization, eliminating the need for hazardous chemicals or intricate synthesis methods, which renders it appropriate for replication and development. Compared to commercial adsorbents like polyacrylic acid grafted carboxymethyl cellulose and activated carbon composite material (PAA/CMC/AC) based hydrogels or biochar from corn cobs, although they have high adsorption capacity, they use expensive materials or production techniques. Considering the simultaneous adsorption of three metal ions, the chemical stability of the hydrogel structure, and the low-cost, sustainable synthesis route, the biochar–hydrogel composites developed in this study offer a balanced compromise between adsorption efficiency, environmental sustainability, and practical applicability. While this study shows encouraging outcomes in controlled laboratory settings, additional research will be undertaken to verify the effectiveness of APCH and PCCH in actual industrial wastewater systems, thus affirming their durability and practical use in intricate treatment scenarios. To align with circular economy principles, future studies will investigate environmentally friendly desorption techniques, such as mild acids or chelating agents, for recovering valuable metals from used hydrogels. This would not only enable resource recovery but also allow for hydrogel reuse, enhancing the overall sustainability and economic feasibility of the proposed material in industrial wastewater treatment systems. Moreover, despite having a lower adsorption capacity compared to advanced engineered adsorbents, APCH and PCCH

Table 4: Comparison of maximum adsorption capacities of various biochar–hydrogel adsorbents

Adsorbent	System type	Target heavy metals	q_e (mg/g)	Source
BHAp	Simultaneous (Pb–Cd–Cu)	Pb(II), Cd(II), Cu(II)	220.08; 28.78; 48.13	(Liu *et al*., 2023)
BHAp	Single-component	Pb(II), Cd(II), Cu(II)	311.16; 92.54; 82.05	(Liu *et al*., 2023)
Corn Stalk Biochar	Single-component	Pb(II), Cd(II)	688.8; 632.0	(Yan *et al*., 2022)
COSAC	Single-component	Pb(II), Cd(II), Cu(II)	18.9; 15.9; 4.8	(Bohli, *et al*., 2017)
PAA–CMC–AC Hydrogel	Single-component	Pb(II), Cu(II)	52.63; 63.41	(Wang *et al*., 2021)
APCH (This study)	Simultaneous (Pb–Cd–Cu)	Pb(II), Cd(II), Cu(II)	0.56; 0.43; 0.41	The current study
PCCH (This study)	Simultaneous (Pb–Cd–Cu)	Pb(II), Cd(II), Cu(II)	0.23; 0.21; 0.07	The current study

demonstrate competitive performance under multi-metal conditions, indicating their viability as sustainable options. One probable limitation is the low biochar loading (3 g in 40 g PAM solution), which restricts the number of available adsorption sites. Increasing the biochar-to-hydrogel ratio, optimizing crosslinking density, or modifying activation protocols could potentially enhance the material's adsorption capacity without compromising its mechanical integrity.

CONCLUSION

This study demonstrates that the APCH clearly outperformed the PCCH, achieving adsorption capacities of 0.56 mg/g for Pb(II), 0.43 mg/g for Cd(II), and 0.41 mg/g for Cu(II), with adsorption kinetics governed by chemisorption following the PSO model (R^2 > 0.96). This substance demonstrates significant promise as a hybrid adsorbent for the concurrent elimination of heavy metals from wastewater. This material has an open porous structure and a high surface area (767.61 m^2/g for PCCH and 802.41 m^2/g for APCH), providing an abundant adsorption interface and facilitating mass transfer. The existence of significant active functional groups (–OH, –COOH, and $–CONH_2$) suggests that adsorption is influenced not only by physical absorption but is also significantly enhanced by specific surface interactions that facilitate chemisorption. FTIR, SEM-EDS, and BET analysis showed that biochar based on biomass waste can be integrated into the polyacrylamide hydrogel network to produce a stable hybrid matrix by combining the surface accessibility of biochar with the hydrophilic transport properties of the hydrogel. The adsorption kinetics for the simultaneous removal of Pb(II), Cd(II), and Cu(II) consistently followed the PSO model (R^2 > 0.96), indicating that chemisorption governs the rate-controlling mechanism. The adsorption capacity exhibited by the PCCH and APCH adsorbents yielded varying results, attributable to the distinct chemical and physical properties and initial characteristics of the materials. The effectiveness of adsorption is affected by the amount of oxygen and nitrogen functional groups capable of interacting with metal ions to create complex or coordination bonds. Other important factors include the availability of pore volume, the distribution of pores, and how easily the material's active sites can be accessed. The limitations of mass transfer and the availability of active sites are affected by changes in the adsorption rate and equilibrium capacity of the material. Specifically, the stronger synergistic effect on APCH indicates that an optimal balance between adsorption capacity and kinetics can be achieved in a competitive system, where simultaneous adsorption is determined by the interconnectedness of transport pathways, pore connectivity, and the availability of functional groups. The results demonstrate that

successful adsorbent design is contingent not just on surface area, but also on the effects of surface chemistry and pore structure influence the adsorption pathways and stages, which regulate the process rate. The adsorption capacity noted in this study is relatively low in comparison to some engineered adsorbents. Nonetheless, it provides benefits associated with sustainability and the availability of biomass waste obtained from local sources. This study illustrates that the integration of activated biochar into a polyacrylamide hydrogel matrix is an efficacious approach for optimization, improving the biochar-to-hydrogel ratio, and modifying the hydrogel network structure to enhance active site accessibility. This strategy enhances the circular economy using biomass waste and the concurrent removal of heavy metals. Additionally, the structural integrity and chemical stability of the synthesized hydrogels point to the feasibility of recovering metals and reusing materials via effective desorption techniques, including acid elution or chelating agents. This study utilizes model solutions to determine adsorption behavior under controlled conditions; however, subsequent studies will concentrate on enhancement factors, including cost and life cycle assessment, adaptation to fixed or continuous flow systems, and application in actual wastewater contexts to support practical implementation.

AUTHOR CONTRIBUTIONS

S. Wardani conceptualized the research idea, designed the study, conducted the investigation, performed the literature review, curated the data, and conceptualized the manuscript. H. Husin, the corresponding author, has contributed to designing and conceptualizing the manuscript, conducting the investigation, analyzing and interpreting the data, and securing funding. M. I. Sulaiman contributed to data interpretation and statistical analysis and assisted in improving the manuscript. H. Desvita participated in analyzing and interpreting data, as well as improving the manuscript. A. Hadi conducted the literature review and contributed to the preparation and drafting 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, 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

1/g	Per gram
/cm	Per centimeter
/min	Per minute
%	Percent
%R	Removal percent
^{o}C	Degree Celsius
AAS	Atomic absorption spectroscopy
AC	Activated carbon
APB	Avocado peel biochar
APCH	Avocado peel composite hydrogel
APS	Ammonium persulfate
BET	Brunauer, Emmett, and Teller
BHAp	Biochar–hydroxyapatite composite
BRIN	National Research and Innovation Agency (Badan Riset dan Inovasi Nasional)
C=O	Carbonyl group
C-H	Aliphatic (alkyl)
C-N	Amina
C-0	C-O bond
C-O-C	Ether linkage
Ca	Calcium
Cd	Cadmium
$Cd(NO_3)_2.4H_2O$	Cadmium (II) nitrate tetrahydrate
Ce	Equilibrium concentration
CH	Composite hydrogel
CMC	Carboxymethyl cellulose
C_0	Initial concentration
$CONH_2$	Polyacrylamide
COO	Carboxylate group
COOH	Carboxylic acid
COSAC	Chemically olive stone activated carbon
Cu	Copper
$CuSO_4.5H_2O$	Copper (II) sulfate pentahydrate
Fig	Figure
FTIR	Fourier transform infrared spectroscopy
g/mg/min	Grams per milligram per minute
g	Gram
h	Hours
HNO_3	Nitric acid
K	Potassium
kV	Kilovolts
k1	Pseudo-first-order rate constant
k2	Pseudo-second-order rate constant
L	Liter
LB	Bottom Loading
LHT	High-Temperature Lifting
LPDP	Indonesian Endowment Fund for Education (Lembaga Pengelola Dana Pendidikan)
m	Mass
m^2/g	Square meter per gram
mL	Milliliter
mL/min	Milliliter per minute
mg/g	Miligrams per gram
mg/L	Milligrams per liter
min	minute
MBA	N,N'-methylenebisacrylamide
Na	Sodium

NaOH	Sodium hydroxide
-NH_2	Amine group
-OH	Hydroxyl group
PAM	Polyacrylamide
Pb	Lead
$Pb(NO_3)_2$	Lead (II) nitrate
PCB	Pineapple crown biochar
PCCH	Pineapple crown composite hydrogel
PFO	Pseudo-first-order
pH	Potential of hydrogen
PSO	Pseudo-second-order
q_e	Adsorption capacity at equilibrium
q_t	Adsorption capacity at time *t*
R^2	Coefficient of determination
rpm	Revolutions per minute
Si	Silicon
SEM-EDS	Scanning electron microscopy-Energy dispersive X-ray spectroscopy
SO_3H	Sulfonic acid
TEMED	Tetramethylethylenediamine
V	Volume of solution
wt%	Weight percent
w/v	Weight per volume

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ORIGINAL RESEARCH PAPER

Integrating green human resource management with environmental performance and human capital sustainability in urban dark store

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable urban dark store ecosystems require human resource practices aligning employee behavior with environmental and operational goals. Green human resource management combines environmental responsibility with workforce operations like hiring, training, performance, communication, and culture. This study assesses green human resource management integration in dark stores and its effects on environmental performance and human capital sustainability. It provides contextual and empirical contributions to a growing retail sector, linking green human resource management practices to measurable environmental and human capital outcomes.

METHODS: A cross-sectional survey of 400 employees across eight Telangana districts, including pickers, packers, storekeepers, managers, operations leads, delivery executives, riders, and human resource personnel, evaluated five green human resource management dimensions: recruitment, training, performance management, internal communication, and sustainable culture using a 25-item Likert scale. Reliability and validity were confirmed via Cronbach's alpha and content validity indices. Analysis included descriptive statistics, comparisons, Pearson correlation, and multiple linear regression to link green human resource management practices with environmental performance and human capital sustainability.

FINDINGS: Adoption of green human resource management practices varied across dark store ecosystems. In Hyderabad, employees reported strong agreement on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) for green recruitment and onboarding (3.96), green training (3.94), performance management and rewards (4.00), internal communication (4.02), and sustainable culture (4.06), while smaller districts showed lower adoption. Executives reported higher adoption than operational staff, though operational employees also showed strong engagement in internal communication (4.02) and sustainable culture (4.06), especially among those aged 25–35 years, female, and full-time. Regression analysis identified sustainable culture ($\beta = 0.225$) and internal communication ($\beta = 0.205$) as predictors, explaining 62% of the variance in environmental performance and human capital sustainability ($R^2 = 0.62$).

CONCLUSION: Integration of sustainable culture and green communication strongly enhances environmental performance and the sustainability of human capital. Recruitment and training show high adoption (3.94–3.96), while performance-linked rewards remain limited (4.00). Strengthening incentives and embedding sustainability across workforce processes are recommended. Future research may examine retention outcomes and wider incorporation of green human resources management methods in dark store ecosystems.

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INTRODUCTION

Sustainable operations in urban dark stores require Human Resource (HR) practices that align employee behaviour with organizational sustainability and human capital goals (Wang and Mohamed Makhbul, 2024). Green Human Resource Management (GHRM) supports workforce sustainability through structured recruitment, training, performance evaluation, communication, and organizational culture, enabling employees to adopt environmentally responsible practices and contribute to long-term human capital and organizational sustainability outcomes (Aftab *et al.,* 2023). Effective GHRM practices enhance environmental performance, stimulate green innovation, and positively influence employee engagement, motivation, and retention (Shahrulnizam *et al.,* 2024). Research highlights that green recruitment, onboarding, structured training, performance-linked rewards, internal communication, and embedding sustainability into culture are critical for fostering sustainable employee behaviours and responsible practices (Chowdhury *et al.,* 2025). Bibliometric and systematic reviews indicate that GHRM has gained increasing global attention as a strategic lever for workforce sustainability and integrates with environmental objectives. Studies in public utilities and the electricity sector demonstrate that GHRM practices improve career quality and promote sustainable human capital and organizational outcomes (Al-Oun and Al-Khasawneh, 2025). Sustainable development goals reinforce the relevance of GHRM in improving employee-driven sustainability and resource efficiency in diverse organizational contexts. (Yong *et al.,* 2020). Urban dark stores represent a distinct context for GHRM research due to their high operational intensity, rapid workforce turnover, reliance on role-diverse employees, and strong performance pressures, which create unique challenges and opportunities for embedding sustainability through HR practices. Comprehensive investigations using bibliometric analysis show that GHRM is closely linked to voluntary green work behaviour among employees (Shah *et al.,* 2024). In the wine industry, green innovation mediates the relationship between GHRM practices and organizational sustainability, highlighting context-specific pathways (Martínez-Falcó *et al.,* 2025). Employee perceptions of individual GHRM practices significantly affect green behaviours, indicating the importance of aligning HR strategies with environmental and workforce development objectives (Garavan *et al.,* 2023). Employee engagement supports the implementation of green operational practices, demonstrating that workforce participation is essential for environmental sustainability (Graham *et al.,* 2023). GHRM adoption promotes organizational culture, green innovation, and employee green behaviours, leading to long-term human capital and sustainability benefits. Structured GHRM practices, such as Green Training (GT), strengthen knowledge sharing and commitment to environmental goals by enhancing competencies, motivation, and improving employee performance and environmental awareness. The existing literature also identifies the role of GHRM in shaping a green psychological climate, emphasizing employee perceptions and organizational culture (San Román-Niaves *et al.,* 2025). High-tech firms show that motivation types and perceptions of greenwashing influence the effectiveness of GHRM practices. Public hospitals illustrate that GHRM implementation supports corporate sustainability and human capital objectives. Research indicates that GHRM plays a critical role in linking workforce practices to organizational sustainability and human capital outcomes. Studies have shown that employee empowerment through GHRM enhances engagement and pro-environmental behaviour (Alam, 2021), while valid measurement scales facilitate structured evaluation of GHRM adoption (Shah, 2019). Strategic management accounting research highlights that GHRM mediates sustainability outcomes across industry sectors, and employee awareness, measured through

sustainability consciousness questionnaires, is a key determinant of GHRM effectiveness. The previous studies also emphasize the mechanisms through which GHRM operates. Knowledge creation and green innovation are reinforced by GHRM practices (Martínez-Egea *et al.,* 2025), and embedding a green organizational culture enhances organizational commitment via job satisfaction (Shahriari *et al.,* 2023). Leadership and organizational culture further mediate the influence of GHRM on workforce sustainability and pro-environmental behaviour. Research in manufacturing and technological contexts shows that green transformational leadership combined with GHRM can improve innovation and organizational sustainability outcomes, while bibliometric studies provide insights into evolving trends and strategic implementation of GHRM practices (Austen and Piwowar-Sulej, 2024). Despite extensive evidence across sectors, several gaps remain. Few studies address urban dark stores, and little is known about how GHRM adoption varies across employee roles, demographics, and specific dimensions such as performance management and rewards. There is also limited research linking GHRM adoption directly to employee engagement, retention, environmental awareness, and alignment with organizational sustainability values in fast-paced retail contexts. Addressing these gaps can inform targeted interventions to strengthen GHRM practices and enhance sustainable workforce development in urban dark store ecosystems. This study aims to examine the implementation and integration of GHRM practices and their effects on environmental performance and Human Capital Sustainability (HCS) in the urban dark store ecosystems of Telangana. The objectives include i) evaluation of adoption and integration of key GHRM dimensions, including recruitment, training, performance management, internal communication, and sustainable culture, across districts and employee roles; ii) assessment of the influence of GHRM practices on HCS outcomes, including engagement, retention, environmental awareness, and alignment with organizational sustainability values; iii) identification of gaps and challenges in implementing specific GHRM dimensions, particularly performance management and rewards, and proposal of sustainability-focused interventions; and iv) provision of practical strategies for managers and policymakers to strengthen GHRM practices and promote sustainable workforce development in urban dark store ecosystems. This study was conducted at the Mittal School of Business, Lovely Professional University, Punjab, and Kalasalingam Academy of Research and Education, Tamil Nadu, India, in 2025.

MATERIALS AND METHODS

Research design

The present study adopted a descriptive and analytical cross-sectional research design to examine the adoption of GHRM practices in urban dark stores and to assess their impact on HCS. A quantitative survey-based approach was employed to systematically capture employees' perceptions across multiple GHRM dimensions, including Green Recruitment and Onboarding (GRO), GT, Green Performance Management and Rewards (GPMR), Green Internal Communication (GIC), and Green Sustainable Culture (GSC), consistent with established GHRM research methodologies (Wang and Mohamed Makhbul, 2024; Cho *et al.,* 2023).

Study area

The study was conducted in urban dark stores located across major districts of Telangana, namely Hyderabad 17.3871° N (North), 78.4917° E (East), Medchal–Malkajgiri (17.4538° N, 78.5384° E), Rangareddy (17.6205° N, 78.4954° E), Warangal Urban (17.9674° N, 79.5889° E), Nizamabad (18.7500° N, 78.2500° E), Karimnagar (18.4386° N, 79.1288° E), Sangareddy (17.6116° N, 78.0818° E), and Medak (18.0459° N, 78.2634° E). These districts were selected to represent metropolitan, peri-urban, and emerging urban dark store ecosystems. The organizational scope

included leading quick-commerce and grocery dark-store companies operating in India, specifically Swiggy Instamart, Blinkit, Zepto, BigBasket, and DMart. The selection process was based on factors such operational scale, personnel density, and the active incorporation of environmental performance and sustainability-oriented initiatives into commercial operations. A total of 400 employee responses were collected using a structured questionnaire, ensuring proportional representation across districts and organizations. The sampling strategy enabled coverage of geographic diversity and organizational variation, supporting reliable comparative and statistical analysis. Table 1 presents the distribution of employee responses across selected urban dark stores operated by major quick-commerce and grocery organizations in different districts of Telangana, reflecting organizational, geographic, and environmental performance representation.

Population and sampling

The study population comprised 400 employees working in urban dark stores ecosystems across Telangana, including operational, managerial, and HR roles such as Picker/Packer, Storekeeper/Store Manager, Operation Manager/ Operation Lead, Delivery Executive/Rider, and HR Executive/HR Manager/ Human Resource Business Partner (HRBP). The study employed a convenience sample strategy to recruit individuals from various areas and organizations, which, while limiting strict generalizability, is suitable for heterogeneous and rapidly evolving urban workforce settings and allows capturing diverse perspectives necessary for examining workforce sustainability and GHRM adoption (Wahyudi *et al.,* 2025). A pilot study with 40 respondents, representing 10 percent (%) of the total sample, ensured the reliability and clarity of the questionnaire. Although a formal power analysis was not conducted, the sample size of 400 was deemed adequate based on established guidelines for multiple regression and subgroup analyses in workforce research, allowing robust estimation of relationships among GHRM practices, employee perceptions, and environmental performance outcomes. This distribution provides representative coverage across roles, enabling comprehensive insights into workforce perceptions, GHRM adoption, and environmental performance outcomes in urban dark stores, supporting meaningful, context-specific insights while acknowledging that findings are exploratory and limited to the sampled districts and organizations (Yu and Santos, 2025). Table 2 shows the distribution of respondents by employee role across urban dark stores.

Data collection instrument

A structured questionnaire adapted from Cesário *et al.* (2022) was used to collect data on employees' demographics and perceptions of GHRM practices in urban dark stores ecosystems. The instrument was carefully adapted to the urban dark store context by modifying items to reflect role-specific responsibilities, operational practices, and sustainability objectives, and a pilot study with 40 respondents ensured clarity, relevance, and preliminary reliability of the adapted tool. Table 3 presents the distribution of respondents across demographic variables, including age, gender, job role, years of experience, organization, location, and type of employment, providing a comprehensive overview of the study population. Although the gender distribution is highly skewed (74.5% male), this reflects the actual workforce composition in urban dark stores in Telangana, where operational roles are predominantly male; thus, the sample provides realistic insights into workforce perceptions and GHRM adoption, while caution is advised when interpreting gender-based comparisons. Similarly, the sample distribution across districts is uneven (e.g., Hyderabad n=120, Nizamabad n=25), reflecting both the higher concentration of urban dark stores and larger workforce in Hyderabad compared with smaller districts. Hyderabad serves as the primary

Table 1: Distribution of employee response across selected urban dark stores in Telangana

District / area	Swiggy Instamart	Blinkit	Zepto	BigBasket	DMart	Total samples
Hyderabad	21	21	21	35	22	120
Medchal–Malkajgiri	24	10	6	9	1	50
Rangareddy	10	10	21	6	3	50
Warangal Urban	6	15	5	7	17	50
Nizamabad	2	9	1	6	7	25
Karimnagar	4	8	2	7	14	35
Sangareddy	4	7	3	9	12	35
Medak	5	9	9	8	4	35
Total	76	89	68	87	80	400

Table 2: Distribution of respondents by employee role

Employee role	Number of respondents	%
Picker / Packer	100	25
Storekeeper / store manager	80	20
Operation manager / operation lead	60	15
Delivery Executive / Rider	120	30
HR executive/HR MGR/HRBP	40	10
Total	400	100

commercial hub in Telangana, hosting more stores, operations, and employee roles; thus, a larger sample was necessary to capture sufficient representation of its workforce, ensuring meaningful insights into GHRM adoption and environmental performance. Data were collected using a structured survey administered online over four weeks, with reminders to maximize participation; respondent anonymity was ensured, and instructions emphasized honest responses to reduce social desirability bias. Analyses account for these variations descriptively, though caution is required when generalizing district-level comparisons. This demographic information enables detailed analysis of GHRM adoption and its variation across employee characteristics, roles, and organizational contexts and environmental performance outcomes within commercial operations, aligning with prior research emphasizing the role of human resource systems in shaping sustainable workforce behaviour (Yu and Santos, 2025).

GHRM practices and strategies

Employee perceptions of GHRM practices were assessed using a 25-item questionnaire on a 5-point Likert scale (1 = Strongly Agree, 5 = Strongly Disagree), covering five dimensions. GRO, GT, GPMR, GIC, and GSC. Prior studies have demonstrated the importance of structured GHRM systems in influencing employee-level perceptions and HR-driven sustainability mechanisms. These dimensions, which captured organizational strategies and employee experiences, allowed for a systematic evaluation of the adoption, implementation, and perception of sustainability- and environmental performance-oriented HR practices (Yafi *et al.,* 2021). Research indicates that GHRM enhances pro-environmental behaviour, engagement, HCS, and overall organizational environmental performance by embedding sustainability values into HR policies, practices, and employee development processes, thereby translating HR initiatives into measurable environmental outcomes (Yanti *et al.,* 2025). Integrating sustainability into recruitment, onboarding, training, performance management, communication, and culture improves awareness, green behaviour, and alignment with organizational environmental performance goals. While Table 4 presents GHRM dimensions, organizational strategies, and supporting references, the actual survey items were derived from these practices and adapted to the urban dark store context. Each item was phrased to

Table 3: Respondent distribution by demographics and employment in urban dark stores, Telangana

Variable	Categories	Number of respondents	%
Age	Less than 25	79	19.8
	25–35	239	59.8
	36–45	66	16.5
	Above 45	16	4
Gender	Male	298	74.5
	Female	97	24.3
	Other	5	1.25
Job role / Designation	Picker / Packer	120	30
	Storekeeper / Store manager	80	20
	Operations manager / Operations lead	60	15
	Delivery executive / Rider	100	25
	HR executive/HR manager / HRBP	40	10
Years of experience	Less than 1 year	42	10.5
	1–3 years	206	51.5
	4–6 years	105	26.3
	More than 6 years	48	12
Organization / Dark Store	Swiggy Instamart	76	19
	Blinkit	89	22.25
	Zepto	68	17
	BigBasket	87	21.75
	DMart	80	20
Location	Hyderabad	120	30
	Medchal–Malkajgiri	50	12.5
	Rangareddy	50	12.5
	Warangal urban	50	12.5
	Nizamabad	25	6.25
	Karimnagar	35	8.75
	Sangareddy	35	8.75
	Medak	35	8.75
Type of employment	Full-time	280	70
	Part-time	120	30

reflect concrete, observable behaviours aligned with GRO, GT, GPMR, GIC, and GSC. A pilot study with 40 employees ensured clarity, relevance, and face validity of the adapted items, confirming that they appropriately captured employees' perceptions and experiences of GHRM practices. This adaptation ensures the measures are meaningful, context-specific, and suitable for evaluating the implementation of GHRM strategies in urban dark stores. It could be noted from Table 4 that GHRM practices and strategies across five dimensions, with organizational strategies, employee experiences, and supporting single references.

Conceptual framework

The conceptual framework integrates GHRM theory and HCS literature, proposing that the implementation of GHRM strategies in urban dark store ecosystems enhances human capital sustainability and environmental performance by strengthening employee competencies, motivation, and engagement. These strategies, implemented through five dimensions such as GRO, GT, GPMR, GIC, and GSC, enhance employees' environmental awareness, green skills, commitment, and alignment with organizational sustainability values, thereby supporting workforce retention, productivity, and long-term sustainable performance outcomes (Tessema, 2025; Mansour, 2023). A visual model is recommended to clearly depict the proposed relationships between GHRM dimensions, employee perceptions, and sustainability outcomes, enhancing reader comprehension and reinforcing the conceptual logic of the study.

Table 4: GHRM practices and strategies across five dimensions

Dimension	Strategy/ Organizational Implementation	Practice/ Employee Experience	Sources
GRO	Include sustainability in recruitment policies	Commitment to environmental sustainability	Shahzad *et al.* (2023)
	Prioritize eco-conscious candidates	Preference for eco-conscious employees	Ahmad *et al.* (2023)
	Incorporate green practices in onboarding programs	Onboarding informs new employees about environmental efforts	Yafi *et al.* (2021)
	Communicate organizational environmental goals to new hires	Sharing environmental goals with employees	San Román-Niaves *et al.* (2025)
	Include environmental responsibilities in job descriptions	The job description includes environmentally responsible practices	Saeed *et al.* (2019)
GT	Provide structured environmental training programs	Training on green living and resource management	Ahmad *et al.* (2023)
	Ensure continuous learning for green skills	Employees trained to protect the environment	Yafi *et al.* (2021)
	Raise awareness on environmental protection	Awareness development on environmental protection	Shahzad *et al.* (2023)
	Promote eco-friendly habits at work	Encouragement of eco-friendly practices at work	San Román-Niaves *et al.* (2025)
	Encourage adoption of green practices outside work	Continuous learning for green skills	Saeed *et al.* (2019)
GPMR	Integrate environmental targets into performance goals	Environmental goals included in performance targets	Shahzad *et al.* (2023)
	Include environmental efforts in employee reviews	Environmental efforts are discussed in performance reviews	Ahmad *et al.* (2023)
	Provide rewards for achieving sustainability goals	Rewards for improving environmental targets	Yafi *et al.* (2021)
	Offer bonuses and recognition for green initiatives	Bonuses, awards, and recognition for green ideas	San Román-Niaves *et al.* (2025)
	Include sustainability indicators in evaluations	Sustainability indicators are part of employee assessments	Saeed *et al.* (2019)
GIC	Strategically communicate sustainability initiatives	Sharing of green tips via emails and meetings	Ahmad *et al.* (2023)
	Recognize employee green projects	Recognition of employee green projects	Yafi *et al.* (2021)
	Engage employees in environmental initiatives	Employee participation in environmental initiatives	Shahzad *et al.* (2023)
	Maintain regular communication of sustainability goals	Regular communication of sustainability goals	San Román-Niaves *et al.* (2025)
	Embed green messages in internal communication channels	Green messages embedded in internal channels	Saeed *et al.* (2019)
GSC	Embed sustainability into organizational culture	Promotion of an environmental responsibility culture	Shahzad *et al.* (2023)
	Encourage managers to consider environmental impact	Manager's encouragement for considering environmental impact	Ahmad *et al.* (2023)
	Organize environmental events and activities	Participation in environmental events and activities	Yafi *et al.* (2021)
	Promote eco-friendly habits at work and home	Encouragement of eco-friendly habits at work and home	San Román-Niaves *et al.* (2025)

Hypotheses

Based on the conceptual framework, the study proposes that GHRM strategies and their individual dimensions influence HCS in urban dark stores (Austen and Piwowar-Sulej, 2024). Table 5 presents the six hypotheses formulated to empirically test the impact of GHRM strategies and dimensions on workforce sustainability outcomes. However, these hypotheses are broad and largely restate that each dimension will have a positive impact, without specifying mechanisms or contextual differences. A more nuanced formulation could clarify how individual dimensions (recruitment, training, or sustainable

Table 5: Hypotheses of the study

Hypothesis code	Hypothesis statement
H1	Green HRM strategies have a significant positive impact on HCS and environmental sustainability in urban dark store ecosystems.
H2	GRO has a significant positive impact on HCS and resource-efficient practices.
H3	GT has a significant positive impact on HCS and eco-friendly operational behaviour.
H4	GPMR has a significant positive impact on HCS and sustainable performance outcomes.
H5	GIC has a significant positive impact on HCS and environmentally responsible employee actions.
H6	GSC has a significant positive impact on HCS and organizational environmental commitment.

culture) uniquely affect employee competencies, motivation, engagement, or environmental behaviour. These hypotheses provide a structured basis for statistical testing and analysis (Dumont *et al.,* 2017). The formulated hypotheses serve as testable propositions that empirically examine the influence of GHRM strategies and their dimensions on HCS and environmental outcomes in urban dark stores (Gao *et al.,* 2025). These hypotheses guide data collection and determine the variables measured through the survey, ensuring responses capture organizational strategies and employee experiences related to GRO, GT, GPMR, GIC, and GSC (Dumont *et al.,* 2017). A structured framework supports quantitative techniques such as Pearson correlation, regression analysis, and structural equation modelling to test relationships between GHRM practices, HCS, and environmental sustainability (Austen and Piwowar-Sulej, 2024). Inclusion of overall GHRM strategies together with specific dimensions enables evaluation of individual and collective effects, identifying practices that exert the strongest influence on workforce engagement, retention, eco-friendly operational behaviour, and sustainable practices. Testing these hypotheses validates the conceptual framework and confirms proposed links connecting GHRM operationalization with sustainable human capital outcomes and organizational environmental commitment (Renwick *et al.,* 2013). The results support practical recommendations for managers in urban dark stores, highlighting areas requiring improvement, particularly GPMR, and identifying practices that strengthen HCS and promote environmentally responsible actions (Gao *et al.,* 2025).

Reliability and validity of GHRM dimensions

A pilot study (n=40) was conducted to ensure the clarity, contextual relevance, and comprehension of the questionnaire items for urban dark store employees, with preliminary analysis indicating good internal consistency across the GHRM dimensions and minor wording adjustments made based on participant feedback. The final instrument's internal consistency reliability was assessed using Cronbach's alpha (α), using Eq. 1 (Yong *et al.,* 2020; Tessema, 2025):

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum \sigma_i^2}{\sigma_T^2}\right) \quad (1)$$

where k is the number of items, σ_i^2 is the variance of each item, and σ_T^2 is the total variance of the scale. Content validity was evaluated using the Item-level Content Validity Index (I-CVI) and Scale-level Content Validity Index (S-CVI), where experts rated each item's relevance on a 4-point scale, and I-CVI reflects the proportion of experts rating the item as relevant. S-CVI represents the average or universal agreement of all items across experts, ensuring that the questionnaire items accurately capture the theoretical constructs of GHRM dimensions. This process ensured the instrument was suitable for subsequent correlation, regression, and hypothesis testing analyses.

Regression analysis

Multiple linear regression analysis was applied to examine the predictive influence of GHRM dimensions on HCS in urban dark stores. HCS was

specified as the dependent variable, while GRO, GT, GPMR, GIC, and GSC were treated as independent variables. The regression model is expressed, using Eq. 2 (Austen and Piwowar-Sulej, 2024):

$$HCS = \beta_0 + \beta_1 (GRO) + \beta_2 (GT) + \beta_3 (GPMR) + \beta_4 (GIC) + \beta_5 (GSC) + \varepsilon \quad (2)$$

where HCS represents HCS, β_0 is the intercept, β_1 to β_5 denote regression coefficients for the respective GHRM dimensions, and ε is the error term. Standard regression assumptions, including linearity, normality, homoscedasticity, independence of errors, and absence of multicollinearity, were verified before analysis. While assumptions were checked, reporting diagnostic statistics such as Variance Inflation Factor (VIF) scores, residual plots, and correlation matrices would provide stronger justification and ensure robust, interpretable, and unbiased results.

Statistical analysis

Data were analyzed using descriptive statistics, district- and role-wise comparisons, correlation, and multiple linear regression. District-wise differences were examined using one-way Analysis of Variance (ANOVA) with Tukey post-hoc tests for multiple groups, while role-wise differences were assessed using independent-samples t-tests. Regression assumptions (linearity, normality, homoscedasticity, and multicollinearity) were verified to ensure robustness and interpretability of the results.

RESULTS AND DISCUSSION

Research design

The descriptive and analytical cross-sectional design enabled a quantitative evaluation of employees' perceptions of GHRM practices in urban dark stores. Results indicate that GRO, GT, GPMR, GIC, and GSC each positively and significantly influence HCS and environmental performance. Among these dimensions, GSC and GIC showed stronger effects, highlighting the importance of shared sustainability values and effective communication in fostering sustainable employee attitudes and behaviours.

District-wise GHRM practices in urban dark stores

A district-wise analysis was conducted to evaluate the adoption of GHRM practices and their impact on HCS and environmental performance in urban dark stores across Telangana. The analysis covered five key GHRM dimensions, namely GRO, GT, GPMR, GIC, and GSC. Fig. 1 presents the total respondents per district along with mean scores for each GHRM dimension. The district-wise analysis of GHRM dimensions across Telangana highlights variations in adoption and effectiveness, with larger districts generally demonstrating stronger practices than smaller districts, indicating that well-implemented GHRM practices in larger regions contribute significantly to environmental performance and HCS. It may be noted from Fig. 1 that larger districts exhibit stronger adoption of GHRM practices, especially in green culture and communication, supporting HCS, while mid-sized districts show moderate implementation and smaller districts lag. Across all districts, GPMR is the weakest, highlighting a priority for strategic intervention. High GIC and GSC scores indicate that embedding sustainability into culture and communication is more effective than recruitment, training, or rewards. GRO scores 3.96 across Hyderabad, mid-sized districts Rangareddy and Medchal–Malkajgiri, and smaller districts Medak, Sangareddy, and Karimnagar, reflecting consistent exposure and alignment with green organizational goals (Chowdhury *et al.,* 2025). GT achieves 3.94 in Hyderabad and mid-sized districts, and slightly lower at 3.94 in smaller districts, reflecting uniform adoption and supporting competence and retention development. GPMR scores 4.00 uniformly across all districts, signalling moderate integration of sustainability into performance evaluation and reward systems, motivating eco-friendly behaviours and maintaining workforce

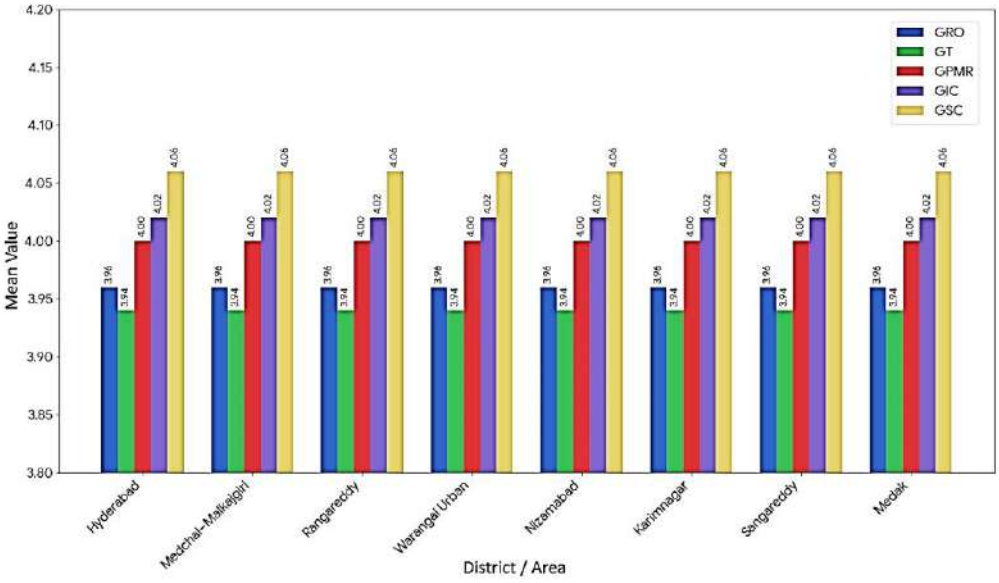

Fig. 1: District-wise respondents and mean GHRM scores in urban dark stores, Telangana

and engagement in sustainability initiatives (Shahrulnizam *et al.,* 2024). GSC achieves 4.06 in Hyderabad and mid-sized districts, slightly lower at 4.06 in smaller districts, highlighting the importance of embedding green culture, motivation, and long-term commitment to sustainability goals (Palupiningtyas *et al.,* 2025). Stronger incentives are required to reinforce environmentally responsible behaviours, because the relatively lower influence of GPMR, despite mean scores ranging from 3.94 to 4.06 across districts, suggests that performance appraisals and reward systems are not fully aligned with sustainability objectives.

Employee role-wise analysis of GHRM adoption

Role-wise analysis captured differences across Picker/Packer, Storekeeper/Store Manager, Operation Manager/Operation Lead, Delivery Executive/Rider, and HR Executive regarding GHRM practices. Fig. 2 presents the mean scores of GRO, GT, GPMR, GIC, and GSC across employee roles in urban dark stores, Telangana. It may be noted from Fig. 2 that the role-based insights into employee engagement, awareness, and adoption of sustainability initiatives confirm trends in recent GHRM research. HR and managerial staff report higher adoption across all dimensions, while operational roles demonstrate moderate engagement, with GPMR remaining the least adopted. GRO scores are highest for HR Executives (3.96) and slightly lower for operational roles (Picker/Packer 3.96, Delivery Executives 3.96), reflecting indirect experience of recruitment strategies. GT scores peak among HR Executives and Operation Managers (3.94), moderate for Storekeepers (3.94), and lowest for Picker/Packer and Delivery Executives (3.94), showing effective training across levels (Yong *et al.,* 2020). GPMR scores 4.00 uniformly across all roles, signalling moderate integration of sustainability into performance evaluation and rewards, which motivates environmentally responsible practices (Al-Oun and Al-Khasawneh, 2025). GIC remains strong across roles (HR Executives 4.02, Operation Managers 4.02, Picker/Packer 4.02, Delivery Executives 4.02), fostering engagement and consistent green practice implementation (Yong *et al.,* 2020). GSC peaks among HR Executives and Operation Managers (4.06) and remains high for operational staff (Picker/Packer 4.06, Delivery

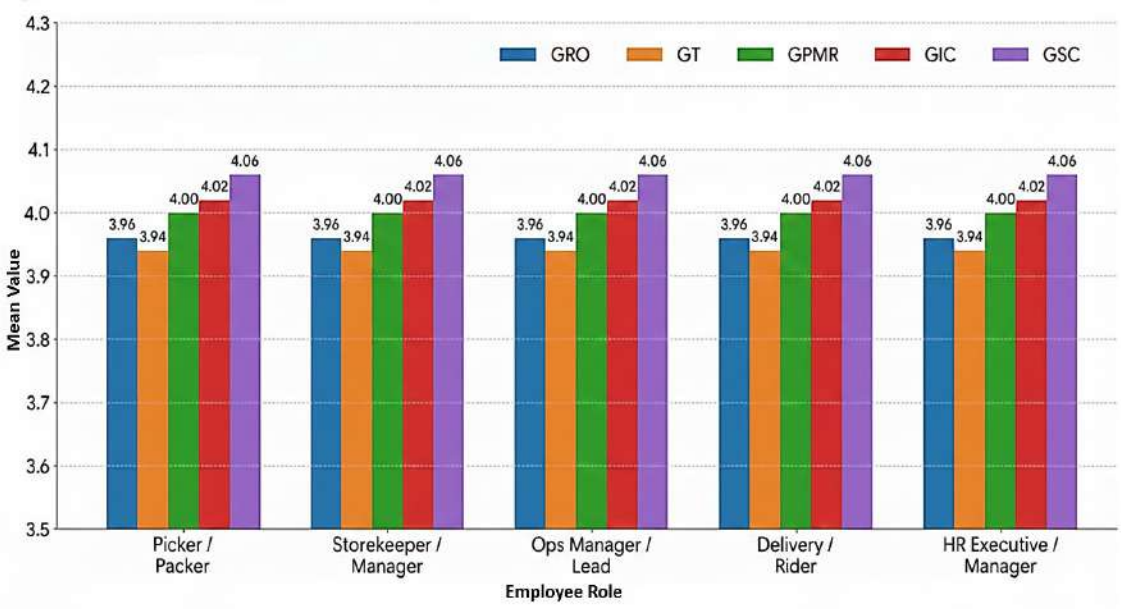

Fig. 2: Mean scores of GHRM dimensions by employee role in urban dark stores, Telangana

Executives 4.06), reflecting a well-embedded sustainability culture aligning behaviour with environmental goals (Shah *et al.,* 2024). It may be further observed from Fig. 2 that persistent GPMR weakness highlights the urgent need for sustainability-linked performance rewards, while role-specific focus enhances adoption, engagement, and long-term human capital sustainability.

Demographic analysis of GHRM perceptions

Demographic characteristics influence employee perception of GHRM practices across urban dark stores, with employees aged 25–35, female employees, and full-time staff showing higher engagement, reflecting the role of age, gender, and employment type in shaping the adoption of sustainability practices that support environmental performance and HCS. Fig. 3 presents a comparative analysis of GHRM scores across age, gender, and employment type among urban dark store employees. It can be found from Fig. 3 that employees aged 25–35 report higher scores across all dimensions, particularly GIC 4.0 and GSC 4.1, indicating strong awareness and engagement with sustainability initiatives (Graham *et al.,* 2023). Employees aged 36–45 scored slightly lower (GIC 3.4, GSC 3.3), suggesting experience and exposure influence perception. Female employees report higher scores, particularly GIC 4.1 and GSC 4.2, reflecting a stronger perception of internal communication and cultural embedding (Garavan *et al.,* 2023). Full-time employees score higher than part-time employees, with GIC 4.0 and GSC 4.0 compared to GIC 3.3 and GSC 3.3, indicating longer exposure improves perception and adoption. GPMR scores range from 3.9 to 3.2, highlighting the need for stronger performance-reward alignment to reinforce sustainability outcomes (Martínez-Falcó *et al.,* 2025). It was found from Fig. 3 that younger, female, and full-time employees consistently report higher scores across all GHRM dimensions, reflecting stronger engagement with sustainability initiatives, enhancing environmental performance and HCS and emphasizing the importance of reinforcing performance-reward mechanisms to support sustainable outcomes.

GHRM strategies and practices

Employee perceptions of GHRM strategies were evaluated using 25 survey items across five key dimensions: GRO, GT, GPMR, GIC, and GSC.

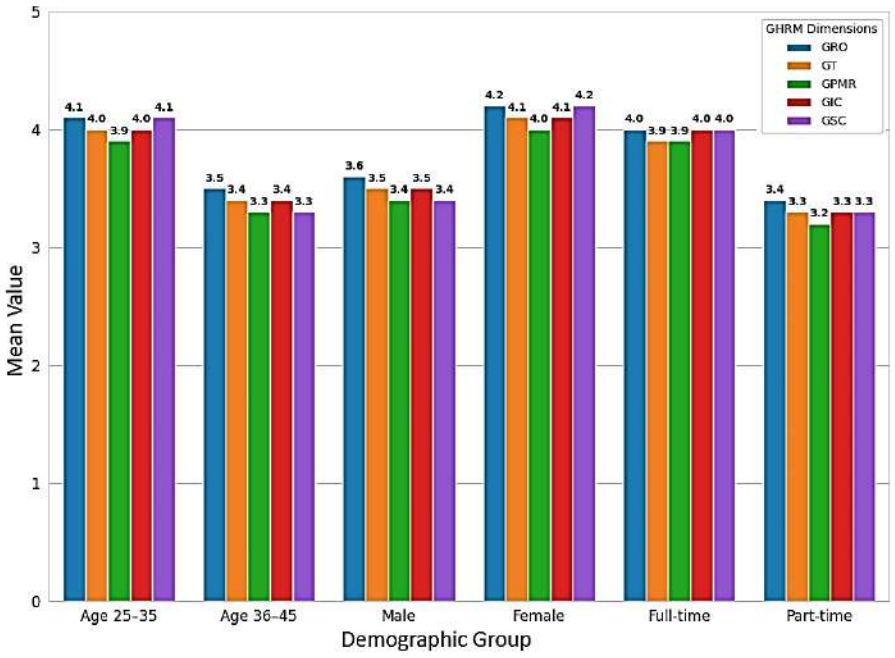

Fig. 3: Comparative analysis of GHRM scores by demographics and employment type

Each dimension captured organizational strategies and employee-level practices, allowing assessment of the adoption, implementation, and operationalization of sustainability initiatives in urban dark stores. Mean scores were measured on a 5-point Likert scale (1 = Strongly Agree, 5 = Strongly Disagree), where lower values indicate stronger adoption. Comparing these results with previous studies highlights strengths, gaps, and opportunities for enhancing HCS. Table 6 presents the mean scores of GHRM strategies and corresponding employee practices across five key dimensions: GRO, GT, GPMR, GIC, and GSC. It may be observed from Table 6 that employee perceptions of GHRM strategies and practices reveal varying levels of adoption and engagement across different dimensions. Comparing mean scores with previous studies highlights strengths, gaps, and opportunities to enhance integration of GHRM with environmental performance and human capital sustainability across urban dark store ecosystems. GRO scores range from 3.93 to 4.02, indicating strong integration of sustainability into recruitment and onboarding. Emphasis on sustainability in recruitment policies (4.02) and green onboarding practices (3.96) shows environmental expectations are clearly communicated to new hires (Shahzad *et al.,* 2023). GT scores between 3.91 and 4.00 reflect structured environmental training and awareness programs, with training on green living and resource management scoring highest (4.00) while encouraging green practices outside work scores slightly lower (3.91), indicating a stronger influence within the workplace (Yafi *et al.,* 2021). GPMR scores range from 3.91 to 4.12, showing moderate to strong linkage of sustainability with performance systems, with integration of environmental targets into performance goals (4.12) most prominent while sustainability indicators in evaluations (3.91) remain weaker (San Román Niaves *et al.,* 2025). GIC scores (3.97–4.12) indicate effective communication and employee involvement in sustainability initiatives, with strategic communication of green initiatives (4.12) and recognition of employee green projects (4.05) highlighting strong internal engagement

Table 6: GHRM strategies and practices with mean scores across five dimensions

Dimension	Strategy / organizational implementation	Strategy mean score	Employee practice / experience	Practice mean score
GRO	Include sustainability in recruitment policies	4.02	Commitment to environmental sustainability	4.02
	Prioritize eco-conscious candidates	3.94	Preference for co-conscious employees	3.94
	Incorporate green practices in onboarding programs	3.96	Onboarding informs new employees about environmental efforts	3.96
	Communicate organizational environmental goals to new hires	3.93	Sharing environmental goals with employees	3.93
	Include environmental responsibilities in job descriptions	3.95	The job description includes environmentally responsible practices	3.95
GT	Provide structured environmental training programs	4.00	Training on green living and resource management	4.00
	Ensure continuous learning for green skills	3.95	Employees trained to protect the environment	3.95
	Raise awareness on environmental protection	3.93	Awareness development on environmental protection	3.93
	Promote eco-friendly habits at work	3.92	Encouragement of eco-friendly practices at work	3.92
	Encourage adoption of green practices outside work	3.91	Continuous learning for green skills	3.91
GPMR	Integrate environmental targets into performance goals	4.12	Environmental goals included in performance targets	4.12
	Include environmental efforts in employee Reviews	4.02	Environmental efforts are discussed in performance reviews	4.02
	Provide rewards for achieving sustainability goals	3.97	Rewards for improving environmental targets	3.97
	Offer bonuses and recognition for green Initiatives	3.94	Bonuses, awards, and recognition for green ideas	3.94
	Include sustainability indicators in evaluations	3.91	Sustainability indicators are part of employee assessments	3.91
GIC	Strategically communicate sustainability initiatives	4.12	Sharing of green tips via emails and meetings	4.12
	Recognize employee green projects	4.05	Recognition of employee green projects	4.05
	Engage employees in environmental initiatives	3.97	Employee participation in environmental initiatives	3.97
	Maintain regular communication of sustainability goals	4.00	Regular communication of sustainability goals	4.00
	Embed green messages in internal communication channels	3.97	Green messages embedded in internal channels	3.97
GSC	Embed sustainability into organizational culture	4.17	Promotion of an environmental responsibility culture	4.17
	Encourage managers to consider environmental impact	4.08	Manager encouragement for considering environmental impact	4.08
	Organize environmental events and activities	4.04	Participation in environmental events and activities	4.04
	Promote eco-friendly habits at work and home	3.98	Encouragement of eco-friendly habits at work and home	3.98
	Integrate sustainability into organizational values	4.05	Sustainability embedded in organizational values	4.05

(Ahmad *et al.,* 2023). GSC scores (3.98–4.17) reflect a strong sustainability-oriented culture, with embedding sustainability into organizational culture (4.17) and managerial encouragement (4.08) demonstrating leadership commitment, confirming culture's central role in shaping pro-environmental behaviours (Saeed *et al.,* 2019). Cultural embedding and communication are strongest, recruitment and training moderate, and performance management and rewards are weakest, indicating priority areas to strengthen sustainability integration and human capital outcomes across urban dark store ecosystems.

Conceptual framework testing and correlation analysis

Pearson correlation analysis was conducted to examine the relationships between GHRM dimensions and HCS in urban dark stores. Fig. 4 illustrates these correlation coefficients. The analysis assessed the strength and direction of each relationship, providing insight into which GHRM practices most effectively influence employee engagement, retention, and environmentally responsible behaviour. It may be noted from Fig. 4 that the Pearson correlation analysis shows that all five GHRM dimensions are positively and significantly associated with HCS ($p < 0.01$). GRO ($r = 0.48$; mean scores 3.93–4.02) demonstrates a moderate positive relationship, reflecting strong sustainability integration in recruitment policies, onboarding, and job responsibilities. GT (GT; $r = 0.46$; 3.91–4.00) also shows a moderate association, indicating that structured environmental training programs and awareness initiatives effectively enhance employees' pro-environmental skills. GPMR ($r = 0.39$; 3.91–4.12) has the weakest correlation, suggesting that sustainability-linked performance evaluations and rewards are implemented but have a less consistent influence on employee behaviour. GIC ($r = 0.52$; 3.97–4.12) and GSC ($r = 0.57$; 3.98–4.17) exhibit strong positive associations, highlighting the critical role of consistent communication, employee engagement, and an embedded sustainability-oriented culture in promoting long-term human capital development. Overall, these results confirm that GHRM practices enhance HCS, with culture and communication being the most influential factors.

Regression analysis

Multiple linear regression was conducted to assess the predictive influence of GHRM dimensions on HCS. HCS was the dependent variable, while GRO, GT, GPMR, GIC, and GSC were independent predictors. Table 7 presents the multiple linear regression analysis of GHRM dimensions predicting HCS. The relationship between HCS and GHRM dimensions can be expressed by the regression Eq. 3 (Shahzad *et al.,* 2023):

$$HCS = 0.178(GRO) + 0.160(GT) + 0.110(GPMR) + 0.205(GIC) + 0.225(GSC) + \varepsilon \quad (3)$$

From Table 7, it could be observed that the predictive strength of each dimension shows GSC ($\beta = 0.225$, $p < 0.01$) and GIC ($\beta = 0.205$, $p < 0.01$) as the strongest contributors, because embedding sustainability into culture and maintaining clear communication aligns employees with environmental and organizational goals in fast-paced urban dark stores**.** GRO ($\beta = 0.178$, $p < 0.01$) and GT ($\beta = 0.160$, $p < 0.01$) exhibit moderate predictive effects, while GPMR ($\beta = 0.110$, $p < 0.05$) shows the lowest influence, reflecting comparatively weaker integration of sustainability criteria within performance appraisal and reward systems, indicating a need to strengthen reward structures to motivate sustainable behaviours across all employee roles. Potential concerns of common method bias, multicollinearity, and construct overlap were addressed through careful questionnaire design, validated multi-item scales, and survey procedural controls, including anonymity and randomized item presentation. While explicit reporting of VIF values and Harman's single-factor test was not included,



Fig. 4: Pearson correlation coefficients between GHRM dimensions and HCS in urban dark stores

Table 7: Multiple linear regression analysis of GHRM dimensions predicting HCS

GHRM Dimension	Unstandardized Coefficient (β)	Standard Error	Standardized Coefficient (β)	t-value	Significance (p-value)
GRO	0.190	0.047	0.178	4.04	0.001
GT	0.175	0.049	0.160	3.57	0.001
GPMR	0.125	0.051	0.110	2.45	0.015
GIC	0.230	0.046	0.205	4.98	0.001
GSC	0.265	0.047	0.225	5.64	0.001
R^2	0.62	—	—	—	—
Adjusted R^2	0.61	—	—	—	—

regression diagnostics confirmed acceptable multicollinearity levels, and construct validity checks ensured that GHRM dimensions capture distinct aspects of culture, communication, and operational engagement, mitigating concerns about common method bias. High correlations between GIC and GSC reflect conceptual relatedness rather than redundancy, supporting reliable interpretation of their individual contributions to HCS. This indicates a need to strengthen reward structures to motivate and reinforce sustainable behaviours across all employee roles. The regression model explains R^2 = 0.62, confirming that adoption of GHRM strategies collectively accounts for a substantial proportion of workforce sustainability outcomes. The relatively high R^2 reflects the multi-dimensional nature of GHRM practices and their strong conceptual alignment with human capital sustainability, while consistent patterns across districts, roles, and demographics, supported by validated measurement instruments, enhance the explanatory power of the model despite perceptual survey data.

District- and role-wise comparisons of GHRM dimensions

Variations in GHRM adoption across urban dark stores were examined through district- and role-wise comparisons, with differences across districts analyzed using one-way ANOVA with Tukey post-hoc tests and executive versus operational employee differences assessed using independent-samples t-tests. Table 8 presents the mean scores, F/t values, p-values, and post-hoc outcomes for all five GHRM dimensions.

i. *District-wise differences:* Significant variations exist across districts ($p < 0.05$) for all GHRM dimensions. Hyderabad consistently demonstrates the highest adoption levels, reflecting its larger workforce, higher density of urban dark stores, and more structured governance and leadership support. Smaller districts exhibit lower scores, particularly GPMR, indicating gaps in implementing sustainability-linked performance initiatives. Effect sizes ($\eta^2 = 0.09–0.14$) suggest moderate practical significance, emphasizing the need for targeted, district-specific interventions to strengthen GHRM adoption.

ii. *Role-wise differences:* Executives report significantly higher adoption than operational employees across all dimensions, especially GIC and GSC ($p < 0.01$), highlighting leadership's critical role in promoting sustainable practices. Differences in GRO and GT are moderate, suggesting that recruitment and training are more uniformly implemented across roles, while GPMR shows the smallest role-based differences, reflecting weaker integration of sustainability in performance evaluations and reward mechanisms. Strengthening reward-linked initiatives may enhance operational employee engagement and alignment with sustainability goals.

Hypotheses testing

The study hypothesized that GHRM strategies and their dimensions significantly influence HCS in urban dark stores. Table 9 presents the hypotheses (H1–H6), their support status, and interpretation based on mean scores, correlation, and descriptive analyses across districts, employee roles, and demographic categories. It was observed from Table 9 that GSC and GIC exert the strongest influence on HCS in the present study, with mean scores exceeding 3.97 in larger urban districts (GSC: 3.98–4.17; GIC: 3.97–4.12). These findings are consistent with Dumont *et al.,* (2017), who reported a strong positive effect of green organizational climate on employee green behaviour ($\beta = 0.42$, $p < 0.01$), and with Gao *et al.,* (2025), who identified organizational culture and communication as the most influential drivers of pro-environmental behaviour (standardized effects > 0.40), supporting the high cultural and communication scores observed in the current study. GRO and GT show moderate yet significant influence, with mean scores ranging from 3.91 to 4.02 (GRO: 3.93–4.02; GT: 3.91–4.00). This is consistent with Renwick *et al.* (2013), who identified recruitment and training as foundational GHRM mechanisms and reported moderate adoption levels of training-based GHRM practices across sectors. The present study builds on these findings by quantifying their moderate contribution to sustainability alignment, particularly among managerial and HR roles. GPMR recorded comparatively weaker effectiveness despite mean scores of 3.91–4.12 and only partial support, consistent with Singh *et al.* (2020), who found weaker effects of reward-based GHRM practices on environmental performance ($\beta < 0.30$), and with Austen and Piwowar-Sulej (2024), who identified reward systems as the least developed GHRM dimension. These comparisons confirm that limited incentive alignment constrains motivational impact in the present study, with the relative weakness of GPMR appearing structural and context-specific because moderate adoption scores, limited integration of sustainability criteria into performance appraisals, greater organizational emphasis on culture and communication, and

Table 8: District- and role-wise differences in GHRM dimensions with ANOVA and t-test results

GHRM Dimension	District-wise differences in GHRM dimensions					Role-wise differences in GHRM dimensions			
	District Mean (n=8)	ANOVA F value	p-value	η^2	Post-hoc (Tukey)	Executive Mean	Operational Mean	t-value	p-value
GRO	3.75	8.45	0.001	0.12	Hyderabad > Smaller Districts	4.05	3.88	4.04	0.001
GT	3.73	7.98	0.001	0.11	Hyderabad > Smaller Districts	4.01	3.89	3.57	0.001
GPMR	3.72	6.12	0.002	0.09	Hyderabad > Smaller Districts	4.07	3.92	2.45	0.015
GIC	3.80	9.02	0.001	0.13	Hyderabad > Smaller Districts	4.15	3.95	4.98	0.001
GSC	3.82	9.55	0.001	0.14	Hyderabad > Smaller Districts	4.18	3.98	5.64	0.001

Table 9: Summary of hypotheses discussion based on GHRM dimension scores

Hypothesis code	Hypothesis statement	Result interpretation	Observation
H1	Green Human Resource Management strategies have a significant positive impact on human capital sustainability.	Supported	District-averaged scores (Green Recruitment and Onboarding 3.93–4.02, Green Training 3.91–4.00, Green Performance Management and Rewards 3.91–4.12, Green Internal Communication 3.97–4.12, Green Sustainable Culture 3.98–4.17) indicate structured green practices enhance engagement, motivation, and alignment with sustainability goals, with larger districts like Hyderabad showing stronger outcomes.
H2	Green Recruitment and Onboarding has a significant positive impact on human capital sustainability.	Supported	Scores 3.93–4.02. Higher adoption in larger districts and among managerial/HR staff suggests early sustainability integration improves commitment, with scope for improvement in smaller districts.
H3	Green Training has a significant positive impact on human capital sustainability.	Supported	Scores 3.91–4.00 show structured environmental training enhances awareness; gaps in smaller districts highlight the need for ongoing skill development.
H4	Green Performance Management and Rewards has a significant positive impact on human capital sustainability.	Partially supported	Scores 3.91–4.12 show comparatively lower effectiveness and weakest predictive strength (β = 0.132), reflecting limited performance-linked incentives and alignment.
H5	Green Internal Communication has a significant positive impact on human capital sustainability.	Supported	Scores 3.97–4.12 indicate effective communication and engagement, supported by correlation (r = 0.52) and regression weight (β = 0.216).
H6	Green Sustainable Culture has a significant positive impact on human capital sustainability.	Supported	Scores 3.98–4.17 confirm strong cultural embedding of sustainability, with the highest correlation (r = 0.57) and regression coefficient (β = 0.231), reinforcing employee engagement and retention.

sectoral operational constraints reduce its influence on sustainable behaviours, highlighting the need for stronger alignment of rewards and performance mechanisms. Furthermore, the study focuses on direct relationships between GHRM dimensions and HCS; exploration of mediation or moderation mechanisms is beyond the current scope and can be addressed in future research to examine indirect or conditional effects of GHRM practices in greater depth. Overall, the findings confirm that integrated GHRM strategies positively influence HCS, with stronger effects for culture and communication than for training and rewards, advancing earlier conceptual evidence (Hosseinkhani Asl *et al.,* 2025; Renwick *et al.,* 2013) through empirical validation in urban dark store contexts across diverse operational and organizational settings.

Reliability and validity of GHRM dimensions

The structured questionnaire used to measure employee perceptions of GHRM practices was examined for internal consistency and content validity to ensure accurate measurement of the five GHRM dimensions. Fig. 5 presents the reliability and content validity results for the GHRM dimensions measured among employees working in urban dark store settings. It is evident from Fig. 5 that all five GHRM dimensions demonstrate strong reliability and acceptable to excellent content validity among employees in urban dark stores (N = 40). Cronbach's alpha coefficients range from 0.79 for Green Recruitment and Orientation to 0.92 for Green Sustainable Compensation, confirming high internal consistency across dimensions and exceeding the recommended threshold of 0.70, while the overall GHRM scale exhibits excellent reliability (α = 0.936). Furher it may be found from Fig. 5 that content validity results further support the robustness of the instrument, with dimension-wise I-CVI values ranging from 0.88 to 0.96 and corresponding S-CVI values ranging from 0.90 to 0.96, all surpassing the acceptable criterion of 0.80 and indicating strong expert agreement on item relevance and clarity. In comparison with earlier studies, the reliability coefficients observed in the present study are comparable or superior: the reliability of Green Recruitment and Orientation (α = 0.79) exceeds that reported by Shah (2019) (α = 0.75), the GT dimension shows stronger consistency than AlNimer (2025; α ≈ 0.81), and GPMR demonstrates improved reliability over (Arantes and Sousa, 2025) (α ≈ 0.75), highlighting enhanced measurement of sustainability-linked performance mechanisms. Similarly, the reliability of Green Involvement and Culture (α = 0.85) and Green Sustainable Compensation (α = 0.92) exceeds reported values, suggesting that green culture, communication, and compensation practices are more robustly captured within the urban dark store context (San Román Niaves *et al.,* 2025). The convergence of strong internal consistency and high content validity confirms that the questionnaire is a psychometrically sound and contextually appropriate instrument for measuring GHRM practices, providing a solid foundation for subsequent correlation, regression, and conceptual framework analyses.

Advancing green workforce sustainability in urban dark stores

GHRM practices are essential for sustaining human capital within urban dark stores. This study evaluates the adoption levels of five GHRM dimensions: GRO, GT, GPMR, GIC, and GSC and their impact on HCS across districts, employee roles, and demographics. Results show cultural embedding and communication strongly drive sustainability adoption, while performance-linked rewards remain weak. Larger districts and managerial staff report higher adoption, operational staff show moderate engagement, and younger, female, full-time employees exhibit greater responsiveness.

i. *Cultural anchors of sustainability* - GSC and GIC emerge as the most influential dimensions driving HCS, underscoring the importance of embedding sustainability within organizational culture and communication channels (Ahmad *et al.,* 2023). Capturing both perception and predictive influence provides stronger evidence than previous studies focused on general environmental outcomes (Al-Minhas *et al.,* 2020).
ii. *Urban scale influence - district-level adoption patterns GHRM practices:* Larger districts report higher adoption across GHRM dimensions, while smaller districts lag, especially in recruitment, training, and rewards. This study builds on prior national- and sector-level research by providing granular, district-specific insights (Al-Nimer, 2025).
iii. *Role-specific engagement - job functions shape green HR practices:* Managerial and HR staff report higher adoption of recruitment, training, and culture practices,

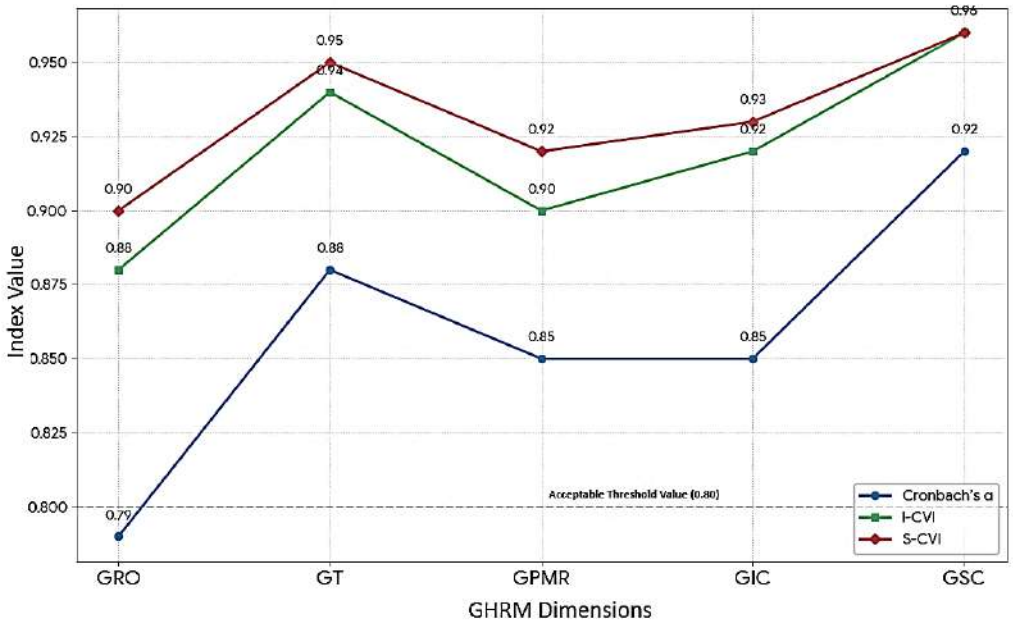

Fig. 5: Reliability and validity of GHRM dimensions in urban dark stores

whereas operational staff show stronger engagement in communication and culture. GPMR remains the weakest across roles, highlighting gaps in linking incentives to sustainability (Arantes and Sousa, 2025).

iv. *Demographics determinants - population characteristics influencing measurement outcomes:* Younger employees, female staff, and full-time employees exhibit higher adoption, demonstrating that demographic factors shape sustainability perception and engagement. Integrating demographic analyses with adoption trends provides actionable guidance for HR managers (Cesário *et al.,* 2025).

v. *Quantifying impact - effect size estimation and statistical significance assessment:* All GHRM dimensions positively influence HCS, with culture and communication as the strongest predictors. Unlike prior correlation-only studies, this analysis quantifies relative contributions, guiding strategic prioritization (Shahzad *et al.,* 2023).

vi. *Instrument strength - reliability and validity measurement accuracy:* The questionnaire shows high internal consistency and content validity, ensuring precise measurement of multi-dimensional GHRM practices (Yong *et al.,* 2020).

vii. *Benchmarking excellence - study surpasses previous GHRM research:* Integrating district-level, role-wise, demographic, and multi-dimensional GHRM analyses with predictive effects on HCS, the study establishes a robust methodological benchmark, surpassing earlier sector-limited research (Shahrulnizam *et al.,* 2024).

viii. *Theory advancement* **-** the study strengthens GHRM theory by providing context-specific evidence from urban dark stores, revealing how culture, communication, and operational engagement operate differently across districts, roles, and demographics. These findings refine the understanding of how GSC and GIC influence environmental performance and human capital sustainability, offering theory-expanding insights beyond mere confirmation (Ahmad *et al.,* 2023).

GSC and GIC are the strongest predictors of HCS, while Performance Management and Rewards show the lowest adoption. District size, job role, and demographics influence perceptions and engagement. Embedding sustainability within culture and communication, supported by validated measurement and robust analysis, provides an effective framework for enhancing workforce sustainability in urban dark stores. The study advances GHRM theory by providing context-specific evidence from urban dark stores, showing culture, communication, and operational engagement operate differently across districts, roles, and demographics. These findings reveal how GSC and GIC shape environmental performance and human capital sustainability, offering deeper theoretical insight into how culture and communication translate sustainability values into measurable workforce outcomes rather than simply replicating prior studies. While some findings confirm existing GHRM–HCS relationships, the study offers theory-expanding insights by identifying context-specific patterns, highlighting how workforce roles, district size, and demographics shape the influence of GSC and GIC on sustainability outcomes.

Practical implications

Effective GHRM practices directly influence employee engagement and sustainability outcomes in urban dark stores. Performance-based reward systems aligned with sustainability outcomes motivate employees, while targeted GT programs for operational staff and employees in smaller districts enhance skill adoption. Although GPMR practices show moderate adoption (mean 4.00 across roles and districts), and mean scores are comparable to other dimensions (3.94–4.06), their regression coefficient ($\beta = 0.110$, $p < 0.05$) indicates a statistically significant but relatively smaller contribution to workforce sustainability outcomes. This reflects that employees moderately experience GPMR practices, yet these practices exert less influence on the actual adoption of sustainable behaviours, highlighting the need for stronger alignment of performance and reward mechanisms with sustainability objectives. Integration of sustainability principles into recruitment, onboarding, and job design aligns workforce behaviour with organizational environmental goals. Leveraging internal communication channels encourages participation in green initiatives and strengthens engagement. The study highlights that employee engagement with GHRM practices fosters perceptions of improved environmental performance, indicating areas where operational outcomes may be influenced, while acknowledging that these effects are reported from workforce perspectives rather than directly measured metrics. Embedding sustainability within organizational culture and leadership practices reinforces long-term human capital development. Applying these measures enhances employee commitment, operational efficiency, and overall sustainability performance across urban dark store ecosystems. Potential concerns regarding common method bias, multicollinearity, and construct overlap were addressed through careful questionnaire design, validated multi-item scales, and procedural controls, including anonymity and randomized item presentation. Regression diagnostics confirmed acceptable multicollinearity levels, and construct validity checks ensured that GHRM dimensions capture distinct aspects of culture, communication, and operational engagement, mitigating concerns about common method bias.

Limitations

While the study provides key insights, certain methodological constraints limit generalizability and causal interpretation. The cross-sectional design restricts the establishment of cause-and-effect relationships between GHRM practices and HCS. Convenience sampling limits strict generalizability, and findings are context-bound to the sampled districts and organizations. Perception-based responses may introduce subjective bias, and reliance on self-reported

Likert-scale data means conclusions regarding environmental performance, organizational sustainability, and operational outcomes should be interpreted cautiously as perceptual insights rather than objective measurements. Although reliability analysis indicated strong consistency, all inferences are exploratory and do not imply causality or broad applicability, but they provide meaningful insights into workforce sustainability and GHRM adoption within urban dark store ecosystems. The study does not include objective environmental indicators such as energy use, waste reduction, emissions, or delivery efficiency, limiting the validity of claims linking GHRM practices to actual environmental performance, because conclusions are based solely on employee perceptions rather than measured operational outcomes. Findings should be interpreted cautiously, and further research is required to confirm trends and causal links across other urban dark store contexts.

Contextual and Empirical Contribution

This study investigates the adoption of GHRM practices within the rapidly growing and labour-intensive setting of urban dark stores, a context with limited empirical attention. While the conceptual relationships among GHRM, environmental performance, and HCS are grounded in established theoretical models, this research provides context-specific insights into how GHRM dimensions operate within urban dark store ecosystems, particularly culture, communication, and operational engagement, and their operation across different districts, workforce roles, and demographic groups. District-wise, role-wise, and demographic-specific analyses generate actionable evidence supporting targeted interventions and policy development. The study contributes incrementally to existing theory by applying prior GHRM–HCS frameworks to a novel operational environment while providing practical guidance for enhancing sustainability and workforce outcomes in urban dark store ecosystems. It provides new theoretical insight by demonstrating how GHRM dimensions operate in this context, revealing district-wise, role-wise, and demographic-specific variations that refine existing GSC and GIC frameworks. These patterns clarify how GSC and GIC influence environmental performance and human capital sustainability in practice.

Recommendations

Practical strategies can enhance GHRM adoption and sustainable human capital development. Structured reward and recognition systems linked to sustainability performance should be implemented. Green skill development and training programs should be conducted across all employee categories, especially in smaller districts. Internal communication should be enhanced to improve awareness and participation in sustainability initiatives. Sustainability principles should be systematically embedded into recruitment, onboarding, and organizational culture. Leadership involvement should be encouraged to promote green practices and reinforce HCS. Implementing these recommendations strengthens workforce engagement and supports sustainable organizational growth across urban dark store ecosystems.

Future scope

Further research can expand understanding of GHRM impacts over time and across regions. Longitudinal studies should be conducted to examine the long-term effects of GHRM adoption on HCS. Regional and cross-country comparisons of GHRM practices in urban dark stores should be explored. Operational performance and environmental outcomes related to GHRM implementation should be assessed. Technology-enabled solutions should be investigated to enhance GHRM adoption and employee engagement in sustainability initiatives. Such research can provide deeper insights for policy-making and the scaling of sustainable workforce practices across urban dark store ecosystems.

CONCLUSION

This study confirms that systematic adoption of GHRM practices plays a critical role in strengthening HCS within urban dark store operations, aligning employee behaviour with environmental goals while supporting organizational performance and long-term operational resilience. Overall, significant district- and role-wise differences (ANOVA) and multiple regression results ($R^2 = 0.62$; GSC $\beta = 0.225$; GIC $\beta = 0.205$) provide clear empirical evidence that GHRM practices, particularly sustainable culture and internal communication, are the strongest determinants of human capital sustainability. Sustainability-oriented HR strategies function not merely as supportive mechanisms but as central drivers of workforce engagement and responsible practice. The integration of green principles into recruitment, training, performance evaluation, communication, and organizational culture cultivates an environmentally responsible workforce capable of sustaining operational efficiency together with ecological accountability. Empirical evidence drawn from a cross-sectional survey across eight districts of Telangana reveals measurable differences in GHRM implementation. Larger districts such as Hyderabad exhibited consistently higher adoption due to structured governance, leadership commitment, and resource availability, while mid-sized and smaller districts recorded comparatively lower levels. Executives reported higher adoption than operational staff, though operational employees also showed strong engagement in internal communication (4.02) and sustainable culture (4.06), especially among employees aged 25–35 years, female employees, and full-time staff. Although earlier interpretations suggested moderate adoption of recruitment and training, the reported mean scores in Hyderabad (green recruitment and onboarding: 3.96; green training: 3.94 on a 5-point Likert scale, 1 = strongly disagree, 5 = strongly agree) indicate high adoption of these practices, particularly among executives and operational employees aged 25–35 years, female employees, and full-time staff, consistent with overall strong engagement across dark store ecosystems. Among the five examined dimensions, Green Sustainable Culture ($\beta = 0.225$) and Green Internal Communication ($\beta = 0.205$) emerge as the strongest predictors of human capital sustainability, jointly explaining substantial variance ($R^2 = 0.62$), indicating that shared values, awareness, and transparent information exchange form the foundation of pro-environmental behaviour. Green Performance Management and Rewards display comparatively weaker predictive influence, indicating the absence of structured incentives and measurable accountability mechanisms that limit the consistent translation of sustainability intentions into action, highlighting the need to strengthen performance-linked rewards and recognition systems to enhance motivation and engagement. The contextual and empirical contribution of the study lies in its focus on urban dark stores, a rapidly growing and operationally intensive retail sector with limited scholarly attention, contributing insights into people-centric sustainability practices that enhance workforce motivation, engagement, and environmental responsibility within fast-paced settings. This context demonstrates that in time-pressured, operationally intensive environments, culture and communication-based GHRM practices (GSC and GIC) exert stronger effects than formal reward systems, thereby refining GHRM theory by highlighting the context-dependent effectiveness of specific HR mechanisms in shaping human capital sustainability. Theoretical implications contribute to GHRM literature by validating human capital sustainability as a measurable outcome, while managerial and policy implications emphasize the need for structured frameworks, leadership commitment, adequate resources, and continuous integration of sustainability into everyday processes. Practical recommendations include the formalization of green reward mechanisms, expansion of targeted green training programs, embedding sustainability

criteria within recruitment and onboarding, strengthening leadership-driven communication, and institutionalization of culture-building initiatives across all employee levels. Certain limitations remain, including a cross-sectional design that restricts causal interpretation, convenience sampling that limits generalizability, and reliance on self-reported perceptions without direct linkage to operational or environmental performance indicators. Future investigations may employ longitudinal assessments, regional or cross-sector comparisons, incorporation of objective metrics related to energy use, waste reduction, delivery efficiency, and emissions, along with exploration of digital HR technologies that facilitate broader adoption. Comprehensive and coordinated implementation of GHRM across culture, communication, training, recruitment, and reward systems remains essential to sustain a motivated, environmentally conscious, high-performing workforce while ensuring responsible organizational behaviour within urban dark stores.

AUTHOR CONTRIBUTIONS

B. Hitesh conceptualized the research problem and objectives, developed the theoretical framework, designed the study methodology, conducted the literature review, coordinated data collection, performed statistical analyses, and prepared the original draft of the manuscript. B. Pretty provided overall academic supervision and guidance, refined the research design and analytical approach, and critically reviewed and edited the manuscript for intellectual clarity, rigour, and coherence. D. Sivakumar contributed to methodological validation, data interpretation, and technical review of the results, and assisted in revising and improving the manuscript. All authors actively contributed to the study, reviewed the final version of the manuscript, and approved it for submission.

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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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The author(s) declared that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	*Percent*
ANOVA	Analysis of variance
GHRM	Green human resource management
GIC	Green internal communication
GPMR	Green performance management and rewards
GRO	Green recruitment and onboarding
GSC	Green sustainable culture
GT	Green training
HCS	Human capital sustainability
HR	Human resource
HRBP	Human resource business partner
HRM	Human resource management
I-CVI	Item-level content validity index
S-CVI	Scale-level content validity index
VIF	Variance inflation factor

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Podcasts

ORIGINAL RESEARCH PAPER

Hydrogen generation from coconut shell bio-oil via steam reforming incorporating energy–exergy analysis

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ABSTRACT

BACKGROUND AND OBJECTIVES: Tropical biomass residues like coconut shells are abundant and relevant for the transition toward low-carbon hydrogen. However, coconut shell bio-oil is rich in oxygenated aromatics that complicate reforming and accelerate catalyst deactivation. While many studies focus on catalyst performance, system-level evaluations that simultaneously measure process performance together with energy–exergy behavior, preliminary environmental indicators, and techno-economic implications for coconut shell bio-oil remain limited. The aims of this study were to tackle this deficiency by extensively analyzing hydrogen production from coconut shell bio-oil via an integrated steam reforming process.

METHODS: The Peng–Robinson method was used to conduct the process simulation in Aspen Plus V11. The bio-oil feed was represented by five compounds based on fast pyrolysis data: phenol (45.42 mole percent), guaiacol (34.34 mole percent), catechol (10.09 mole percent), vanillin (6.38 mole percent), and furfural (3.77 mole percent). Steam reforming was integrated with water–gas shift and pressure swing adsorption. Operating conditions were evaluated within the range of 600 to 1000 degree Celsius and 5 to 9 bar. Energy–exergy analysis, a gate-to-gate environmental assessment, and a techno-economic evaluation were performed.

FINDINGS: Hydrogen production increased sharply from 600 to 700 degree Celsius and then plateaued at 0.2332 to 0.2338 kilograms per hour above 800 degree Celsius, while pressure provided only modest gains. Heat integration indicates that the heat released from the water–gas shift (2.564 kilowatts) almost compensates for the duty of the reformer/pre-heater duty (2.620 kilo Watt), increasing exergy efficiency from 46.7 percent to 54.3 percent. The environmental assessment reports a net carbon intensity of 8.5 kilograms carbon dioxide equivalent per kilogram hydrogen with a corresponding water usage of 18.5 liters per kilogram hydrogen. The techno-economic assessment indicates strong scale sensitivity, with capital cost of 2,743,530 United States Dollar and annual operating cost of 1,292,780 United States Dollar under the stated basis.

CONCLUSION: The screening supports a practical operating window around 700 to 800 degree Celsius. Enhanced benefits are more effectively achieved through advancements in heat recovery, steam management, purification recovery, residue valorization, and scale-up analysis instead of escalating temperature escalation beyond the plateau region.

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INTRODUCTION

The escalating global climate crisis and the volatility of fossil fuel markets have accelerated the transition toward a green hydrogen economy (Jaradat *et al*., 2024). Hydrogen is regarded as a potential energy carrier that can aid in the decarbonization of challenging sectors, yet the predominant production methods continue to be fossil-based, particularly steam methane reforming. Consequently, biomass-to-hydrogen pathways have attracted increasing interest, with steam reforming and gasification recognized as leading thermochemical options (Wang *et al*., 2025; Mustapha *et al*., 2025). However, catalytic steam reforming of bio-oil remains technically challenging due to the high oxygen content of the feed and rapid catalyst deactivation through coking and sintering (Farrapeira *et al.,* 2024). This situation necessitates the development of resilient catalyst systems and staged configurations to sustain hydrogen yield (Setiabudi *et al*., 2020; Di Stasi *et al*., 2021; Shao *et al*., 2025). Coconut shells (Cocos nucifera) are a significant agricultural waste product in tropical regions, yet they are often not fully utilized (Gani *et al*., 2024). Fast pyrolysis can convert this residue into bio-oil, an energy-dense liquid with advantageous logistics compared to solid biomass (Mustapha *et al*., 2025), and coconut-shell bio-oil is reported to be rich in phenolic oxygenates (Novita *et al*., 2023; Anggraini et *al*., 2024; Vilas-Boas *et al*., 2025). Reforming coconut-shell bio-oil, while promising, is a complex process due to the presence of heavy aromatic oxygenates like phenol and guaiacol, which can encourage coke formation and thermal polymerization, which in turn hastening catalyst deactivation (Fernandez *et al*., 2022; Kontchouo *et al*., 2022). While process-intensification concepts such as electrified or sorption-enhanced configurations are being explored (Bolívar Caballero *et al*., 2025; Comendador *et al*., 2025), conventional steam reforming remains the most mature baseline for process design, benchmarking, and comparative assessment (Landa *et al.,* 2023). Significantly, the composition of coconut-shell bio-oil can fluctuate based on seasonal changes, geographic location, and pyrolysis conditions, which in turn influences the relative quantities of oxygenated aromatics, light oxygenates, and water. To enable transparent steady-state screening in Aspen Plus, this work adopts a five-compound surrogate that captures the dominant lignin-derived oxygenated aromatics governing reforming severity, while explicitly acknowledging that minor acids, aldehydes, and oligomeric fragments are not represented (Vanegas *et al.,* 2025). As these deviations may influence absolute hydrogen yield, stability, and energy demand, they are considered a source of uncertainty that should be limited through sensitivity analysis instead of being presumed to be insignificant. A specific gap in the literature is the limited availability of unified, process-level studies for coconut-shell bio-oil reforming that simultaneously connect unit-level utility duties and heat-integration opportunities with exergy-loss distribution, preliminary gate-to-gate environmental indicators, and pilot-scale techno-economic implications under a consistent mass-and-energy basis. Consequently, this study thoroughly assesses hydrogen generation from coconut shell bio-oil through a combined steam reforming–water gas shift–pressure swing adsorption method, detailing process efficiency alongside energy–exergy characteristics, gate-to-gate environmental metrics, and pilot-scale techno-economic implications across a screened temperature and pressure range. This study has been conducted in Medan, Indonesia, in 2025.

MATERIALS AND METHODS

Feedstock Characterization

Precise compositional validation is essential for thermodynamic modeling. Drawing from experimental fast pyrolysis data reported in Fardhyanti *et al*. (2018) and reinforced by recent

Table 1: Coconut shell bio-oil composition with comprehensive thermodynamic properties (Fardhyanti *et al*., 2018)

Component	Formula	Chemical abstracts service (CAS)	Mole weight in kilogram per kilomole (kg/kmol)	Percent (%)	ΔHf (kJ/kmol)	Specific exergy (kJ/kg)
Furfural	$C_5H_4O_2$	98-01-1	96.086	3.77	-151,000	27,100
Phenol	C_6H_6O	108-95-2	94.113	45.42	-96,399	26,360
Vanillin	$C_8H_8O_3$	119-36-8	152.150	6.38	-464,300	33,030
Guaiacol	$C_7H_8O_2$	150-76-5	124.139	34.34	-249,000	31,410
Catechol	$C_6H_6O_2$	123-31-9	110.112	10.09	-269,400	24,740

studies (Anggraini *et al*., 2024), the representation of coconut-shell bio-oil utilizes five model compounds as summarized in Table 1. Phenol and guaiacol dominate the surrogate composition, consistent with the lignin-rich nature of coconut shells (Cocos nucifera), and are used as practical indicators to capture the thermodynamic behavior of lignin-derived aromatic oxygenates during steam reforming. Coconut-shell bio-oil is inherently multi-component and can vary with feedstock origin and pyrolysis conditions; therefore, the five-compound surrogate is adopted to retain model transparency and robust property handling in Aspen Plus for steady-state process screening while reflecting the dominant oxygenated aromatics that govern reforming severity and coking tendency. Minor acids, aldehydes/ketones, and oligomeric fragments are not specifically represented, indicating that the actual syngas composition and deactivation propensity in practical operations may differ from the model; therefore, the findings are primarily viewed as comparative steady-state trends across operating conditions rather than a fully detailed kinetic description. A structured multi-parameter sensitivity on surrogate composition is recommended to quantify the robustness margin of the reported operating window.

Reaction kinetics and validation parameters

To ensure the accuracy of the simulation, steam reforming reactions were conducted utilizing Arrhenius kinetics obtained from literature that concentrates on comparable aromatic oxygenates; the relevant kinetic parameters (pre-exponential factor and activation energy) are reported in Table 2. Due to the scarcity of specific Arrhenius parameters for complex oxygenated intermediates like vanillin, catechol, and furfural in the open literature, a lumped-kinetic approach was adopted. The kinetic parameters of the nearest structural analogs, as presented in Table 2, were utilized to model these minor components. Specifically, catechol and vanillin were mapped to the phenol reforming kinetics due to their shared phenolic ring stability, while furfural was modeled assuming similar reactivity to guaiacol. This conservative assumption posits that the cleavage of the aromatic ring—represented by the dominant species phenol and guaiacol—constitutes the rate-determining step in the reforming of coconut shell bio-oil surrogates. This technique confirms that the energy barriers involved in converting refractory aromatics are not minimized.

Process description

The Aspen Plus model starts from a pre-pyrolyzed coconut-shell bio-oil feed, represented by a defined five-compound surrogate mixture. The swift pyrolysis of solid coconut shells is not represented in simulations and is regarded as an upstream step that lies outside the modeled boundary. In this work, COMB-BIO denotes the

Table 2: Validated kinetic parameters for steam reforming reactions

Reaction	Rate expression	Pre-exponential factor (A) (mol/kg/s/bar)	Activation Energy (Ea) (kJ/mol)	Sources
Phenol reforming	$r_1 = k_1 [C_6H_6O][H_2O]^{0.5}$	2.4×10^6	125.3	Baamran and Tahir, 2021
Guaiacol reforming	$r_2 = k_2 [C_7H_8O_2][H_2O]^{0.6}$	1.8×10^6	108.3	Kontchouo *et al.*, 2022
WGS reaction	$r_3 = f(T)$ (Equilibrium)	–	–	Ebrahimi *et al.*, 2020*

Note: WGS kinetics were modeled to approach equilibrium as detailed in reviews by (Ebrahimi *et al.*, 2020)

pre-reforming/steam-reforming reactor (Aspen unit ID) where overall decomposition and steam-reforming reactions are represented under reforming conditions; therefore, COMB-BIO should not be interpreted as a combustor or a solid-biomass pyrolysis unit. The simulation of the process was created utilizing Aspen Plus V11, employing the Peng–Robinson property method to accurately depict the thermodynamic phase behavior of mixtures derived from bio-oil (Ding *et al.*, 2023; Feng *et al.*, 2023). Fig. 1 provides a schematic overview of the integrated reforming–WGS–PSA hydrogen production system and is organized into three operational zones: input conditioning (Green Box), thermochemical conversion (Red Box), and purification (Blue Box). The process begins in the pre-treatment stage where water is heated in WTR-STRG (Heater) from 25 °C to 400 °C at 1.216 bar (heater duty 4.542 kW) and the bio-oil surrogate is heated in BIO-STRG (Heater) from 25 °C to 400 °C at 1.013 bar (heater duty 0.032 kW). Both streams are combined in the MIXER at 400 °C to form a homogeneous vapor-phase feed at a controlled steam-to-carbon ratio of S/C = 2.5 (adiabatic mixing), which helps reduce coking risk for aromatic oxygenates (Baamran and Tahir, 2021). The mixture is then fed to COMB-BIO (RGibbs) operated at 9 bar and heated from 400 °C to 800 °C (heater duty 2.620 kW) to represent pre-reforming under steam-reforming conditions. The outlet stream proceeds to the main reformer SMR (RPlug) operated at 9 bar and 800–1000 °C (reactor geometry L = 2.5 m, D = 0.15 m), followed by the WGS (RPlug) at 150 °C and 9 bar (L = 1.2 m, D = 0.10 m). Downstream gas–liquid separation is represented using FLASH1 (Flash2) at 150 °C and 9 bar, and hydrogen purification is represented by ABSOR-R1 (Sep) at 150 °C and 9 bar with a fixed hydrogen recovery assumption of 95%. Table 3 provides a summary of the unit blocks, model types, and operating conditions employed in the Aspen Plus simulation. The integrated reforming–WGS–PSA flowsheet is modeled at steady state to enable consistent screening of operating variables; catalyst regeneration and transient operation (start-up/shutdown/load changes) are not simulated and are treated as practical limitations for future dynamic and deactivation-informed studies. Temperature is considered the principal screening variable, whereas pressure is treated as secondary within the specified range, with S/C held constant at 2.5 for comparison purposes. All Aspen Plus simulations were executed using uniform property-method settings and consistent numerical convergence controls across all cases, with convergence verified through stable mass and energy balance closure over the complete flowsheet and reproducible results for repeated runs at identical operating conditions to ensure that reported trends are not numerical artifacts. Methods of reforming, including autothermal and oxidative reforming, could potentially reduce the need for external heat by providing a portion of the reaction heat through regulated oxidation. However, these schemes introduce oxygen handling and trade-offs in hydrogen yield, product-gas dilution, and emissions. Consequently, this study emphasizes standard steam reforming as the foundational setup, whereas the comparative assessment of autothermal and oxidative methods is designated for subsequent studies.

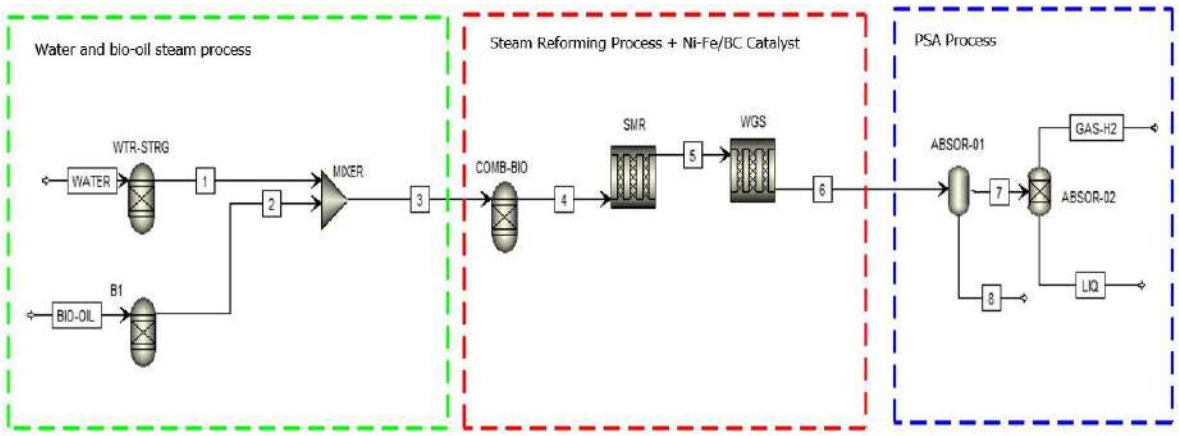

Fig. 1: Aspen Plus flowsheet of the integrated hydrogen production system from coconut-shell bio-oil surrogate

Table 3: Process equipment configuration and operating conditions

Equipment ID	Type	Function	Operating conditions	Key parameters
WTR-STRG	Heater	Steam generation	25°C - 400°C, 1.216 bar	Q = 4.542 kW
BIO-STRG	Heater	Bio-oil vaporization	25°C - 400°C, 1.013 bar	Q = 0.032 kW
MIXER	Mixer	Feed preparation	400°C, S/C = 2.5	Adiabatic mixing
COMB-BIO	RGibbs	Pre-reforming	400°C - 800°C, 9 bar	Q = 2.620 kW
SMR	RPlug	Steam reforming	800-1000°C, 9 bar	L = 2.5 m, D = 0.15 m
WGS	RPlug	Water-gas shift	150°C, 9 bar	L = 1.2 m, D = 0.10 m
FLASH1	Flash2	Gas-liquid separation	150°C, 9 bar	Two-phase separation
ABSOR-R1	Sep	H_2 purification	150°C, 9 bar	Recovery = 95%

Techno-economic assessment (TEA) parameters

The economic feasibility of the proposed coconut-shell bio-oil-to-hydrogen process was evaluated using a levelized cost framework. Capital and operating costs were generated from the Aspen Plus flowsheet via Aspen Process Economic Analyzer (APEA) based on the mapped equipment and operating conditions, and reported as a pilot-scale screening TEA intended to compare scenarios on a consistent basis (Ochieng and Sarker, 2025). Previous TEA studies emphasize that hydrogen cost is sensitive to capital intensity, utilities demand, and scale/logistics effects, highlighting the importance of transparent CAPEX/OPEX assumptions in levelized cost reporting (Cook and Hagen, 2023; Xu *et al.*, 2019). The hydrogen production expense was indicated as the levelized cost of hydrogen (LCOH, USD/kg H_2) and was computed according to Eq. 1 (Ochieng and Sarker, 2025):

$$LCOH = \frac{(\text{TCI.CRF}) + \text{OPEX}}{P_{annual}} \quad (1)$$

where TCI is the total capital investment (USD), OPEX is the annual operating cost (USD/year), and P_{annual} is the annual hydrogen production (kg H_2/y), yielding USD/kg H_2. The capital recovery factor (CRF) used to annualize the capital investment over the project lifetime *n* with discount rate *i* was calculated using Eq. 2 (Ochieng and Sarker, 2025):

$$CRF = \frac{i(1+\text{i})^n}{(1+\text{i})^n - 1} \quad (2)$$

In this study, the TEA is reported on the modeled pilot-scale basis (bio-oil surrogate feed 1.0 kg/h and steam feed 5.0 kg/h at S/C = 2.5), producing approximately 0.1849 kg H_2/h; assuming continuous operation of 8,760 h/year, this

corresponds to P_{annual} = 1,620 kg H_2/year (4.44 kg/day). Based on the APEA output, TCI = USD 2,743,530 and OPEX = USD 1,292,780/year, including utilities of USD 36,558/year (electricity). For the baseline scenario, the bio-oil feedstock cost is set to USD 0/year to represent a residue-valorization case; inclusion of bio-oil procurement/production costs would increase LCOH. Consequently, the reported LCOH values ought to be understood as indicators of feasibility at the pilot scale, based on the stated criteria. It is advisable to conduct scale-up and sensitivity analyses to assess the effects of capacity, operating hours, feedstock price/logistics, utilities, and potential carbon pricing on hydrogen cost.

Life cycle assessment methodology

A gate-to-gate life cycle assessment (LCA) was performed to quantify the Global Warming Potential (GWP) associated with hydrogen production in the integrated reforming–WGS–PSA system. The system boundary includes the unit operations associated with the bio-oil surrogate and water/steam feeds entering the process, extending to the purified hydrogen product at the PSA outlet. The upstream processes—including the collection of coconut shells, logistics for transport, and the generation of bio-oil through fast pyrolysis (which encompasses decisions regarding coproduct allocation)—are excluded from the current boundary and are recognized as priority areas for future expansion from cradle to gate. The functional unit is defined as 1 kg of purified H_2 produced at the PSA outlet. The net carbon intensity of hydrogen (CI_{net}, kg CO_2-eq/kg H_2) was determined using Eq. 3 (Osman *et al.*, 2024):

$$CI_{net} = \Sigma(m_i . EF_i) + \left(E_{Elec} . EF_{grid}\right) - C_{credit} \quad (3)$$

where m_i is the mass flow of material inputs within the gate-to-gate boundary (kg), EF_i is the emission factor for each material (kg CO_2-eq/kg), E_{Elec} is the electricity consumption (kWh), EF_{grid} is the grid emission factor (kg CO_2-eq/kWh), and C_{credit} represents the biogenic carbon credit. Life-cycle inventory data for energy use were taken directly from the Aspen Plus simulation outputs and normalized to the functional unit using the modeled hydrogen production basis. Impact assessment was performed using the ReCiPe midpoint method, and the emission factor for the Indonesian electricity grid was sourced from the ecoinvent database (Osman *et al.*, 2024). As this study constitutes a feasibility-level, pilot-scale screening study, uncertainties associated with grid emission factors, the efficiency of heat integration, and the exclusion of upstream bio-oil production and logistics remain inadequately quantified. Consequently, the GWP results presented should be viewed as preliminary estimates within the defined gate-to-gate boundary. Future studies will broaden the evaluation to cradle-to-gate by incorporating upstream inventory for bio-oil production, regional transportation scenarios adjacent to coconut-processing locations, and conducting sensitivity and uncertainty analyses to measure the reliability of the reported carbon-intensity results.

Sensitivity and uncertainty considerations

Sensitivity was assessed by screening reformer temperature and operating pressure while keeping the bio-oil surrogate composition and S/C ratio constant for comparability. Uncertainties in bio-oil variability, heat integration, PSA recovery, and economic inputs are acknowledged qualitatively as limitations of this pilot-scale steady-state study. Future studies will assess robustness by employing bounded multi-parameter sensitivity and probabilistic sampling to determine confidence limits for yield, efficiency, emissions, and LCOH.

RESULTS AND DISCUSSION

Model validation

The temperature-driven trends observed in the simulation are in agreement with thermodynamic expectations for steam reforming of oxygenated aromatic surrogates, suggesting that elevated reforming temperatures facilitate conversion and hydrogen generation prior to reaching a practical plateau. To rigorously verify the model's accuracy, the simulation results were benchmarked against experimental data reported by (Baamran and Tahir, 2021) for the steam reforming of phenolic model compounds under comparable conditions (T=700◦C). The validation compared the predicted conversion efficiency against the literature values. The model predicts a carbon conversion of 86.5% at 700°C, which demonstrates excellent agreement with the experimental phenol conversion of 89.1% reported for Ni-based catalysts under similar operating regimes. This corresponds to a mean absolute percentage error (MAPE) of approximately 2.9%. The minor deviation can be ascribed to the presumption of steady-state operation without explicit coke-mediated catalyst deactivation kinetics. Nevertheless, the low magnitude confirms that the adopted thermodynamic framework in Aspen Plus accurately reflects the reforming severity of coconut shell bio-oil surrogates.

Reactor behavior and hydrogen profile

The behavior of the Steam Methane Reforming (SMR) reactor was examined using axial profiles along the plug flow reactor (RPlug) to verify stability and continuous conversion. Fig. 2 illustrates the hydrogen (H_2) mass fraction profile. While the numerical increase in mass fraction appears modest (from 0.033100 to 0.033195), this specific range is characteristic of a high-steam system (S/C = 2.5), where the overall mass balance is dominated by heavy water vapor relative to the low-molecular-weight hydrogen . Crucially, the steady rise throughout the reactor's length substantiates that the catalytic bed is successfully converting the bio-oil surrogate into hydrogen without kinetic stagnation zones, validating the reactor design. Correspondingly, Fig. 3 presents the temperature profile, showing a slight decrease from 800°C at the inlet to 798.6°C at the outlet. In a standard adiabatic reformer, a sharp temperature drop would occur due to the strong endothermicity of the reforming reactions. However, the observed mild drop (<1.5°C) indicates that the external heat supplied to the reactor effectively compensates for the reaction enthalpy. This operating regime is considered optimal since it ensures that high reaction temperatures (>798°C) throughout the bed, thereby sustaining favorable kinetics and minimizing low-temperature zones that could induce coking. For a holistic view, Fig. 4 superimposes these axial profiles to demonstrate the coupling between thermal energy consumption and product formation. The inverse correlation—where there is a slight decrease in temperature as the hydrogen mass fraction increases—demonstrates the effective use of provided heat to facilitate the endothermic reforming process. The stability of these profiles confirms that the reactor operates under near-isothermal conditions, maximizing conversion efficiency along the entire catalytic length.

Process performance and optimization

The simulation results presented in Table 4 show that the hydrogen (H_2) production rate (kg/h) increases with reforming temperature but exhibits diminishing returns beyond 800°C. Across the examined pressures (5–9 bar), H_2 production rises from 0.208–0.213 kg/h at 600°C to 0.228–0.229 kg/h at 700°C, then approaches a plateau of 0.233–0.234 kg/h at 800–1000°C. The effect of pressure is secondary to temperature: at 600°C, higher pressure slightly increases H_2 production,

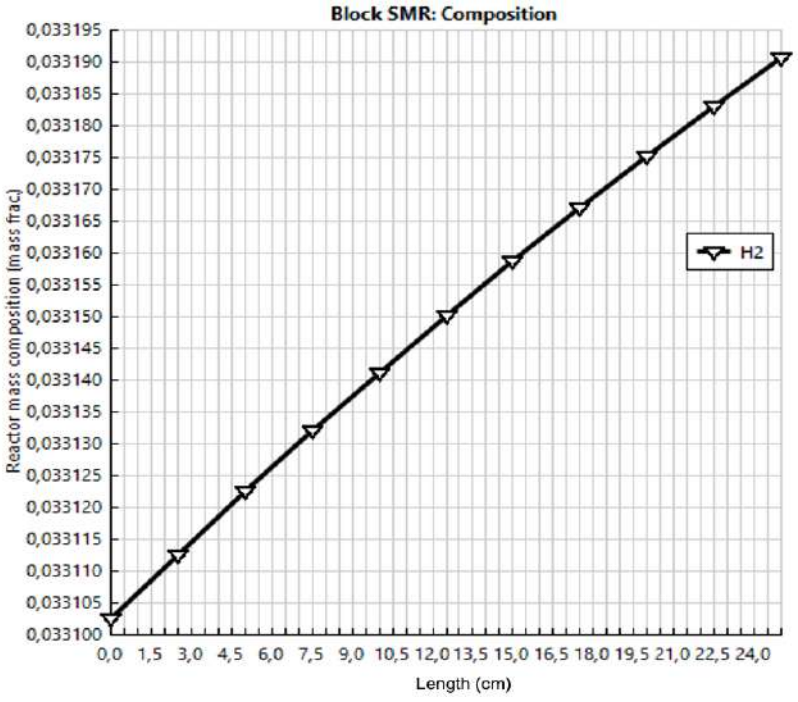

Fig. 2: The simulation result of the SMR

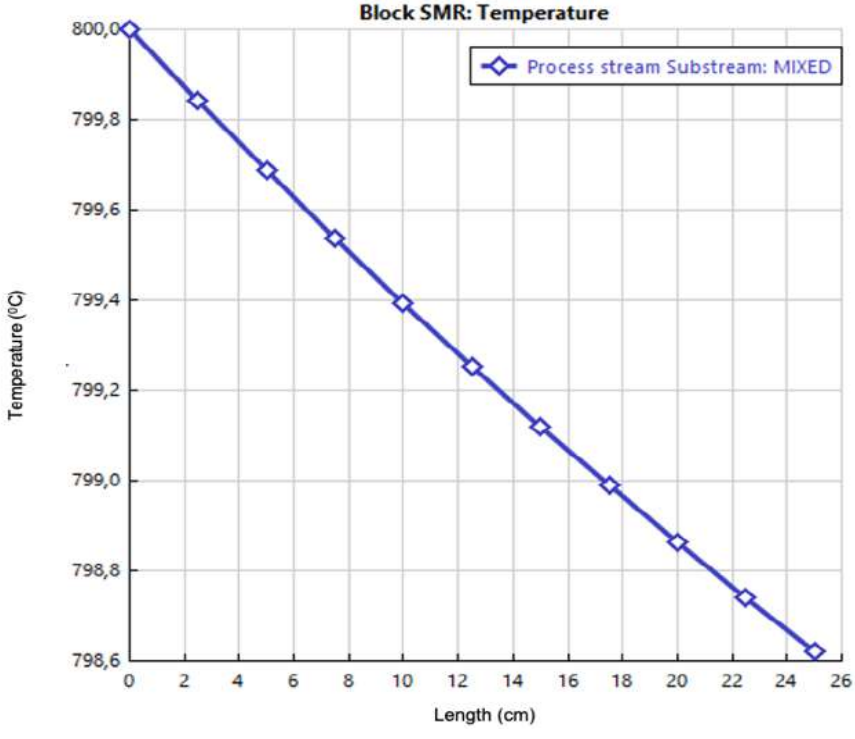

Fig. 3: The temperature profile along the SMR reactor

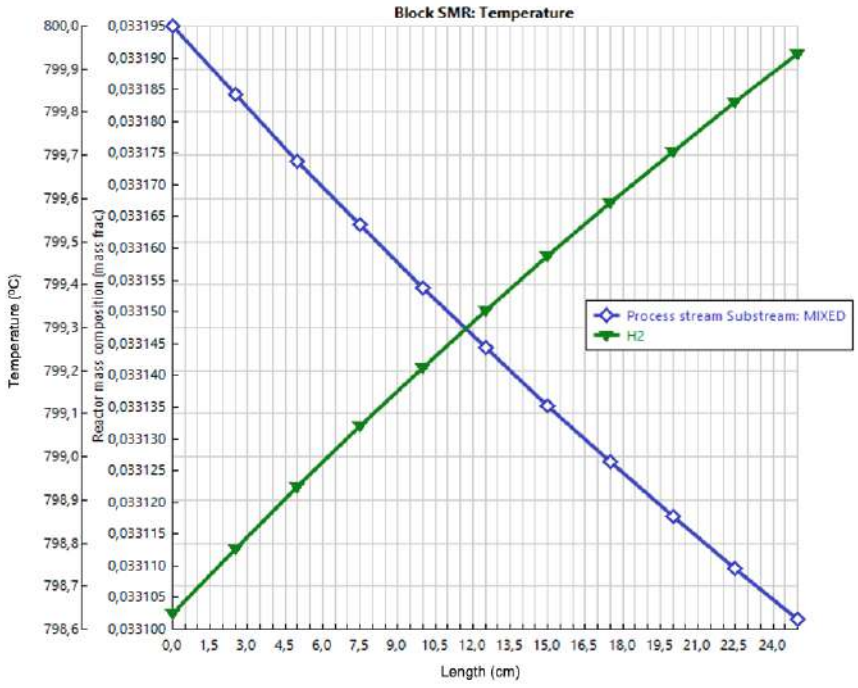

Fig. 4: Axial profiles of reactor temperature and hydrogen (H_2) along the length of the SMR reactor

Table 4: Effect of temperature and pressure on H_2 production rate from coconut shell bio-oil

Temperature	Hydrogen production (kg/h)				
	Pressure (bar)				
	5	6	7	8	9
600	0.207829	0.208247	0.209511	0.211255	0.213236
700	0.229479	0.229115	0.228773	0.228546	0.228446
800	0.232701	0.233036	0.233155	0.23318	0.233168
900	0.232863	0.233368	0.233587	0.233697	0.23374
1000	0.232774	0.233343	0.233619	0.233747	0.233806

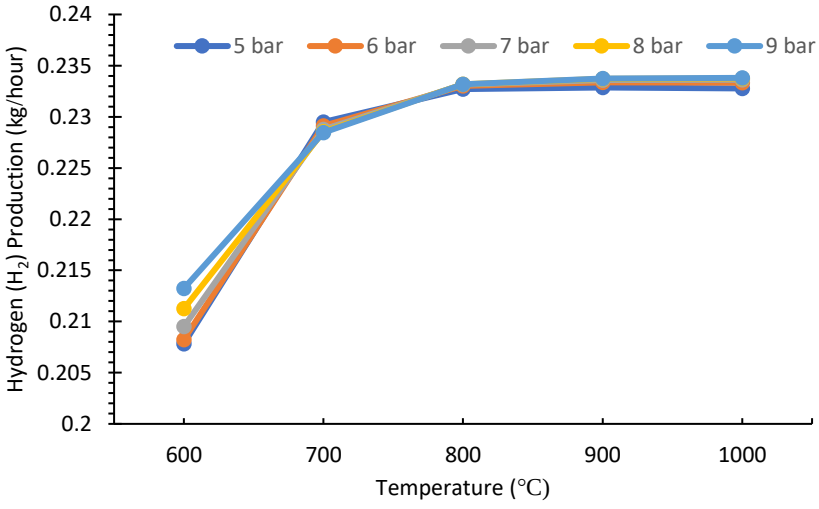

Fig. 5: The relationship between reaction temperature and the hydrogen (H_2) production

whereas at temperatures ≥800°C the results converge, indicating only marginal additional gains from pressure under high-temperature operation. Fig. 5 visualizes the temperature–pressure trends and highlights the practical operating window implied by the plateau behavior. The suggested operating range of 700–800°C is corroborated by the evident trade-off between conversion improvements and the declining incremental H_2 production that takes place beyond 800°C. While uncertainties in surrogate composition, heat-integration effectiveness, and purification recovery can shift absolute values of yield and efficiency, the plateau behavior is expected to persist under realistic perturbations because reforming extent in this domain is primarily governed by temperature-driven equilibrium and steam availability. Consequently, in addition to temperature, the primary factors anticipated to enhance net performance are expected to be steam availability (S/C), effective heat recovery, and hydrogen recovery in purification; these parameters are prioritized for expanded multi-parameter sensitivity analysis in forthcoming studies. While Table 4 and Fig. 5 establish the temperature–pressure trend and the hydrogen production plateau, selecting a practical operating window also benefits from considering additional performance indicators. Consequently, Table 5 consolidates representative cases by merging hydrogen production rate with thermal efficiency and carbon conversion, thereby enabling a multi-metric evaluation of process performance across the operating domain.

Table 5 enhances the production trends by detailing representative operating points in conjunction with the hydrogen production rate, thermal efficiency, and carbon conversion. Increasing temperature from 600°C to 1000°C improves thermal efficiency from 45.2% to 63.4% and raises carbon conversion from 78.3% to 94.8%, indicating progressively more complete conversion at higher severity. In contrast, the hydrogen production rate approaches a plateau, it increases from 0.2078 kg/h at 600°C to 0.2291 kg/h at 700°C, but only changes marginally to 0.2332–0.2338 kg/h across 800–1000°C. This collective evidence indicates a feasible operational range of 700–800°C, where a notable increase in hydrogen production occurs in comparison to 600°C. Additionally, increasing the temperature further leads to only marginal extra hydrogen production, despite ongoing advancements in conversion and efficiency.

Individual Component Implications

Understanding component-level behavior helps interpret catalyst requirements for reforming oxygenated bio-oil surrogates. Literature reveals that furans and phenolic oxygenates (including furfural, guaiacol, and phenol) can display varying levels of apparent reformability and hydrogen selectivity influenced by temperature and steam availability. It has been noted that guaiacol reforming has been reported to deliver high hydrogen selectivity under steam reforming conditions (Kontchouo *et al.*, 2022). Phenolic structures typically exhibit greater thermal resilience and may necessitate increased severity for complete conversion, aligning with kinetic analyses presented in earlier reforming studies (Baamran and Tahir, 2021). Because this work does not include explicit coke-kinetics or catalyst deactivation modeling, coking is discussed qualitatively: lower temperature, higher pressure, and insufficient steam-to-carbon ratio (S/C) can increase deposition risk for aromatic oxygenates, whereas higher temperature and higher S/C tend to suppress carbon formation by promoting gasification of carbon precursors. Consequently, it is advisable to conduct carbon-formation

Table 5: Summary of hydrogen production optimization results

Temperature (°C)	Pressure (bar)	Hydrogen production rate (kg/h)	Thermal Efficiency (%)	Carbon Conversion (%)
600	5	0.2078	45.2	78.3
700	6	0.2291	58.7	86.5
800	7	0.2332	62.1	92.8
900	8	0.2337	63.2	94.2
1000	9	0.2338	63.4	94.8

preheater match, additional recovery may be boundary analysis and utilize deactivation-informed modeling as future endeavors to establish operability limits throughout the operating window.

Energy and heat integration analysis

The process energy balance reveals a significant opportunity for heat integration, supported by principles reviewed by (Yuan and Mao, 2024). The Water–Gas Shift (WGS) reactor functions as a heat source, emitting 2.564 kW, while the reforming pre-heating/reformer section (COMB-BIO) serves as a significant heat sink, requiring 2.620 kW. The detailed energy duty profile of the major process units and the corresponding heat-integration potential are summarized in Table 6 (Energy duty profile and heat integration). Consequently, the recovery of WGS heat for pre-heating upstream can diminish the need for external heating and enhance overall energy efficiency; under the reported duties, WGS heat can cover a significant portion of the COMB-BIO heating requirement, leaving steam generation/preheating (WTR-STRG, 4.542 kW) remaining the primary user of external energy (Santos *et al*., 2024). Beyond this WGS-to available from hot reformer effluents, PSA tail gas utilization, and flue-gas heat via an expanded heat-exchanger network. Due to the fact that heat integration is depicted in a simplified format at the pilot scale and is contingent upon the effectiveness of exchangers and thermal losses, the integration benefits reported in Table 6 should be viewed as a feasibility-level estimate; nevertheless, the comparative temperature–pressure trends remain valid for process screening. Inefficient heat recovery would result in elevated external utility expenses, which in turn would escalate energy consumption, emissions, and hydrogen prices. Nevertheless, the practical operating range continues to be qualitatively sound, since the observed H_2 plateau is is chiefly determined by high-temperature reforming thermodynamics.

Exergy analysis and thermodynamic efficiency

Exergy analysis establishes a comprehensive framework to detect irreversibilities and measure the effectiveness of energy utilization (Szargut, 2007). Using the reference environment defined in the Methods section (T_o and P_o) and computing the feed chemical exergy from the five-compound surrogate mixture, the overall exergy efficiency in the base case (without heat integration) is 46.7%. After applying the heat-integration scheme, exergy efficiency increases to 54.3%, reflecting reduced external utility demand and improved internal heat recovery. Stream-wise results show that the liquid residue stream carries a higher exergy rate (0.350 kW) than the purified hydrogen stream (0.194 kW), indicating that a non-negligible fraction of the feed's chemical exergy remains in unconverted heavy/condensable species. Consequently, upcoming designs ought to assess residue valorization (for instance, controlled combustion for process heat or upgrading routes) rather than treating the residue solely as waste.

Life cycle assessment evaluations

A preliminary gate-to-gate LCA was performed to quantify the environmental sustainability of the proposed process (schematically depicted in

Table 6: Energy duty profile and heat integration

Section	Block	Duty (W)	Notes	Loss (kW)	Input (kW)
Input steam + bio-oil	WTR-STRG	4542	Heat input (storage heater)	0	4,542
Input steam + bio-oil	BOILSTRG	32	Heat input (boiler storage)	0	0,032
Input steam + bio-oil	MIXER		Usually Q=0; add HEAT block if needed		
Steam reforming + Ni-Fe/BC	COMB-BIO	2620	Combustion heat to reformer	0	2,62
Steam reforming + Ni-Fe/BC	SMR	0	Assumed adiabatic; set if not	0	0
Steam Reforming + Ni-Fe/BC	WGS	-2564	Heat removed (loss if unrecovered)	2,564	0
PSA	ABSOR-01	-12	Cooling duty / loss	0,012	0
PSA	ABSOR-02	-1398	Cooling duty / loss	1,398	0
PSA	MIX-PSA		Add if any		

Table 7: Gate-to-gate life cycle inventory

Type	Component	Value	Unit	Basis / Assumption
Inputs				
Feedstock	Bio-oil surrogate	5.41	kg	Mass balance calculated from 1.0 kg/h feed yielding 0.185 kg H_2/h
Utility	Waterc Consumption	18.5	L	Total process and cooling water requirement
Energy	Process energy	Derived	-	Includes reformer heating and auxiliary power (represented in emission factor)
Outputs				
Product	Hydrogen (H_2)	1.00	kg	Functional Unit (99.9% purity assumption)
Emission	Total CO_2-equivalent	12.8	kg	Gross process and energy emissions before biogenic credit
Waste	Solid residue	Negligible	kg	Assumed trace formation under steady-state operation

Table 8: Environmental impact analysis

Impact category	Value	Units	Basis
Net carbon intensity	8.5	kg CO_2-eq/kg H_2	Grid electricity mix
Process energy emissions	12.8	kg CO_2-eq/kg H_2	Before bio-credit
Bio-oil carbon credit	-4.3	kg CO_2-eq/kg H_2	Biogenic uptake
Water consumption	18.5	L/kg H_2	Including cooling

Fig. 1). In order to maintain transparency, the comprehensive life cycle inventory (LCI) that encompasses material and energy flows is presented in Table 7. Based on this inventory, the net carbon intensity is calculated at 8.5 kg CO_2-eq/kg H_2 (summarized in Table 8). This value is derived from gross process emissions of 12.8 kg CO_2-eq/kg H_2 primarily influenced by grid electricity and heating, and is adjusted by a biogenic carbon credit of −4.3 kg CO_2-eq/kg H_2 attributed to the renewable origin of the biomass. Crucially, this performance is competitive against conventional fossil-based routes. *standard steam* methane reforming (SMR) typically emits 9–11 kg CO_2-eq/kg H_2, while coal gasification can exceed 19 kg CO_2-eq/kg H_2 (Osman *et al.*, 2024). Consequently, the suggested bio-oil reforming method presents a possible carbon reduction of about 15–20% in comparison to the industry benchmark. The assessment assumes a "zero-burden" approach for the coconut shell waste, meaning no upstream agricultural emissions are allocated to the residue. However, the process entails a water consumption of 18.5 L/kg H_2 (Abawalo *et al.*, 2025), which is higher than typical SMR (~10 L/kg H_2), highlighting a trade-off between carbon reduction and water intensity. Subsequent efforts will expand this gate-to-gate boundary into a complete cradle-to-gate evaluation to measure the effects of the supply chain, particularly focusing on the transportation and production logistics of bio-oil.

Table 9: Detailed economic analysis breakdown

Cost component	Annual cost (USD/y)	Remarks
Energy (Electricity)	36,558	From Utilities + Summary: electricity rate 53.812 kW, cost 4.17043 USD/h ($0.078/kWh); annualized in Summary
Raw materials	0	From Summary: Total Raw Materials Cost = 0
Utilities (Water)	0	Not reported as a separate cost in Utilities
Maintenance and labor / other fixed opex	1,256,222	Calculated as: Total Operating Cost − Utilities − Raw materials = 1,292,780 − 36,558 − 0
Total operating cost	1,292,780	From summary

Techno-economic evaluation

A techno-economic assessment was performed to determine the cost framework of the suggested hydrogen production method based on a modeled pilot-scale approach. The updated operating-cost breakdown (Table 9) gives a total OPEX of USD 1,292,780/year. It is important to note that the high contribution of fixed operating costs (maintenance, labor, and overhead), calculated at approximately USD 1.25 million/year, results in a disproportionately high LCOH due to the pilot-scale capacity of the modeled system (4.4 kg H_2/day). In a decentralized pilot scenario, these expenses primarily reflect research and technical personnel instead of persistent industrial transitions. A preliminary scale-up projection indicates that increasing the plant capacity to a semi-industrial scale (e.g., 1,000 kg H_2/day) would dilute these fixed costs significantly, reducing the specific cost contribution of labor by over 95%. Consequently, the present economic outcomes ought to be regarded as a cautious feasibility benchmark for small-scale residue valorization, instead of an optimized commercial production expense.

CONCLUSION

This study evaluated hydrogen generation from coconut shell bio-oil using an integrated steam reforming–WGS–PSA steady-state process model, combining process performance with energy–exergy, techno-economic, and preliminary gate-to-gate environmental indicators. The parametric screening substantiates that temperature is the leading influence on the extent of reforming in the studied domain: hydrogen production increases substantially from 600°C to 700°C (from 0.2078 kg/h to 0.2291 kg/h) and then approaches a plateau across 800–1000°C (0.2332–0.2338 kg/h), indicating diminishing returns beyond 800°C. Consequently, a feasible operating temperature range of 700–800°C is established for the studied pressure range, where significant improvements are realized without depending on further increases in temperature that result in only minimal additional hydrogen. Multi-metric evaluation strengthens this operating-window selection. As temperature increases, thermal efficiency rises from 45.2% to 63.4% and carbon conversion increases from 78.3% to 94.8%, showing progressively more complete conversion at higher severity even when incremental hydrogen gains become small. Energy and heat integration analysis also reveals the points at which improvements can have the most substantial effect at pilot scale: the duty profile indicates that WGS heat release (2.564 kW) can offset most of the upstream reforming pre-heating demand in COMB-BIO (2.620 kW), while steam generation/preheating (WTR-STRG, 4.542 kW) remains the dominant external energy consumer. Consequently, enhancements in future performance are anticipated to be more impactful when focused on heat recovery, steam

management, and purification recovery rather than pursuing additional temperature increases beyond the plateau region. Consistent with this interpretation, overall exergy efficiency increases from 46.7% (non-integrated case) to 54.3% (integrated case). The results obtained from the stream analysis indicate that the liquid residue stream possesses a greater exergy rate of 0.350 kW compared to the purified hydrogen stream, which has an exergy rate of 0.194 kW. This observation implies that the valorization of the residue, such as through controlled combustion for process heat or alternative upgrading methods, may further improve thermodynamic efficiency. The techno-economic and environmental results should be interpreted as feasibility-level indicators for the modeled pilot-scale basis. The distribution of operating expenses is largely characterized by fixed and miscellaneous items, totaling USD 1,292,780 annually for operating expenses and USD 36,558 per year for electricity. This suggests a considerable sensitivity of unit cost to throughput, operating hours, and and the distribution of fixed costs, highlighting the importance of conducting a scale-up TEA with transparent cost structures. The preliminary gate-to-gate LCA reports a net carbon intensity of 8.5 kg CO_2-eq/kg H_2 under the assumed grid mix, while upstream activities (coconut shell collection, transport, and bio-oil production) remain outside the present boundary. The current screening has several key limitations, including the surrogate representation of bio-oil chemistry, simplified treatment of minor components and PSA performance, as well as the lack of modeling for catalyst deactivation and dynamic operability modeling (start-up/shutdown/transients). These constitute prioritized directions for forthcoming studies, along with a broadened multi-parameter sensitivity (including S/C optimization, heat-integration effectiveness, and PSA recovery), and scale-up plus cradle-to-gate TEA/LCA to evaluate minimum viable capacity and regional decentralized deployment scenarios.

AUTHOR CONTRIBUTIONS

R. A. Syahputra, as the lead author, was responsible for the conceptualization of the research framework, development of the simulation methodology, execution of Aspen Plus modeling, analysis and interpretation of the simulation results, and preparation of the original manuscript draft. B. Wirjosentono was responsible for validating the simulation model, organizing and curating the research data, and developing graphical representations of the results. H. Susilo carried out the techno-economic evaluation, including cost modeling and economic feasibility assessment, and interpreted the economic performance indicators. K. Wijaya contributed by providing strategic conceptual direction and evaluating the scientific coherence of the manuscript. D. H. Sinaga contributed by overseeing methodological consistency and conducting in-depth critical revision of the manuscript. S. Gea, as the corresponding author, was responsible for overall project coordination, acquisition of research funding, and final review and editing of the manuscript prior to submission.

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CONFLICT OF INTEREST

The authors declared that there was 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
A	Pre-exponential factor in Arrhenius equation
ABSOR-01	PSA unit block 1 (Aspen unit ID)
ABSOR-02	PSA unit block 2 (Aspen unit ID)
ABSOR-R1	Hydrogen purification separator block (Aspen unit ID)
APEA	Annualized project economic analysis
bar	Pressure unit (1 bar = 10^5 Pascal)
BC	Biochar (catalyst support)
BIO-STRG	Bio-oil preheating/storage heater (Aspen unit ID)
BOILSTRG	Boiler storage / preheating unit (Aspen unit ID)
CAPEX	Capital expenditure
CAS	Chemical Abstracts Service
CH_2	Chemical energy content of hydrogen
CH_4	Methane
CInet	Net carbon intensity
CO	Carbon monoxide
COMB-BIO	Combustor/furnace providing heat to the reformer (Aspen unit ID)
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CRF	Capital recovery factor
D	Diameter
day	Day (time unit)
Ea	Activation energy
Eelec	Electricity consumption
EF	Emission factor
EFgrid	Grid electricity emission factor
Eq.	Equation
Fe/BC	Iron on biochar catalyst
FLASH1	Flash separator block (Aspen unit ID)
GWP	Global warming potential
h	Hour (time unit)
HEN	Heat exchanger network
H_2	Hydrogen
kg	Kilogram

kg CO_2-eq/kg H_2	Carbon intensity unit (kilogram CO_2-equivalent per kilogram hydrogen)
kg/day	Kilogram per day
kg/h	Kilogram per hour
kg/kmol	Kilogram per kilomole
kg/year	Kilogram per year
kJ	Kilojoule
kJ/kg	Kilojoule per kilogram
kJ/kmol	Kilojoule per kilomole
kJ/mol	Kilojoule per mole
kW	Kilowatt
kWh	Kilowatt-hour
L	Liter (volume unit); also used to denote reactor length in geometry specification
L/kg H_2	Liter per kilogram of hydrogen (water consumption unit)
LCA	Life cycle assessment
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
m	Meter (length unit)
MAPE	Mean absolute percentage error
MIX-PSA	Mixer upstream of PSA (Aspen unit ID)
MIXER	Mixer block combining steam and bio-oil (Aspen unit ID)
Mol	Mole
Mol/kg/s/bar	Mole per kilogram per second per bar (kinetic rate unit)
Mol/mol	Molar ratio
MW	Molecular weight
Ni-Fe/BC	Nickel–iron on biochar catalyst
NiFe	Nickel–iron (bimetallic catalyst)
N_2	Nitrogen
OPEX	Operating expenditure
Pa	Pascal (pressure unit)
Pannual	Annual hydrogen production
PPKM/PKS	Internal grant scheme code (as cited in the grant number)
PR	Peng–Robinson equation of state
PRSV	Peng–Robinson–Stryjek–Vera equation of state
PSA	Pressure swing adsorption
RMAT	Reactor model analysis tool
RMSE	Root mean square error
RPlug	Plug-flow reactor model block in Aspen Plus
R^2	Coefficient of determination
S	Second (time unit)
S/B	Steam-to-bio-oil ratio
S/C	Steam-to-carbon ratio
SESR	Sorption-enhanced steam reforming
SMR	Steam methane reforming
TCI	Total capital investment
TEA	Techno-economic analysis/evaluation
UNIMED	Universitas Negeri Medan (State University of Medan), Indonesia
USD	United States dollar
WGS	Water–gas shift
WTR-STRG	Steam generation/storage heater (Aspen unit ID)
Year	Year (time unit)

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Podcasts

CASE STUDY

Pulp and paper mill wastewater treatment using specially designed units in combination with electrocoagulation and low-cost ecofriendly materials

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ABSTRACT

BACKGROUND AND OBJECTIVES: Industrial wastewater generated from manufacturing, processing, and chemical treatments contains a range of organic and inorganic pollutants that significantly deteriorate water quality. Conventional techniques, including chemical coagulation–flocculation and membrane filtration, while commonly employed, frequently encounter challenges when addressing complex and highly concentrated industrial effluents. Within this framework, electrocoagulation has appeared as a viable alternative technology. The key objective of the present study was to assess the efficacy of electrocoagulation combined with filtration, adsorption, and biomaterial-based treatment units in reducing the pollutant load of paper mill effluents.

METHODS: Paper mill effluent was collected and subjected to electrocoagulation followed by multistage filtration using three different prototype designs. Physicochemical parameters and heavy metal concentrations were analysed before and after treatment. The metals assessed included chromium, copper, iron, nickel, zinc, manganese, and lead. The ionic composition of untreated and treated effluents was assessed using high-pressure ion chromatography. Three treatment unit designs were developed: Design 1 comprised an electrocoagulation unit followed by adsorption and biomaterial-based filtration; Design 2 incorporated electrocoagulation, adsorption, biological treatment, and ultraviolet disinfection using plastic containers mounted on a mild steel frame; and Design 3 utilized glass units arranged on a mild steel stand to evaluate treatment efficiency under controlled conditions. Affordable biomaterials such as tea powder, bagasse, sawdust, wooden peels, coconut shell, and coconut husk were used as adsorbents.

FINDINGS: The holistic treatment method revealed a considerable decrease in pollutant concentrations, including heavy metals and ionic species. Electrocoagulation destabilized colloids and facilitated metal removal, while biomaterials enhanced adsorption efficiency. Among the three designs, integrated systems demonstrated the most superior overall treatment performance. Overall, at 30 minutes. electrocoagulation operation, iron-iron rods and iron-aluminium configurations showed the most stable and effective performance, achieving comparatively lower electrical conductivity (1411–1743 micro-Siemens), total dissolved solids (905–1026 milligrams per liter), chemical oxygen demand (514–600 milligrams per liter), and hardness (368–480 milligrams per liter) than other electrode combinations.

CONCLUSION: The study confirms that electrocoagulation combined with biomaterial-based filtration is an effective and cost-efficient option for treating industrial wastewater. The extensive application of this comprehensive method has the capacity to be more financially efficient than standard treatment systems.

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INTRODUCTION

Natural water resources are depleting, posing a serious threat to the sustainability of life on Earth. (Bănăduc *et al*., 2022). This concern is notably critical in developing countries like India, where fast-paced population and industrial growth, along with a lack of adequate effluent treatment systems, intensify the difficulties surrounding water sustainability (Sathya *et al*.,2022). Outflow of industrial wastewater is still among the largest sources of pollution to the environment (Mahmoud, *et al*., 2021). Wastewater reuse and recycling have attracted research focus to recover nutrients and mitigate environmental degradation (Fito *et al*., 2021). Despite their effectiveness, traditional physico-chemical treatment techniques come with significant operational expenses for eliminating soluble chemical oxygen demand (COD), which makes them less viable than more affordable options (Yu *et al*., 2020). Chemical treatment can introduce secondary pollutants into wastewater, highlighting the need for more sustainable treatment approaches (Hanafi and Sapawe, 2020). Electrocoagulation (EC) is demonstrating to be a highly effective, efficient, and eco-friendly technique for eliminating metals and other pollutants from water systems (Ammar *et al*., 2023). Some of the areas where EC has been employed with success include America and South America and Europe (Magnisali *et al*., 2022). Its effectiveness has been confirmed on a variety of effluents like oil mill wastewater (Ghahrchi *et al*., 2021), tannery effluents (Villaseñor-Basulto *et al*., 2022), municipal wastewater (Hu *et al*., 2023), nitrite-contaminated water (Benekos *et al*., 2021) and fluoride-bearing solutions (Vishwakarma, and Srivastava, 2024), textile (Asfaha *et al*., 2022) and restaurant wastewater (Zhang *et al*., 2022). Electrochemical treatment can be applied to a diverse array of industrial effluents and has demonstrated greater effectiveness through EC (Magnisali, *et al*., 2022). It entails the movement of an electric current between dissolved solenoid anodes (typically made of aluminium (Al), iron (Fe) or an alloy thereof; in an electrochemical reactor (Yasri, 2020). In this process, in-situ generation of coagulants is achieved using an anodic dissolution (Al-Marri *et al*., 2023). Electrodes made of Al, specifically have proved to perform well in the elimination of turbidity, colour as well as COD in wastewater (Igwegbe *et al*., 2021). Prior studies have established that EC is very effective in the removal of pollutants, attributed to its green credentials, operational ease, and affordability (Bajpai *et al*., 2022). This mechanism operates on the principle of neutralizing charges and forming metal hydroxide flocs that intertwine and capture the pollutants (Yasri *et al*., 2020). The compositions of industrial effluents are often indeterminate, comprising both organic and inorganic pollutants (Manikandan and Saraswathi, 2023). Conventional treatments like coagulation-flocculation and membrane filtration are effective but costly and require skilled personnel (Shamshad and Rehman, 2025). Inexpensive adsorbents derived from agricultural by-products such as nutshells, wood, bone, and peat have attracted interest for their potential transformation into activated carbons (Ungureanu *et al*., 2023). Activated charcoal, composed mainly of fine carbon particles, has high adsorption capacity due to its abundant micropores and large surface area (Heidarinejad *et al*., 2020). The efficacy of activated carbon adsorption is closely tied to the selection of activation agents and the carbonization conditions that control pore development (Heidarinejad *et al*., 2020; Sevilla *et al*., 2021). Such adsorbents have adjustable surface characteristics and a variety of functional groups to remove contaminants (Raninga *et al*., 2023). Activated carbon is also among the best adsorbents to use in the elimination of organic and heavy metal contaminants in wastewater (Gul *et al*., 2022). This has been created through a wide array of precursors, which encompass agricultural and industrial byproducts such as cocoa husks (Fasakin *et al*., 2024), periwinkle shells (Eke-Emezie *et al*., 2022), walnut shells, coconut shells, palm kernel shells and bamboo stems (Devi *et al*.,

2024). Some other resources--olive stones, bagasse, pecan shells, seeds of palm tree, and pulp from apple have also been reported to be appropriate in the production of activated carbon (Ungureanu *et al*., 2023; Negm *et al*., 2024; Gupta *et al*., 2024). Municipal and industrial wastewater, containing heavy metals and organic compounds, can be effectively treated using adsorption methods. Their effectiveness of these materials is influenced by the size of the adsorbent pores, the surface chemistry, and interactions with the adsorbate (An *et al*., 2022). Recent advances in environmental biotechnology have established biosorption as a sustainable method for pollutant removal (Filote *et al*., 2021). Biological biosorbents, comprising algae and microorganisms, present benefits such as low expense, significant effectiveness, decreased sludge generation, the potential for regeneration, and the recovery of metals (Meena *et al*., 2021). An example of algae that is found in the brown seas is high affinity to heavy metal ions (Nowicka, 2022). Furthermore, the creation of biosorbents from natural or waste biomaterials represents an environmentally sustainable method for managing wastewater (Mohanrasu *et al*., 2025; Boakye *et al*., 2022). In the present investigation, a hybrid treatment approach combining EC with activated carbon adsorption for industrial effluent remediation, emphasizing the optimization of critical operational parameters such as potential of hydrogen (pH), current density, applied voltage, electrode spacing, and treatment duration. Additionally, the potential of low-cost, plant-derived biomaterials as sustainable adsorbents was assessed, contributing to the development of eco-friendly and efficient EC-based treatment systems. The study additionally assesses optimized design configurations of the uniquely developed treatment units, which are intended to regulate retention time and mixing efficiency to improve pollutant removal performance. Electrode arrangement and flow pathways were designed to ensure uniform mixing and effective contact between contaminants and treatment media, thereby promoting efficient biosorption and filtration processes and resulting in improved treatment efficiency and stable system operation. The optimum EC operating window for pulp and paper mill wastewater was identified using Al and iron electrodes at an applied voltage of 25 V and current of 2 A, with an effective treatment duration of 60 minutes (min). Performance evaluation at 15, 30, 45, and 60 min indicated progressive pollutant removal, with the integrated eco-friendly filtration units enhancing overall treatment efficiency. The stepwise incorporation of EC with economical biomaterial filtration improves the destabilization and coagulation of colloidal particles, subsequently leading to efficient adsorption and biofiltration processes. This integrated treatment approach significantly improves the removal efficiency of key water quality parameters. The substantial reduction in electrical conductivity (ECe) and total dissolved solids (TDS) clearly indicates the effectiveness of the combined system. The objective of this study is to create an EC system and designs that integrate environmentally friendly adsorbents to attain optimal treatment performance. The foundational experimental studies were conducted between 2017 and 2020 at the Department of Environmental Science, Fergusson College, Pune, India.

MATERIALS AND METHODS

Sample collection

Wastewater samples were collected from a paper production industry based in Pune, Maharashtra (India). These samples were collected in plastic cans, appropriately labeled, and then stored in the research laboratory. The wastewater parameters of the paper industry effluent were examined using standard and commonly accepted methods. The baseline wastewater samples were representative of routine pulp and paper mill operations and were collected using well-mixed, representative sampling procedures, ensuring reliable and consistent characterization of the influent. The

recorded decreases in critical parameters after treatment correspond to the expected results of the treatment procedure applied, thus affirming its effectiveness. The biomaterials were selected based on availability, cost-effectiveness, porosity, and adsorption potential, with their physicochemical properties directly governing the removal of paper mill–specific pollutants. The primary objective was to emphasize the costs associated with material and structural design, derived from comprehensive experimental research centered on the manipulation of specific parameters; a thorough overall cost–benefit analysis has not been incorporated at this point.

EC treatment

The experimental installation was operated in the Department of Environmental Science, Fergusson College (Autonomous), Pune, India. The setup was connected to a digital rectifier, and samples were collected and analyzed at treatment intervals of 15, 30, 45, and 60 min. EC was performed using aluminium (Al) and iron (Fe) electrodes, either individually or in combination. Plate electrodes had dimensions of 13 centimeters (cm) × 5 cm × 0.2 cm, while rod electrodes measured 13 cm × 2 cm × 2 cm. To ensure a uniform and effective surface area, the electrodes were immersed to a depth of 10 cm in the effluent for all experimental runs. A supply of direct current at 2 A was introduced via the rectifier, with Fe attached to the positive electrode (anode) and Al functioning as the negative electrode (cathode) across all configurations. The reaction mixtures were continuously stirred at 500 revolutions per minute (rpm). Heat generation was observed following the initiation of EC, and temperature variations were monitored and recorded at predetermined time intervals corresponding to the analyzed parameters. Each experimental run was conducted with 1000 milliliters (mL) of wastewater. After the treatment, the effluent underwent additional physicochemical analysis. Prior to each run, the electrodes were thoroughly cleaned with acetone to remove any surface deposits and ensure reproducibility.

Various physical and chemical parameter assessments from paper mill effluent

The pH of the water samples was measured using an ELICO LI-127 digital pH meter. Turbidity, expressed in nephelometric turbidity units (NTU), was determined using a $^{CL-}$52D ELICO nephelometer based on light scattering by suspended particles. Ece in micro-Siemens (µS) and TDS (mg/L) were analysed using an ELICO EC–TDS meter (Model CM-183). The gravimetric method was employed to determine total solids (TS), and total suspended solids (TSS) were computed using the relationship TS = TDS + TSS. COD was estimated by the standard reflux method, wherein 20 mL of sample was digested with 10 mL of 0.25 N potassium dichromate and 30 mL of sulfuric acid silver sulphate (H_2SO_4 + Ag_2SO_4) solution. Biochemical oxygen demand (BOD) was determined after an incubation period of 3 days at 27 °C. Water hardness was evaluated using the ethylenediaminetetraacetic acid (EDTA) titrimetric method, which quantifies calcium and magnesium ions responsible for hardness. Sodium (Na^+) and potassium (K^+) concentrations were measured using a Systronics-128 flame photometer, and readings were compared against standard calibration curves. Metals and essential minerals, including chromium (Cr^{3+}), copper (Cu^{2+}), Fe^{3+}, nickel (Ni^{2+}), zinc (Zn^{2+}), and lead (Pb^{2+}), were analysed in both treated and untreated samples. The analyzed samples were assessed in accordance with standard protocols utilizing a PerkinElmer 3030A atomic absorption spectrophotometer (AAS). Additionally, selected anions and cations in the wastewater were quantified using high-pressure ion chromatography (HPIC) by the method suggested by Tóth *et al.* (2016). All analytical methods were validated using appropriate standards, systematic calibration procedures, to ensure accuracy, reproducibility, and compliance with regulatory guidelines. The confirmation of reproducibility

and reliability was achieved by obtaining consistent results across multiple experiments and different operating conditions, with only slight variability in treatment performance.

EC cum waste biomaterial filtration designs

Fig. 1 provides the prototype design of the three units. Three layouts are made on filtration units. The following are the specifications of the three designs. The study mainly concentrated on creating an innovative treatment system and minimizing essential water quality parameters. The prototype was intentionally developed as a laboratory-scale, proof-of-concept system with the primary focus on establishing fundamental treatment performance. Nevertheless, due consideration was given to industrial scalability, particularly in terms of treatment capacity and modular design. The chosen components and operational parameters were selected to facilitate future scaling by means of suitable adjustments, such as sensor-driven controls and energy efficiency improvements. The design framework allows adaptation for large-scale applications and has potential relevance not only for pulp and paper mill effluents but also for other industrial wastewater streams.

Design 1

This design was utilized for the processing of paper mill effluent and consisted of EC, adsorption, and biomaterial-based treatment units. In the EC unit, Fe and Al plate electrodes of approximately 13 cm in length were used. The electrodes were immersed to a depth of 10 cm in wastewater, with Fe serving as the anode and Al as the cathode. The treatment was carried out by applying a current of 25 V and 2 A for a duration of 1 hour. The biomaterials utilized in the treatment of effluent included tea powder, bagasse, wood sawdust, wooden peels, coconut shell, and coconut husk, among others. The biomaterials showed low to moderate clogging potential, which was monitored and managed to maintain effective flow and treatment efficiency. The total cost to fabricate this assembly was around $150.00. Tea powder was obtained from tea stalls while the waste generated by sugar juice centers as bagasse was collected from the city. The treatment of the effluent involved the use of coconut husk, coconut shells, and sawdust. The second unit of this treatment involved powdered activated carbon (PAC) as 0.5 gram per liter (g/L) and consisted of six vertical units for biosorbents. The retention time for Design 1 was 60 min for EC, and 30 min for each biosorbent treatment.

Design 2

The treatment system was designed using plastic containers mounted on a steel stand and consisted of seven containers, each with a capacity of 4 L. The aim of this comprehensive design was to sequentially expose the effluent to EC, adsorption, biological, and ultraviolet (UV) treatments. The effluent was processed through all treatment units, and the final outlet was analyzed for pH, ECe, TDS, salinity, turbidity, hardness, COD, and Cl^-. Container 1 functioned as the screening unit and was equipped with a 20 micrometer (μm) sieve at the entrance, whereas Container 2 served as the settling tank, where the wastewater was retained for 1 h. A 6 Volt (V) fan was mounted on the top lid to provide agitation, and mixing was carried out for 30 min. Container 3 was designated for EC treatment and was equipped with Fe and Al plate electrodes of approximately 13 cm in length. The electrodes were immersed to a depth of 10 cm, with Fe acting as the anode and Al as the cathode. A direct current of 25 V and 2 A was applied for 1 h, with the treatment duration selected based on prior pilot studies. Furthermore, drumstick powder was incorporated as a natural coagulant at a concentration of 1 g/L to improve treatment efficiency. Container 4 was used for sand filtration combined with PAC. In this unit, approximately 2 kg of well-washed sand treated with 0.1 normal hydrochloric acid (N HCl) and PAC at a concentration of 0.5 g/L were employed. A provision was made for the removal of excess

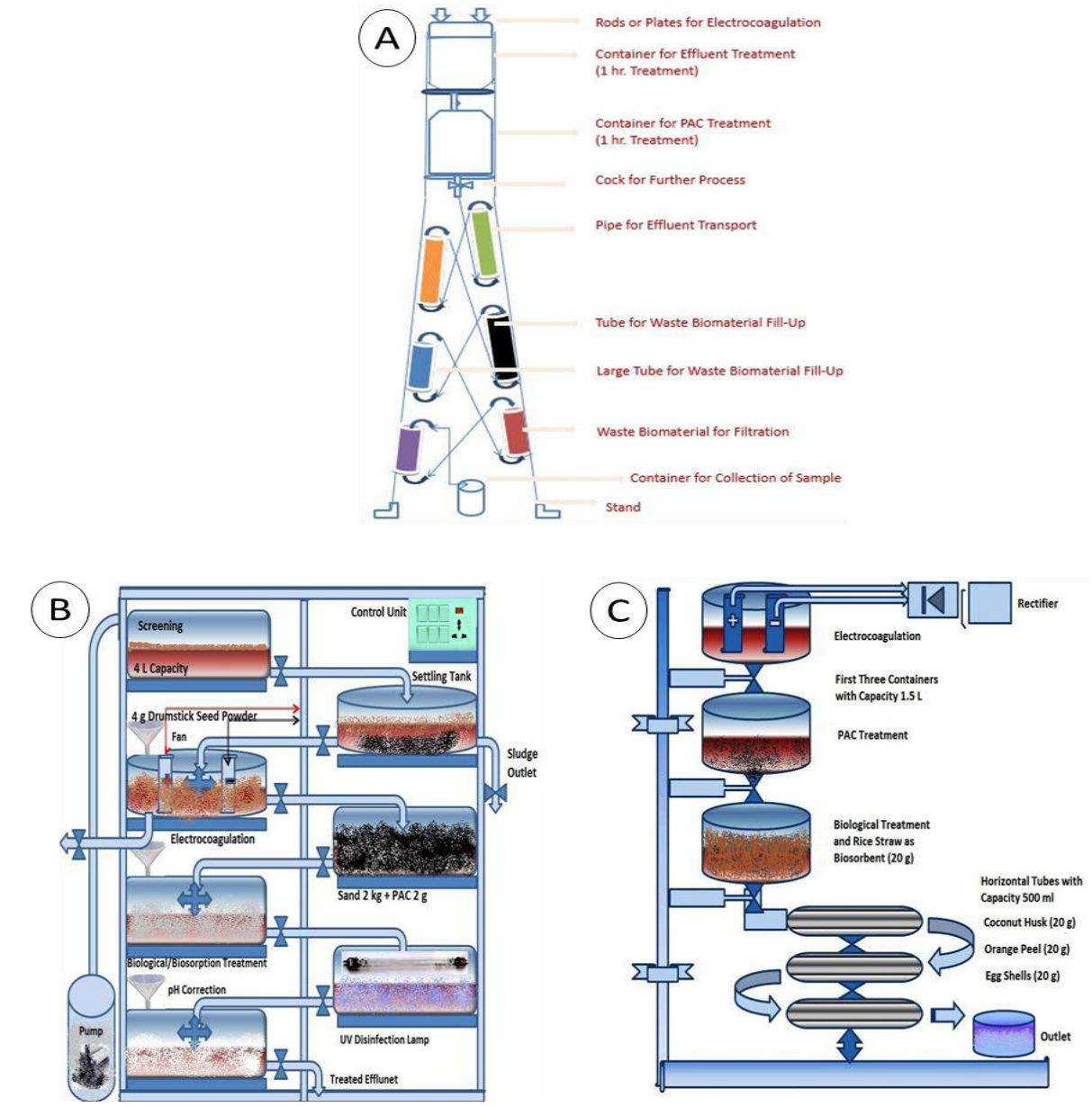

Fig. 1: Prototype design A: Design 1; B: Design 2; C: Design 3

sludge and effluent residues. The incorporation of PAC in conjunction with sand filtration was designed to produce a synergistic effect and boost overall treatment performance. Container 5 was designated for biosorbent treatment. A total of 50 g of each natural biosorbent was pretreated by washing with 0.1 N HCl, followed by oven dehydration. Following the pretreatment process, the effluent was subjected to treatment utilizing a combined biosorbent mixture that included coconut husk, neem bark, rice straw, and orange peels, and was allowed to settle for 30 min. Subsequently, biological treatment was carried out in the same container by inoculating *Pseudomonas aeruginosa* culture at a dosage of 20 milliliters per liter (mL/L) and incubating at room

temperature for 24 h. *Pseudomonas aeruginosa* was safely used in both designs, with proper containment and UV post-treatment ensuring effective microbial removal and safe treated wastewater. Aeration was achieved through a small fan installed at the upper part of the container and operated by a 12 V motor. UV disinfection was performed in Container 6, where a 6 V UV lamp was horizontally fixed at the top and securely enclosed with an Al sheet. This unit functioned as the disinfection chamber, providing 30 min of UV exposure to the treated effluent. Container 7 was employed for pH correction, in which lime was incorporated to bring the wastewater pH to neutral conditions. Approximately 1000 mL of the fully treated effluent was collected separately from the outlet for physicochemical parameter analysis. The total fabrication cost of the entire treatment assembly was approximately $200.00.

Design 3

The system was constructed utilizing six glass container units affixed to a steel stand with clamps. The first three units, each with a capacity of 1.5 L, were arranged vertically, while the remaining three units, each of 250 mL capacity, were fixed horizontally to the stand. This arrangement facilitated the simultaneous vertical and horizontal management of the effluent by incorporating EC, adsorption, and biological methods in a treatment assembly that merges EC with biosorption. The effluent was passed sequentially through all treatment units, and the selected water quality parameters were analyzed. EC treatment in Unit 1 was carried out as described previously. Unit 2 was utilized for PAC treatment, with PAC administered at a concentration of 0.5 g/L, functioning both as an adsorbent and as a medium for holding excess sludge and suspended solids. Unit 3 was designated for natural biosorbent treatment, in which approximately 20 g of rice straw was added. Prior to use, the rice straw was thoroughly washed and oven dried. The effluent was permitted to stay in contact with the biosorbent for a duration of 10 min, following which biological treatment commenced in the same unit by aseptically adding *Pseudomonas aeruginosa* anaerobic culture at a concentration of 20 mL/L. The mixture was then incubated at room temperature for 24 h.

Statistical analysis

The values of the tested parameters are expressed as mean ± standard deviation (SD), based on three experimental replicates. This study utilized a two-way analysis of variance (ANOVA) to evaluate the influence of electrode material (Al-Al, Fe-Fe, and Fe-Al) and electrode geometry (Plates vs. Rods) on key water quality parameters.

RESULTS AND DISCUSSION

In the current investigation, a multistage treatment approach was adopted to study the effectiveness of EC along with PAC and other biosorbents for the treatment of paper mill effluent. The discussion corresponds with recent literature from the EC, and the interpretations are rooted in the experimental data of the study, with the trends observed agreeing with findings previously documented. The eco-friendly materials displayed different adsorption efficiencies: coconut shell and husk had the highest capacity and selectivity, tea powder and bagasse showed moderate removal, while sawdust and wooden peels required longer contact times. The overall effectiveness of the combined treatment was also evaluated. The biomaterials that have been selected are sustainable and can be reused multiple times, with methods such as simple thermal drying, mild chemical washing, or biological regeneration methods feasible while maintaining their eco-friendly nature and adsorption efficiency. EC produced a compact, easily dewaterable sludge amounting to approximately 10–15 percent (%) of the wastewater, with potential for safe reuse or valorization after proper stabilization. Nonetheless, this aspect was not the primary focus of the current study. Moreover, a decline in

Table 1: Initial characteristics of the effluent

S. No.	Parameters	Paper mill effluent
1	Color	Faint grey
2	Odor	Unpleasant
3	pH	5.63 ±0.24
4	EC (µS)	2269 ±21.21
5	TDS (mg/L)	1552 ±16.97
6	TSS (mg/L)	576.5 ±10.61
7	TS (mg/L)	2128.5
8	Turbidity (NTU)	48 ±4.24
9	Hardness (mg/L)	412.5 ±17.68
10	COD (mg/L)	915 ±35.36
11	BOD (mg/L) 5 days at 20°C	277.5 ±3.54
12	TKN (mg/L)	77 ±1.98
13	Na (mg/L)	183.5 ±7.78
14	K (mg/L)	52.5 ±4.95
15	Cl (mg/L)	217.7 ±6.66

the levels of water parameters, including pH, ECe, TDS, salinity, turbidity, hardness, and COD were observed. While EC primarily facilitates rapid TSS removal through floc formation, the present study placed greater emphasis on TDS as a key parameter. The effluent's profile at the outset indicated a higher likelihood of pollution (Table 1). Undoubtedly, the differences in the characteristics of the effluent are associated with seasonal processing and the materials generated in the industry. Variations in influent pH, organic load, color intensity, and metal content influenced treatment efficiency by altering coagulation and adsorption behavior. The integrated system maintained stable performance due to its adaptable EC and biomaterial-based treatment units. Each treatment stage performs a specific function- EC destabilizes pollutants, adsorption captures residual organics, and biological treatment further degrades providing synergistic pollutant removal efficiency. The ionic composition modifies EC by affecting the conductivity of the solution and the generation of coagulants, which subsequently determines the efficiency of treatment. The observed reduction, particularly in COD, indicates improved wastewater biodegradability and reflects the effectiveness of the integrated treatment design. EC using Al and iron plates is a suitable and effective method for the treatment of the selected effluent. The recommended EC–biomaterial system demonstrates similar pollutant removal efficiencies and exhibits more stable operational performance compared to earlier methods, resulting in improved reductions in color, organics, and solids (Hugar and Marol, 2020; Pandey and Thakur, 2020; Bassyouni *et al.,* 2023; Caglak *et al.,* 2023; Dogan *et al.,* 2025).

Initial parameters of paper mill effluent

The initial assessment of the paper mill effluent is summarized in Table 1. The effluent was observed to be faint grey in color with an unpleasant odor. It exhibited an acidic pH (5.63 ± 0.24) with high ECe with 2269 ± 21.21 (µS) and TDS 1552 ± 16.97 (mg/L). Elevated levels of total suspended solids (576.5 ± 10.61 mg/L), total solids (2128.5 mg/L), turbidity (48 ± 4.24 NTU), and hardness (412.5 ± 17.68 mg/L) were also recorded. The organic load of the effluent was high, as indicated by COD (915 ± 35.36 mg/L) and 5 days BOD at 20°C (277.5 ± 3.54 mg/L). Additionally, the effluent contained measurable concentrations of total Kjeldahl nitrogen (TKN) (77 ± 1.98 mg/L), Na (183.5 ± 7.78 mg/L), K (52.5 ± 4.95 mg/L), and Cl (217.7 ± 6.66 mg/L).

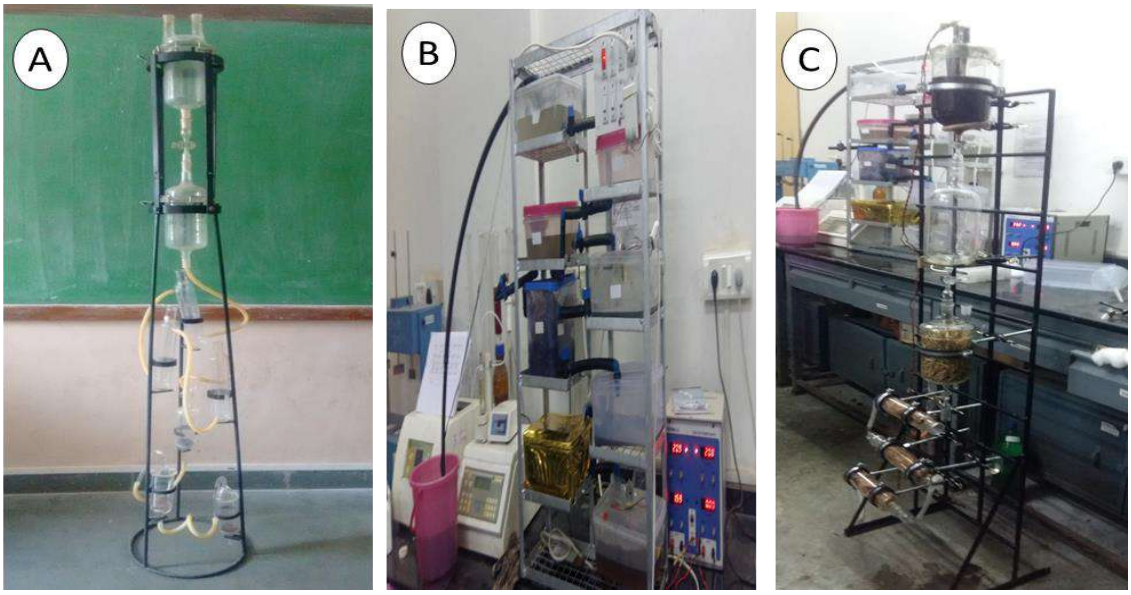

Fig. 2: Construction of filtration units. A: Design 1, B: Design 2, C: Design 3

Experimental setup of three designs

Fig. 2 illustrates the construction of the filtration units for the three prototype designs. Design 1 consisted of eight individual units, Design 2 comprised of seven containers, each with a capacity of 4 L, and Design 3 was composed of six glass units.

Comparative study between three designs

The comparative configuration and operational features of the three treatment designs developed for pulp and paper mill wastewater are summarized in Table 2. At a broader level, Design 1 integrates EC, adsorption, and biomaterial-based treatments. Design 2 includes EC, adsorption, biological treatment, UV disinfection, sand filtration, and sedimentation units. Design 3 consists of EC, adsorption, biological treatment, and biosorption processes. In contrast to Design 1, Designs 2 and 3 include extra treatment elements like biological processes, UV treatment, filtration methods, and prolonged retention time, thus providing a more thorough treatment strategy. The comparative analysis of the three prototype designs represents the novel aspect of this study. The comparison presented in the Table 2 underscores the distinctions in treatment performance across various designs, delivering valuable insights into the optimal configuration for pulp and paper mill effluent. While the focus is on paper mill wastewater, the findings and design principles are broadly applicable to other types of industrial wastewater, demonstrating the versatility and potential scalability of the integrated treatment approach. All vital experimental specifics, encompassing the type of electrode, dimensions, applied voltage, and current, have been provided. These parameters enable the assessment of energy requirements and process scalability, supporting reproducibility and allowing estimation of operational efficiency for larger-scale applications.

Changes in water parameters after EC and waste biomaterial treatment of paper mill effluent

Three different electrode configurations comprising Al and iron plates or rods were employed during the EC step. The configurations included Al-Al, Fe-Fe, and Al-Fe electrode pairings (Igwegbe *et al.*, 2021; Adou *et al.*, 2022;

Table 2: Comparative treatments of all three designs for pulp and paper mill effluent

Main purpose	Design 1	Design 2	Design 3
treatment Methods	EC, adsorption, biomaterial treatment	EC, adsorption, biological, UV treatment, sedimentation, sand filtration	EC, adsorption, biological treatment, biosorption
Materials used	Tea powder, bagasse, wood sawdust, coconut shell, coconut husk	Drumstick powder, sand, PAC, coconut husk, neem bark, rice straw, orange peels	Coconut husk, rice straw, orange peel, eggshells
Container structure	Not applicable	Seven plastic containers (4 L each) on mild steel stand	Six glass units (three 1.5 L vertical, three 250 mL horizontal) on steel stand
EC details	Fe (+) and Al (-) plates, 25 V, 2 A, 10 cm dip, 60 min	Fe (+) and Al (-) plates, 25 V, 2 A, 10 cm dip, 60 min	Fe (+) and Al (-) plates, 25 V, 1 A, 60 min
Biosorbent treatment	Tea waste, bagasse, sawdust, coconut shell/husk	Coconut husk, neem bark, rice straw, orange peles (30 min)	Rice straw, coconut husk, orange peel, eggshells (30 min)
Biological treatment	Not Provided	*Pseudomonas aeruginosa* (20 mL/L, 24 h, aeration)	*Pseudomonas aeruginosa* (20 mL/L, 24 h, No special aerator used)
UV treatment	Not Provided	6 V UV lamp, 30 min	Not included
Filtration method	PAC (0.5 g/L)	Sand filtration (2 kg sand + 0.5 PAC g /L)	PAC (0.5 g/L)
Retention time	EC for 60 min, biosorbent for 30 min	Sedimentation for 60 min, EC for 60 min, biosorbent for 30 min, biological for 24 h	EC for 60 min, biosorbent for 10 min, biological for 24 h
Parameters tested	Not tested	pH, EC, TDS, salinity, turbidity, hardness, COD, Cl^-	pH, EC, TDS, salinity, turbidity, hardness, COD, Cl^-
Construction cost	$150.00	$200.00	$200.00

Mousazadeh *et al*., 2023). The reactor's design, including electrode polarity and the choice of sacrificial electrode, was aimed at maximizing the efficiency of pollutant removal while ensuring consistent EC performance. Tables 3–5 present the physicochemical characteristics of textile industrial effluent treated using EC process. The parameters evaluated included pH and turbidity (NTU) (Table 3), Ece (µS) and TDS (mg/L) (Table 4), COD (mg/L) and total hardness (mg/L) (Table 5). The untreated effluent exhibited a highly acidic pH of 3.52 ± 0.02. EC treatment was carried out for up to 60 min, during which the pH gradually increased and reached approximately 6.00 ± 0.06. Across all electrode configurations, a rise in both pH and temperature was detected during the treatment period of 15 to 60 min. EC has been widely demonstrated as an effective method for treating paper mill wastewater. Using perforated iron electrodes, Pandey and Thakur (2020) achieved 95% COD and 67% color removal within 20 min at pH 7.15 and 20 mA/cm², underscoring the feasibility of swift and cost-effective treatment. Similarly, EC of paper mill black liquor with Al electrodes removed up to 85% color, with RSM optimization ($R^2 = 0.99$) confirming superior efficiency over conventional adsorption (Bassyouni *et al.,* 2023). Enhancing EC with electrooxidation (EC–EO) and Oxone (O_3) further improved treatment, achieving >98.4% removal of COD, color, and lignin using Fe–Fe and Ti/Pt–graphite electrodes, while maintaining practical energy consumption for high-strength effluent (Dogan *et al.,* 2025). Iron electrodes have also been effective in reducing multiple parameters simultaneously, including TDS (51%), turbidity (65%), TOC (68%), and COD (70%) at pH 8, 20 V, and 60 min, with RSM and ANOVA confirming high statistical reliability ($R^2 = 0.95$, $p < 0.001$) (Hugar and Marol, 2020). Moreover, combining EC with hydrogen peroxide (H_2O_2) or calcium hypochlorite [$Ca(OCl)_2$] pre-treatment enhanced the removal of tannin and lignin (92–94%) and reduced COD (~48%), with EC–H_2O_2 being more energy-efficient

Table 3: Changes in selected water parameters after EC of paper mill effluent

Time (min)	Effluent temperature (°C)	pH						Turbidity (NTU)					
		Al-Al Plates	Al-Al Rods	Fe-Fe Plates	Fe-Fe Rods	Fe- Al Plates	Fe-Al Rods	Al-Al Plates	Al-Al Rods	Fe-Fe Plates	Fe-Fe Rods	Fe-Al Plates	Fe-Al Rods
15	42	3.52 ± 0.02	3.54 ± 0.10	3.25 ± 0.07	3.19 ± 0.09	5.94 ± 0.06	5.84 ± 0.04	6.55 ± 0.35	6.5 ± 0.14	5.75 ± 0.07	2.85 ± 0.07	1.55 ± 0.07	1.35 ± 0.07
30	49	4.65 ± 0.03	3.63 ± 0.03	4.97 ± 0.06	4.42 ± 0.13	6.18 ± 0.08	6.16 ± 0.06	4.3 ± 0.28	4.3 ± 0.28	4.8 ± 0.00	1.82 ± 0.04	1.3 ± 0.14	1.1 ± 0.85
45	59	5.83 ± 0.04	4.76 ± 0.07	5.73 ± 0.07	5.78 ± 0.10	6.73 ± 0.08	6.66 ± 0.06	3.85 ± 0.07	3.75 ± 0.07	3.65 ± 0.35	0.25 ± 0.07	0 ± 0.00	0 ± 0.00
60	72	6.00 ± 0.06	4.96 ± 0.04	5.74 ± 0.04	5.91 ± 0.11	5.49 ± 0.10	5.28 ± 0.09	2.25 ± 0.21	3.05 ± 0.21	3.3 ± 0.14	0.05 ± 0.07	0.25 ± 0.07	0.1 ± 0.00

Table 4: Changes in selected water parameters after EC of paper mill effluent

Time (min)	Effluent temperature (°C)	ECe (µS)						TDS (mg/L)					
		Al-Al Plates	Al-Al Rods	Fe-Fe Plates	Fe-Fe Rods	Fe- Al Plates	Fe-Al Rods	Al-Al Plates	Al-Al Rods	Fe-Fe Plates	Fe-Fe Rods	Fe- Al Plates	Fe-Al Rods
15	42	1507.5 ± 24.75	1450 ± 14.14	1832 ± 12.73	1260.5 ± 6.36	2030 ± 14.14	1500 ± 49.50	1022.5 ± 17.68	1057.5 ± 9.19	1123 ± 18.38	1115.5 ± 7.78	1108 ± 12.73	1113.5 ± 16.26
30	49	1420.5 ± 10.61	1275.5 ± 7.78	1687.5 ± 3.54	1743 ± 26.87	1472.5 ± 3.54	1411 ± 12.73	1130.5 ± 7.78	905.5 ± 12.02	949.5 ± 9.19	965 ± 14.14	990 ± 7.07	1026.5 ± 7.78
45	59	1053 ± 22.63	1020 ± 9.90	1413.5 ± 14.85	1240.5 ± 20.51	1632 ± 4.24	1329.5 ± 12.02	985 ± 5.66	822.5 ± 13.44	721.5 ± 12.02	849 ± 9.90	828 ± 15.56	841 ± 33.94
60	72	1370 ± 11.31	1281.5 ± 9.19	1672 ± 16.97	1300 ± 14.14	1733.5 ± 12.02	1169 ± 9.90	963 ± 7.07	862.5 ± 9.19	868 ± 9.90	1001 ± 14.14	991 ± 11.31	872 ± 15.56

Table 5: Changes in selected water parameters after EC of paper mill effluent

Time (min)	Effluent temperature (°C)	COD (mg/L)							Hardness (mg/L)				
		Al-Al plates	Al-Al rods	Fe-Fe plates	Fe-Fe rods	Fe- Al plates	Fe-Al rods	Al-Al Plates	Al-Al rods	Fe-Fe plates	Fe-Fe rods	Fe- Al plates	Fe-Al rods
15	42	618.5 ± 23.33	664.5 ± 6.36	610.5 ± 14.85	701 ± 12.73	616 ± 12.73	648.5 ± 9.19	420 ± 7.07	440 ± 7.07	382.5 ± 3.54	415 ± 14.14	392.5 ± 10.61	392.5 ± 3.54
30	49	549 ± 16.97	547 ± 12.73	595 ± 5.66	600 ± 16.97	514 ± 15.56	572.5 ± 7.78	402.5 ± 3.54	410 ± 7.07	335 ± 14.14	480 ± 7.07	367.5 ± 10.61	370 ± 14.14
45	59	584.5 ± 20.51	459 ± 12.73	521.5 ± 14.85	542 ± 14.14	446.5 ± 7.78	432 ± 9.90	387.5 ± 3.54	422.5 ± 3.54	370 ± 7.07	415 ± 7.07	312.5 ± 3.54	327.5 ± 3.54
60	72	503 ± 8.49	527.5 ± 10.61	485.5 ± 19.09	473 ± 7.07	455 ± 9.90	546 ± 16.97	415 ± 0.00	505 ± 14.14	350 ± 7.07	435 ± 14.14	315 ±1 4.14	300 ± 14.14

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and EC–$Ca(OCl)_2$ performing better for recalcitrant pollutants (Caglak *et al.,* 2023). Collectively, these studies highlight the multifunctionality of EC and its hybrid configurations as efficient, scalable, and flexible approaches for the thorough treatment of wastewater from the paper industry. Most experimental runs showed fluctuating trends in ECe, TDS, COD, and hardness across time and electrode combinations; however, Fe–Fe (rods) and Fe–Al (plates/rods) exhibited comparatively stable and effective performance, with optimum treatment observed at 30 min of EC operation, where Fe–Fe rods achieved lower ECe and TDS (1743 µS and 965 mg/L) along with reduced COD and hardness (600 and 480 mg/L), while Fe–Al configurations also showed notable reductions in ECe (1472–1411 µS), TDS (990–1026 mg/L), COD (514–573 mg/L), and hardness (368–370 mg/L), indicating superior pollutant removal efficiency. After EC treatment, the paper mill effluent was subjected to further procedure as per the design. The EC was the first step common to all designs. The integrated system demonstrates high cost-effectiveness due to the use of locally available biomaterials, low current densities for EC, and minimal maintenance requirements for the specially designed units, indicating a practical and energy-efficient approach for sustainable effluent treatment. Expanding the units offers the chance to extend the life of electrodes and preserve a smooth flow of biomaterials, which guarantees stable and efficient functioning. The integrated treatment system was validated to be resilient over prolonged operation, sustaining reliable performance despite encountering some limitations.

Natural biosorbent treatment of paper mill effluent by using Design 1

Table 6 summarizes the water quality parameters analyzed after the combined EC and natural biosorbent treatment of paper mill wastewater using Design 1. The biosorbents applied in this design included PAC, bagasse, coconut shell, coconut husk, wooden peels, and tea powder. Post-treatment, the effluent pH increased toward near-neutral conditions, reaching 6.03 ± 0.13. A noticeable reduction in ECe, TDS, and salinity was observed. Nonetheless, there was no significant change in turbidity and copper concentrations post-treatment. The process also led to decreased levels of total hardness, COD, and chloride (Cl^-) content. Furthermore, the concentrations of Cr, Fe, and Ni were effectively reduced during the treatment. The variation and comparative trends of key water quality parameters following EC and biosorbent treatment are further illustrated in Fig. 3. From Fig. 3, it may be observed that Fe–Al plates and rods were found to be better for the for the reduction in contamination potential of paper mill effluent. The treatment demonstrated improved effectiveness when administered for 60 min, with tea powder and wooden peels being the waste biomaterials that yielded superior results. Through the application of PAC, tea powder, and wooden peels, the metal concentration in the effluent was markedly diminished. The results obtained using Fe–Al plates and rods were improved compared to other treatments, which can be attributed to adsorption and increased filter affinity.

Natural biosorbent treatment of paper mill effluent by using Designs 2 and 3

Table 7 illustrates the alterations in specific water parameters after biosorbent treatments, which encompass both Biosorbent and Biological treatment of the effluents utilizing Designs 2 and 3. The pH, EC, and TDS values for Design 2 were lower compared to Design 3 treatments. After treatments in Design 2, the pH reached approximately 6.32–6.42, while in Design 3 it was lower (5.37–5.6). Salinity and Hardness decreased in Design 2 (Salinity: 9.05 ± 0.92 mg/L, Hardness: 80 ± 7.07 mg/L) compared to Design 3 (Salinity: 86.68 ± 12.76 mg/L, Hardness: 120 ± 7.07 mg/L). COD and Cl^- values after biological treatment in

Table 6: Changes in selected water parameters after EC and natural biosorbent treatment of paper mill effluent by using design 1

Parameters	PAC	Bagasse	Coconut shell	Coconut husk	Wooden peels	Tea powder
pH	5.7 ±0.02	5.28 ±0.09	5.09 ±0.16	3.65 ±2.08	5.89 ±0.15	6.03±0.13
EC (µS)	1130±7.07	1188±14.14	1213±15.56	1279.5±18.5	983.5±7.78	963 ±8.49
TDS (mg/L)	697.5±12.02	736 ±15.56	805 ±22.63	815 ±19.80	649.5±12.02	631.5±10.61
Salinity (mg/L)	360.5±9.19	374±9.90	399±14.14	417.5±10.61	338±9.90	314±14.14
Turbidity (NTU)	0.11±0.02	0.19±0.07	0.14±0.03	0.23±0.02	0.08±0.01	0.11±0.02
Hardness (mg/L)	240±7.07	255±14.14	265±14.14	282.5±10.61	215±14.14	207.5±17.68
COD (mg/L)	415.5±7.78	445.5±14.85	463.5±16.26	493.5±12.02	400±14.14	380.5±7.78
Cl^- (mg/L)	98.7±5.30	110±7.07	108.71±5.30	114±5.30	92.5±7.07	75±7.07
Cr (mg/L)	1.23	1.45	1.58	1.98	0.98	0.95
Cu (mg/L)	0.55	1.28	1.23	1.21	0.51	0.56
Fe (mg/L)	2.16	22.65	18.65	16.54	1.56	1.65
Ni (mg/L)	0.52	1.58	1.65	1.27	0.42	0.40
Zn (mg/L)	0.42	0.78	0.95	0.57	0.38	0.31
Mn (mg/L)	0.31	0.95	0.84	0.95	0.21	0.22
Pb (mg/L)	0.009	0.77	0.71	0.88	0.11	0.14

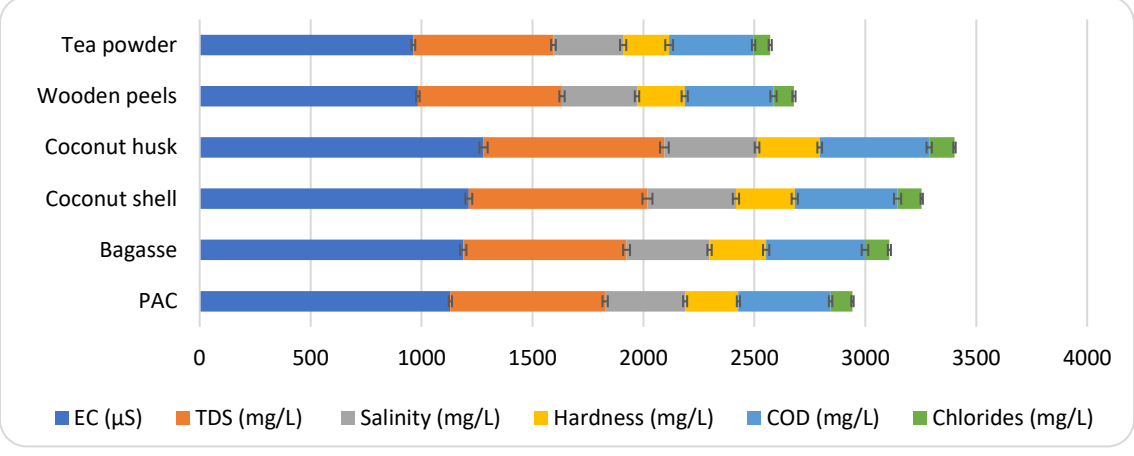

Fig. 3: Changes in selected water quality parameters after EC and natural biosorbent treatment of paper mill effluent using Design 1

Table 7: Changes in selected water parameters after EC and natural biosorbent treatment of the effluents by using designs 2 and 3

Parameters	Design 2		Design 3	
	Treatment Unit 5 (Biosorbent)	Treatment Unit 5 (Biological)	Treatment Unit 3 (Biological)	Treatment Units 4,5 and 6 (Biosorbents)
	For 30 min	For 24 h	For 24 h	For 30 each
pH	6.32 ± 0.24	6.415 ± 0.21	5.6 ± 0.14	5.37 ± 0.14
EC (µS)	522 ± 14.14	509.5 ± 24.75	658 ±15.56	647.00 ± 14.14
TDS (mg/L)	356 ± 28.28	347.5 ± 27.58	451.5 ±14.85	442.00 ± 15.56
Salinity (mg/L)	130.5 ± 9.19	9.05 ± 0.92	66.495 ± 8.69	86.68 ± 12.76
Turbidity (NTU)	0.95 ± 0.21	0.35 ± 0.21	0.55 ± 0.21	0.14 ± 0.08
Hardness (mg/L)	82.5 ± 10.61	80 ± 7.07	115 ± 28.28	120.00 ± 7.07
COD (mg/L)	200.5 ± 24.75	186 ± 18.38	249.5 ± 24.75	252.50 ± 7.78
Cl^- (mg/L)	83.75 ± 5.30	48.75 ± 5.30	57.5 ± 7.07	62.50 ± 3.54

Design 2 (COD: 186 ± 18.38 mg/L, Cl^-: 48.75 ± 5.30 mg/L) were lower than in Design 3 (COD: 252.5 ± 7.78 mg/L, Cl^-: 62.5 ± 3.54 mg/L). However, Design 3 showed slightly greater reduction in Turbidity (0.14 ± 0.08 NTU) compared to Design 2 treatments (0.35 ± 0.21 NTU). EC has been recognized as an effective strategy for addressing effluents from pulp and paper mills. According to Öztürk and Özcan (2020), the use of aluminum electrodes achieved a COD removal of as much as 54%, exceeding the performance of chemical coagulation techniques. Building on this, Coimbra *et al*. (2020) demonstrated that EC of kraft pulp bleaching filtrates not only removed up to 88% DOC but also increased biodegradability (BOD/COD) by 1.7–2.1 times, highlighting its role in enhancing subsequent biological treatment while reducing color and toxicity. Further improvements in efficiency were reported with unified EC, achieving high removal of turbidity (94%), TDS (92%), TOC (90%), COD (92%), BOD (87%), and color (98%) while minimizing sludge generation, indicating advantages over conventional EC (Marol and Hugar, 2022). The feasibility of scaling EC for continuous operation was also confirmed, with Al electrodes removing ~80% COD, TOC, TDS, and color under optimized flow conditions (Pandey *et al*., 2025), and hybrid EC–electrooxidation approaches achieving up to 99% turbidity, 100% color, and 90% COD removal with practical energy use (Ozyurt *et al*., 2017). Low current EC further demonstrated energy-efficient pre-treatment potential, achieving >95% color removal, >70% tannin/lignin removal, and improved biodegradability, supporting integration with biological treatment (Wagle *et al*., 2020). Beyond treatment, valorization of pulp and paper wastes into biomaterials illustrates sustainable "waste-to-wealth" strategies (Haile *et al*., 2021), and integrated treatment methods enhance both environmental and economic performance (El-Baz *et al*., 2024). This study, building on recent advancements, is dedicated to optimizing the EC-based treatment of effluent pulp and paper mill, aiming for effective pollutant removal, scalable operation, and energy-efficient methodologies.

Ions and heavy metals concentrations after natural biosorbent treatment by using Designs 2 and 3

Furthermore, the analysis of the EC and waste biomaterial treatment revealed a reduction in COD, turbidity, EC, and hardness values, suggesting that the process is effective in the treatment of the specified wastewater. Tibebe *et al*., (2022), reported that the EC achieved high removal efficiencies for phosphate (97%), turbidity (99%), ECe (89%), total nitrogen (88%), ammonia (87%), and BOD (66%), demonstrating its effectiveness in treating textile industry effluents. In addition, Akinlabi *et al*., (2025) demonstrated that a bipolar EC reactor with Al electrodes effectively removed turbidity, color, BOD, COD, TSS, and TDS from textile and cassava wastewaters, though odor removal remained moderate. Concentric Al-tube EC reactor effectively reduced TDS, TSS, HCO_3^-, Cl^-, and calcium (Ca^{2+}) in real oily saline wastewater, highlighting its potential as a pre-treatment method for high-salinity industrial effluents (AlJaberi *et al*., 2020). Effluents originating from the pulp and paper industry, along with other intricate liquid wastes, ought to be processed utilizing EC and waste biomaterial methods. The reduction in turbidity, COD, ECe, and hardness during EC demonstrates the effectiveness of the technique. The sludge generated during the treatment process was discovered to contain valuable nutrients suitable for reprocessing (Kumar and Sharma, 2022). The applied current, electrolyte concentration, and pH influenced the removal efficiencies of COD, turbidity, and ECe, and sludge production rate. The EC utilizing Al–Fe electrodes is proposed as a viable and cost-effective approach for effluent treatment. The treatment time of 45 min was optimal. The inter-electrode distance of 4 cm was more favorable for metal removal. Fe–Al rods and plates both treated

Table 8: Ions and heavy metals (mg/L) concentrations of the treated effluent after EC and natural biosorbent treatment by using Design 2 and 3

Parameters	Ions	Design 2		Design 3	
		Treatment Unit 5 (Biosorbent)	Treatment 5 (Biological)	Treatment Unit 3 (Biological)	Treatment Units 4,5 and 6 (Biosorbents)
		For 30 min	For 24 h	For 24 h	For 30
Anions (mg/L)	F^-	55.00	47.00	44.69	23.85
	Cl^-	159.52	149.90	133.19	67.89
	NO_2^-	5.60	6.40	14.36	3.56
	SO_4^{2-}	45.00	28.00	102.42	69.33
	PO_4^{3-}	34.00	39.00	66.14	45.78
Cations (mg/L)	Li^+	3.51	2.58	3.54	1.54
	Na^+	82.52	54.02	78.45	69.25
	NH_4^+	17.73	7.67	22.64	15.88
	K^+	17.9	9.05	79.42	52.64
	Mg^{2+}	64.02	49.13	146.5	91.7
	Ca^{2+}	60.1	29.57	102.4	46.03
Heavy metal content (mg/L)	Cr^{3+}	3.06	2.81	3.71	1.20
	Pb^{2+}	1.35	1.17	1.82	0.65
	Ni^{2+}	0.57	0.17	0.47	0.30
	Zn^{2+}	0.21	0.18	0.17	0.36

Table 9: Overall reactions during EC

1)	Anodic reaction	$Al(s) \rightarrow Al^{3+}(aq) + 3e^-$
2)	Cathodic reaction	$3H_2O + 3e^- \rightarrow 3OH^-(aq) + 3/2H_2(g)$
3)	Overall reaction	$Al^{3+}(aq) + 3OH^-(aq) \rightarrow Al(OH)_3(s) + 3/2H_2(g)$

the effluent efficiently after 45 min, where Fe–Al plates proving more effective than the rods in this combination. Table 8 presents the concentrations of major ions and heavy metals (mg/L) in the treated effluent following electrocoagulation and natural biosorbent treatment using Designs 2 and 3, enabling a comparative assessment of treatment performance across both experimental designs. From Table 8, it may be found that, Using Design 2, a clear reduction in major anions and cations, including fluoride (F^-), Cl^-, Na^+, Ca^{2+}, lithium (Li^+) and magnesium (Mg^{2+}), was observed after biological treatment when compared with biosorbent treatment. Significant decreases in ammonium (NH_4^+), potassium, and calcium concentrations indicated effective nutrient removal. Heavy metals such as Cr^{3+}, Pb^{2+}, and Ni^{2+} were also substantially reduced, demonstrating improved metal control following biological treatment. Similarly, in Design 3, most anions and cations exhibited a declining trend after biological treatment, with notable reductions in F^-, Cl^-, sulfate (SO_4^{2-}), phosphate (PO_4^{3-}). Cations including Mg^{2+}, Ca^{2+}, NH_4^+ also showed improvement; however, their concentrations remained comparatively higher than those observed in Design 2 in several cases. The levels of heavy metals, especially chromium and lead, were diminished; however, the performance remained relatively moderate in comparison to Design 2. Huang *et al*., (2020) reported that Cl^- ions enhance Al floc formation and improve the removal efficiency of Cu^{2+} and Ni^{2+} removal during electrocoagulation. Additionally, Kim *et al*. (2020) showed that electrocoagulation utilizing Fe and Al electrodes effectively removed Cu, Ni, Zn, and Cr from metal plating wastewater, with Fe electrodes exhibiting higher efficiency and alkaline pH favoring metal hydroxide precipitation, while cyanide presence inhibited Ni removal. The ion treatment of PCB wastewater, achieving concentrations below 1 mg/L within three min. It was recorded that weight of the Al rods/plates was changed enough after EC. Anode dissolution is greater with rise in the current density according to the law of Faradays (Yu *et al*.,2021). Conversely,

Table 10: Significant factors across all tests

S. No	Parameter	Material significant	Geometry significant	Interaction significant
1	pH	Yes (p=0.019)	No	No
2	Turbidity	Yes (p<0.001)	No (p=0.058)	Yes (p=0.032)
3	ECe	Yes (p=0.048)	Yes (p=0.009)	No
4	TDS	No	No	No
5	COD	No	No	No
6	Hardness	Yes (p<0.001)	Yes (p=0.011)	No

aluminium hydroxide generated during the EC process eliminates the ions and organic substances, capturing the dissolved contaminants that precipitate, thereby resulting in a minor increase in the efficiency of COD removal (Phu *et al*., 2025). To make Al cation, Al anodes are utilized. These forms hydroxylated species. Reactions that occur through the EC with the use of Al electrode are shown in Table 9 (Shirkoohi *et al*.,2022; Choteau *et al*.,2020). As the distance between the electrodes decreases, the electrical resistance of the system diminishes, which in turn facilitates better current flow between the electrodes (Zuo *et al*., 2023). A decrease in inter-electrode spacing makes the ions migration time in the EC cell shorter, hence leading to high cleaning capability through a reduced working duration (Mousset *et al*., 2024). The existing density may be diminished as a function of the precipitation and the loss of metallic ions throughout the treatment process (Yang *et al*., 2023). However, the ECe of the solution remains largely unchanged due to the continued presence of dissolved salts and ionic species in the water solution (Shcherbakov *et al*., 2021). The specially designed EC designs after post-treatment filtration using low-cost natural adsorbents showed improved treatment efficiency for paper mill industrial effluent. Moreover, additional categories of industrial wastewaters can also be effectively managed through the use of the same or adapted biomaterials, presenting a viable, environmentally responsible, sustainable, and considerate approach to wastewater treatment. In other similar technological advances, wastewater and polluted drinking water can be employed for electroporation-based techniques (Huo *et al*., 2022). EC represents a treatment approach that is akin to others, yet it is distinct in that it refrains from adding chemical coagulants to the wastewater. This method relies on an electrochemical process, using an electric current to extract contaminants (Shahedi *et al*., 2020; Padmaja *et al*., 2020; Akhter *et al*., 2021). EC in combination with electroporation and electrochemical oxidation combines both irreversible and reversible processes of electroporation (Pi *et al*., 2022). Table 10 summarizes the primary findings and statistical interactions essential for optimizing the treatment process.

Significant drivers of treatment efficiency

Material selection was the primary driver of water chemistry changes, showing high significance ($p < 0.001$) for turbidity and hardness removal where the Fe–Al (Mix) electrodes achieved the lowest average values (~0.7 NTU and 347 mg/L). This bimetallic configuration also significantly influenced effluent stability ($p = 0.0186$) by maintaining a higher pH (~6.0), suggesting an inherent electrolytic buffering mechanism. Additionally, material choice impacted ECe ($p = 0.0476$), with Fe-based systems exhibiting higher residual ECe levels than Al–Al configurations due to differential ionic release.

The role of electrode geometry

While geometry was secondary for most parameters, it was a critical factor for ECe (p =

0.0087) and Hardness (p = 0.011). Plates consistently resulted in higher ECe values across all materials. In Al-Al and Fe-Fe systems, Rods typically resulted in much higher hardness levels, whereas Plates were more successful in preserving lower hardness levels.

Critical interaction effects (material × geometry)

A significant interaction effect was observed only for Turbidity (p = 0.0316). This signifies that the effect of geometry is contingent upon the material utilized. In Al-Al and Fe-Al systems, geometry had negligible effects on turbidity. In Fe-Fe systems, geometry was decisive: Rods dramatically reduced turbidity (1.24) compared to Plates (4.38).

Non-significant parameters (TDS and COD)

Interestingly, neither material nor geometry exerted a significant influence on TDS (p = 0.92) or COD (p = 0.62). The considerable residual error present in these models implies that, concerning these parameters, the efficiency of removal could be determined by operational factors (for instance, current density or reaction time) instead of the physical setup of the electrodes. Fe-Al (mixed) electrodes are recommended for superior turbidity removal and hardness control. Plate geometry should be prioritized if the objective is to minimize hardness in mono-metallic systems. Fe-Fe rods represent a specific niche optimization for turbidity reduction if mixed-metal systems are unavailable.

CONCLUSION

In conclusion, the findings of the research suggest that the integration of EC with filtration utilizing waste biomaterials represents an efficient method for treating wastewater. The integrated technology proved highly efficient in reducing key pollution indicators. Significant decreases in COD, TDS, and ECe demonstrate the effectiveness of the specially designed treatment units in improving effluent quality. Each phase of treatment serves a distinct purpose—EC destabilizes contaminants, adsorption seizes leftover organics, and biological treatment further breaks down substances, enhancing the efficiency of pollutant removal. The proposed EC–biomaterial system achieves comparable pollutant removal effectiveness and more steady operational performance. EC involves the application of an electric current to aqueous media containing suspended, emulsified, or dissolved pollutants, promoting their aggregation and subsequent separation. The process is characterized by a high level of environmental compatibility, primarily due to low sludge generation and reduced requirements for chemical additives. EC has proven to be environmentally efficient, technically feasible, and economically viable for the treatment of toxic industrial-scale wastewater. Large-scale implementation is expected to reduce operational costs compared to laboratory studies. In this context, the EC–biomaterial filtration system using Fe–Al electrodes combined with natural filters such as waste tea powder and wooden peels proved effective for treating pulp and paper mill effluents. The selected biomaterials are eco-friendly and can be reused multiple times, necessitating only simple drying and mild washing, which allows them to maintain their adsorption efficiency. The ionic composition affects EC by modifying solution conductivity and coagulant formation, which in turn governs treatment efficiency. The Fe–Al electrode combination at neutral pH (pH 7) exhibited superior performance compared to other electrode and biomaterial combinations tested. An electrode gap of 4 cm was identified as optimal for achieving a balance between enhanced metal removal, uniform current distribution, and efficient mass transfer within the EC cell. The study further suggests that scaled up or modified EC assemblies, incorporating novel design parameters and eco-friendly adsorbent materials, can be effectively applied for the treatment of complex industrial wastewaters. The processed effluent complies with regulatory discharge standards and is appropriate for internal recycling; however, the

presence of specific mixed pollutants requires additional verification for irrigation purposes. The study's limitations include the variabilities in energy consumption during EC, variable sludge characteristics, microbial survivability, and on-field scale-up uncertainties. In addition, scaling up the specially designed units presents challenges mainly prolonging electrode life, and prevention of biomaterial clogging to maintain stable operations. The integrated treatment system demonstrated its robustness during prolonged operation, consistently delivering performance even in the face of certain limitations. The proposed system offers environmental benefits by minimizing chemical use, lowering carbon footprint, and valorizing waste-derived eco-friendly materials for pollutant removal.

AUTHOR CONTRIBUTIONS

A.J. Mahdi designed and conducted the experiments, performed data analysis, and finalized the results. M.M. Alqazzaz assisted in experimental work, data analysis, and contributed to manuscript drafting and revision. A.V. Mane conceptualized and supervised the study, prepared the original draft of the manuscript, interpreted the results, and was responsible for critical review, editing, and finalization 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, 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
µS	Micro Siemens
AAS	Atomic absorption spectrophotometer
NH_4^+	Ammonium
Al	Aluminium
Al-Al Plates	Aluminium plates

Al-Al Rods	Aluminum rods
BOD	Biochemical oxygen demand
Ca^{2+}	Calcium
$Ca(OCl)_2$	Calcium hypochlorite
Cl^-	Chloride
COD	Chemical oxygen demand
Cr^{3+}	Chromium
Cu^{2+}	Copper
EC	Electrocoagulation
ECe	Electrical conductivity
F^-	Fluoride
Fe	Iron
Fe-Fe Plates	Iron plates
Fe-Fe Rods	Iron rods
h	Hour
H_2O_2	Hydrogen peroxide
HCl	Hydrochloric acid
K^+	Potassium
Li^+	Lithium
Mg^{2+}	Magnesium
mg/L	Milligram per Liter
g/L	gram per liter
mL	Milliliters
mL/L	Milliliters per liter
µm	micrometers
Na^+	Sodium
Ni^{2+}	Nickel
NO_2^-	Nitrite
N	Normal solution
NTU	Nephelometric turbidity unit
PAC	Powdered activated carbon
Pb^{2+}	Lead
pH	Potential of hydrogen
PO_4^{3-}	Phosphate
rpm	Revolutions per minute
Ag_2SO_4	Silver sulfate
SO_4^{2-}	Sulfate
TDS	Total dissolved solids
TS	Total solids
TSS	Total suspended solids
V	Volt
Zn^{2+}	Zinc

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ORIGINAL RESEARCH PAPER

Green supply chain management in big data analytics and competitive advantage in the energy sector

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ABSTRACT

BACKGROUND AND OBJECTIVES: The global move toward sustainability, supported by national plans like Saudi Vision 2030, requires the combination of new technologies with environmental planning. The analysis of big data has the potential to enhance environmental performance; however, the precise methods by which it contributes to establishing a green competitive advantage remain largely unclear. This is especially true for the renewable energy sector during changing market conditions. The study objectives were to explain the connections between big data analytics and green competitive advantage. This study investigates the direct impact of big data analytics on achieving a green competitive advantage, while also exploring the contributions of green supply chain management and green human resource management in this relationship. It also tests how market turbulence changes these relationships within Saudi Arabia's renewable energy industry.

METHODS: A quantitative method was used. Data were collected via questionnaire given to 420 employees working in Saudi renewable energy companies. The conceptual framework for the study is established utilizing the resource-based view in conjunction with capabilities theory. Partial least squares structural equation modeling was applied to assess direct, mediating, and moderating effects simultaneously.

FINDINGS: The analysis indicates that big data analytics have a substantial positive direct influence on competitive green advantage, while also enhancing both green human resource management and green supply chain management. Green human resource management significantly mediates the relationship between big data analytics and green competitive advantage, whereas green supply chain management exhibits a negative mediating effect, suggesting implementation-related challenges in the studied context. Furthermore, market fluctuations reinforce the association between green supply chain management and green competitive advantage, whereas diminishing the link between green human resource management and green competitive advantage.

CONCLUSION: The findings confirm that big data analytics represents a critical organizational capability for achieving a competitive green advantage; however, its effectiveness depends on the nature of internal green management practices and external market conditions. The study underscores the significance of synchronizing digital investments with effective green human resource strategies, while also meticulously reevaluating green supply chain initiatives. These insights provide practical guidance for managers and policymakers seeking to leverage data-driven technologies to support sustainability objectives in line with Saudi Vision 2030.

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INTRODUCTION

Big data has become a reality that must be addressed as one of the most important resources for companies today. If handled appropriately and without bias, it greatly enhances both economic and social progress (Sangpetch and Ueasangkomsate 2023; Guilhem and Klein, 2024; Singh *et al.,* 2025). Leveraging big data can bolster and improve decision-making by elevating the quality of the data gathered, which subsequently enhances the decisions made by managers, ultimately supporting and improving the financial performance of business organizations (Du and Lv, 2024; Rashid *et al.,* 2024; Tetteh *et al.,* 2025). Furthermore, it tracks all changes that take place, providing a precise representation of the physical world and fostering competition based on innovation rather than solely on products (Mousa *et al.,* 2025a). Today, data is considered a key asset of companies through which they seek to achieve increased operational efficiency, risk management, and investment efficiency to achieve a green competitive advantage (GCA) (Mehmood *et al.,* 2025; Mousa *et al.,* 2025a). Since big data holds great potential to generate useful insights regarding the production and consumption aspects of the entire business cycle (Riggs *et al.,* 2023; Mehmooda *et al.,* 2025), it can be leveraged to understand the requirements and processes of each stage in this cycle, thus streamlining and creating sustainable business systems to achieve GCA for organizations, becoming more vital in daily lives (Awan *et al.,* 2021; Guilhem and Klein, 2024). Consequently, this study intends to evaluate the influence of big data analysis (BDA) on green supply chain management (GSCM) and green human resource management (GHRM) in the pursuit of achieving GCA. Studying big data in green fields is gaining increasing importance due to the potential it provides for understanding environmental patterns, making more sustainable decisions, and enhancing commitment to environmentally friendly practices. The COVID-19 pandemic has resulted in the most significant global catastrophe in recent decades, adversely affecting health systems and the economies of societies globally (Das *et al.,* 2024; Gupta *et al.,* 2024). Amid the COVID-19 pandemic, the industrial sector witnessed disruptions in GSCM worldwide (Jalil *et al.,* 2024). The study by Belhadi *et al.* (2023) recommended guiding companies to effectively adopt big data analytics (BDA) to enhance their environmental performance considering the global shift towards sustainability and a green economy (Song *et al.,* 2023). The Saudi Vision 2030 outlines a strategic plan aimed at diversifying the national economy beyond oil, clearly recognizing the existing lack of development in a competitive renewable energy sector. This context offers a critical and unique research setting for analyzing the rapid, policy-driven development of a green energy sector within an economy historically centered on oil. Investigating the link between sophisticated technological capabilities, including BDA, and innovative green operational practices, specifically GSCM and GHRM, yields new insights for developing economies experiencing sustainable transitions (Mehmood *et al.,* 2025; Mousa *et al.,* 2025a). Despite growing recognition of the "green transformation," empirical evidence indicates that the adoption of BDA technologies to specifically enhance GSCM and GHRM remains limited and insufficiently studied, particularly within this high-priority sector (Al-Khatib, 2023; Rashid *et al.,* 2024). In order to fill this gap, the study formulates a comprehensive conceptual framework based on dynamic capabilities (DC) Theory and the resource-based view (RBV). It positions BDA not merely as a tool but as a higher-order dynamic capability (Teece *et al.,* 2016) essential for configuring green resources**.** The study specifically investigates the unresolved question of how BDA translates into GCA through the concurrent, yet distinct, mediating pathways of GHRM and GSCM (Yoshikuni *et al.,* 2025). Furthermore, it highlights market turbulence (MT) as a significant moderating factor, investigating a boundary condition that is often disregarded in the green management literature within developing economic environments (Alghamdi *et al.,* 2024; Pratono, 2024; Wu *et al.,* 2024). This

approach theoretically advances green transformation understanding by examining how the efficacy of dynamically configuring BDA with green practices is externally influenced by market conditions, thereby extending the RBV and DC frameworks into the green domain (Dubey *et al.,* 2021). Therefore, this study aims to identify the importance of big data analysis in green human resource management (Sobaih, 2019), green supply chain management, and Green competitive advantage by confronting market disruptions. Thus, the study problem can be solved by answering the question: Is there an impact of big data analysis on green supply chain management, green human resource management, and green competitive advantage? Do green supply chain management and green human resource management mediate the relationship between big data analysis, green supply chain management), and green competitive advantage? Does market turbulence modify the relationship between green human resource management and green supply chain management on green competitive advantage? This study was conducted in Kingdom of Saudi Arabia, in 2025.

MATERIALS AND METHODS

General theoretical design

Theory of dynamic capabilities

Theory of DC provides a robust framework for understanding how organizations respond to environmental uncertainty and MT (Teece, 2018a; Wu *et al.,* 2024). Differing from static perspectives that stress the importance of resource ownership, this theory centers on the capabilities of firms to detect opportunities and threats, take advantage of strategic options, and adjust resources in light of environmental change (Teece, 2018b; Warner *et al.,* 2019). In contemporary business environments characterized by rapid technological change, intensified competition, and increasing regulatory pressure, DC play a critical role in enabling long-term sustainability and strategic adaptation (Wang and Ahmed, 2007). In environments characterized by elevated MT companies that do not possess these capabilities face the dangers of strategic inflexibility, diminishing performance, or potentially exiting the market (Wang *et al.,* 2024; Mousa *et al.,* 2025a). Recent studies suggest that analytics-driven capabilities enhance firms' capacity to transform environmental disruptions into opportunities for innovation and growth, thereby sustaining competitive advantage despite uncertainty (Teece *et al.,* 2016). In this study, BDA is conceptualized as a dynamic capability that supports organizational learning, real-time decision-making, and adaptive responses to MT, particularly in sustainability-oriented contexts.

Theory of resource-based view (RBV)

The RBV posits that firms achieve competitive advantage by possessing valuable, rare, inimitable, and organizationally embedded resources. From this perspective, BDA represents a strategic resource that enhances firms' ability to deploy and amplify other internal capabilities, including GSCM and GHRM (Atobishi and Podruzsik, 2025). By leveraging BDA, organizations can improve environmental operational efficiency, forecast demand fluctuations, support real-time decision-making, and enhance coordination across green initiatives (Yu *et al.,* 2021). Importantly, RBV suggests that analytics capabilities do not generate competitive advantage in isolation; rather, they enhance the value of complementary organizational resources. This study broadens the scope of RBV by merging it with DC theory, contending that enhanced analytical competencies, such as BDA, are required but not adequate for securing a green competitive advantage. In turbulent and regulation-intensive environments, firms must not only possess analytics resources but also effectively align them with organizational practices such as GSCM and GHRM to translate data into sustainable strategic outcomes (Chen *et al.,* 2023; Dubey *et al.,* 2021; Mousa *et al.,* 2025b; Wamba *et al.,* 2017).

Green competitive advantage

GCA refers to a firm's ability to achieve superior market performance through environmentally responsible strategies that are difficult for competitors to imitate (He and Wang, 2023; Vehbi *et al.,* 2025). Organizations that adeptly incorporate environmental innovation with their strategic positioning can bolster their corporate image, reach new markets, and secure enduring competitive benefits (Zameer *et al.,* 2022; Astuti and Datrini, 2021). In the contemporary business environment, environmental regulation has evolved from a compliance mechanism into a strategic driver of innovation and competitiveness. Companies that actively embrace environmentally friendly technologies and practices are in a stronger position to reap the rewards of regulatory backing, stakeholder confidence, and new prospects in clean and sustainable sectors (Ali *et al.,* 2020; Soto *et al.,* 2025; Rahman *et al.,* 2026).

Hypothesis development

The impact of BDA on GCA

BDA refers to an organization's capability to process large volumes of diverse and high-velocity data and transform them into valuable insights that support strategic decision-making (Gupta *et al.,* 2019; Zhu, and Yang, 2021). In contexts focused on sustainability, BDA empowers companies to oversee resource usage, monitor environmental emissions, and enhance operational processes in real time, thereby supporting environmentally responsible strategies and cost efficiencies (Dubey *et al.,* 2021; Bag *et al.,* 2020). Prior studies suggest that BDA enhances firms' ability to identify green market opportunities, understand environmentally conscious customer preferences, and develop sustainable products and services that strengthen competitive positioning (Wamba *et al.,* 2020). Empirical evidence further suggests that analytics-based insights encourage green innovation, which is a vital route to sustainable performance and long-term competitiveness (Cui *et al.,* 2021; Dubey *et al.,* 2023; Nilashi *et al.,* 2025; Haylemariam *et al.,* 2025). Therefore, the following hypothesis was derived.

H1: BDA has a positive impact on GCA

The impact of BDA on GHRM

BDA plays an increasingly important role in supporting GHRM by enabling organizations to collect, integrate, and analyze employee-related and organizational behavior data to support sustainability-oriented decision-making (Awan *et al.,* 2021; Khan *et al.,* 2024). Organizations can utilize workforce analytics to enhance green training, performance assessments, employee engagement, and motivation in accordance with environmental objectives (Renwick *et al*., 2013; Yong *et al*., 2020). Prior empirical studies demonstrate that BDA significantly supports the implementation of GHRM practices by improving information transparency, managerial control, and evidence-based human capital development (Mahmood *et al.* 2023; Gallo *et al.,* 2023; Teece *et al.,* 2016). In light of this, the subsequent hypothesis was formulated.

H2: BDA has a positive impact on GHRM

The impact of BDA on GSCM

BDA has been widely recognized as an important enabler of GSCM. It enhances firms' information-processing capacity by integrating environmental data across procurement, logistics, production, and supplier networks (Shi *et al.,* 2023). By minimizing information asymmetry and enhancing forecasting precision, analytics-based systems facilitate environmental monitoring, energy efficiency, and waste reduction throughout the supply chain (Belhadi *et al.,* 2023; Gallo *et al.,* 2023). Empirical studies consistently indicate a favorable correlation between BDA and green supply chain practices, including green integration, supplier collaboration, and environmental performance (Al-Khatib, 2023; Benzidia *et al.,* 2021; Gallo *et al.,* 2023; Mehmooda *et al.,* 2025; Rashid *et al.,* 2024). Taking this into account, the ensuing hypothesis was established.

H3: BDA has a positive impact on GSCM

The impact of GHRM on GCA

GHRM represents a collection of organizational policies and practices that strive to enhance employees' awareness of environmental matters, their skills, motivation, and participation in sustainability initiatives (Mustafa *et al.,* 2024; Soto *et al.,* 2025). From a DC' perspective, human capital represents a critical micro-foundation through which firms transform strategic resources into competitive outcomes. Prior studies present substantial evidence indicating that GHRM positively impact GCA by promoting environmental innovation, the strengthening of employee commitment, and the advancement of organizational learning (Ayyash and Mousa, 2025; Mustafa *et al.,* 2025; He and Wang, 2023; Shaikh *et al.,* 2026). Considering this, the next hypothesis was derived.

H4: GHRM has a positive impact on GCA

The Impact of GSCM on GCA

GSCM refers to the integration of environmental considerations into supply chain processes, including sourcing, logistics, and collaboration with suppliers (Theeraworawit *et al.,* 2022). The literature generally suggests that GSCM enhances competitive advantage by reducing resource consumption, improving efficiency, and strengthening environmental reputation (Abdallah *et al.,* 2024; Theeraworawit *et al.,* 2022; Gelmez *et al.,* 2024). Nonetheless, the efficacy of GSCM might be influenced by contextual elements including sector maturity, supplier preparedness, and regulatory demands. In emerging or highly regulated contexts, green supply chain initiatives may initially increase operational complexity and costs, potentially limiting their immediate contribution to competitive advantage (Zhu *et al.,* 2023). Thus, the following hypothesis was derived.

H5: GSCM has a significant impact on GCA

The role of MT in moderating the link between GSCM and GCA

MT reflects the degree of unpredictability and rapid change in customer preferences, technologies, and competitive conditions (Dubey *et al.,* 2021). In challenging circumstances, organizations encounter heightened demands to modify their supply chain frameworks, sourcing approaches, and coordination systems. Prior research suggests that the effectiveness of green supply chain practices is contingent upon environmental dynamism, as turbulence amplifies the importance of flexibility, responsiveness, and real-time coordination (Singh *et al.,* 2025; Khan *et al.,* 2024). This emphasizes the crucial function of flexible sourcing strategies that facilitate the reorganization of operations. Therefore, MT is expected to influence the strength of the relationship between GSCM and green competitive advantage. Considering this, the next hypothesis was derived.

H6: MT moderates the positive link between GSCM and GCA.

The role of MT in modifying the link between GHRM and GCA

MT also shapes the effectiveness of human-centered organizational practices. While GHRM supports sustainability through employee development and engagement, highly turbulent environments may disrupt long-term human resource initiatives due to uncertainty, job insecurity, and rapid operational changes (Islam *et al.,* 2025; Raouf and Esmaeel, 2025). Although some studies suggest that turbulence enhances the strategic value of adaptive human capital (Zhou *et al.,* 2024; Shaikh *et al.,* 2026). Some suggest that high levels of volatility could diminish the effectiveness of HR-related practices on performance outcomes. Accordingly, this study examines the moderating role of MT without assuming its direction. Considering this, the following hypothesis was derived.

H7: MT moderates the link between GHRM and GCA.

GSCM as a Mediating Variable between BDA and GCA

Previous studies (Dubey *et al.,* 2021; Yoshikuni *et al.* 2025) propose that GSCM may mediate the

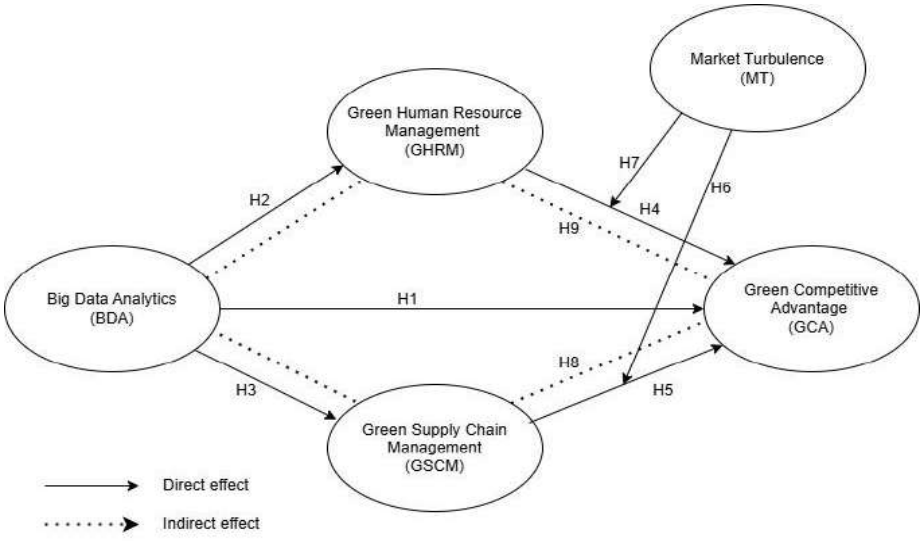

Fig. 1: The research model

relationship between BDA and GCA by translating analytics-driven insights into operational sustainability outcomes. However, this mediation assumes sufficient maturity and integration of green supply chain practices. In scenarios where the implementation of GSCM is largely motivated by compliance requirements or where operational capabilities are underdeveloped, its role as a mediator may be constrained. Therefore, this study empirically examines the mediating role of GSCM without presuming a positive mediation effect Considering this, the following hypothesis was derived.

H8: GSCM mediates the link between BDA and GCA.

GHRM as a mediating variable between BDA and GCA

GHRM is expected to serve as an important internal mechanism through which BDA capabilities are converted into green competitive advantage. Moreover, the successful integration of data-driven insights provided by BDA is significantly dependent on the skills, awareness, and motivation of employees to foster sustainable decision-making and practices (AlNuaimi *et al.,* 2021; Liu *et al.,* 2025). Empirical evidence suggests that organizations with strong GHRM practices are better able to leverage analytics capabilities to enhance environmental performance and competitive outcomes (Yong *et al.* 2020; Dubey *et al.,* 2021). Considering this, the following hypothesis was derived.

H9: GHRM mediates a positive link between BDA and GCA.

The proposed research model depicted in Fig. 1 reveals the direct impact of BDA on green competitive advantage, the mediating roles of GHRM and GSCM, along with the moderating role of MT.

Research design

This study utilizes a quantitative, cross-sectional research framework to investigate the aforementioned relationships. A structured questionnaire was used as the primary data collection instrument. The measurement adopted Likert's' Scale, where 1 = strongly disagree and 5 = strongly agree. Fig. 1 depicts the conceptual framework of this study, which includes an independent variable (BDA), a dependent variable (GCA), a mediating variable (GSM and GHRM), and a moderating variable (MT).

Table 1: Demographic backgrounds of the participants

Demographic data	Frequency	Percent (%)
Gender		
Male	289	68.8
Female	131	31.2
Total	420	100.0
Age		
From 18 to below 28 years	63	15.0
From 28 to below 38 years	105	25.0
From 38 to below 48 years	147	35.0
Above 48 years	105	25.0
Total	420	100.0
Working years		
1to Less than 4 years	101	24.0
4 to less than 8 years	167	39.8
8 to less than 12 years	102	24.3
12 years and above	50	11.9
Total	420	100.0
Education		
High School and less	88	21.0
Diploma	70	16.7
Bachelor's degree	202	48.1
Higher studies	60	14.3
Total	420	100.0
Job Level in the company		
Senior Level	72	17.1
Middle Level	240	57.1
Junior Level	108	25.7
Total	420	100.0

Note: Percentages may not be exactly 100% due to rounding.

Study sample

To ensure representativeness, respondents with various organizational profiles were invited from Saudi Arabian renewable energy companies, including senior, middle, and junior levels as detailed in Table 1. In aiming to engage employees possessing operational insight, the sample encompasses a variety of viewpoints across organizational hierarchies. From 430 initial responses, 420 valid questionnaires were retained for analysis after removing 10 due to incompleteness or inconsistency (97.7% validity rate). The final sample of 420 exceeds the minimum requirement for partial least squares structural equation modeling (PLS-SEM) analysis (Hair *et al.,* 2019), and its demographic composition across age, gender, education, and job level supports broad representativeness within the sector.

RESULTS AND DISCUSSION

Assessment of measurement model

Structural equation modeling using SmartPLS-4 was adopted to assess the model. T PLS-SEM was selected due to its suitability for complex research models involving mediation and moderation effects, its robustness to non-normal data distributions, and its predictive orientation (Hair *et al*., 2019). The measurement model was evaluated by examining indicator reliability, internal consistency reliability, and convergent and

Table 2: Results of the measurement model

Variable/ sources	Items and Questionnaire questions	Outer loading	VIF	α	CR	AVE
BDA (Mousa *et al.*, 2025b)	1. "The renewable energy sector provides appropriate training for employees to use data analysis tools".	0.879	1.687	0.868	0.872	0.656
	2. "The renewable energy sector uses advanced analytics techniques to enhance decision making".	0.840	1.430			
	3. "In the renewable energy sector, the importance of big data and its analysis enhances the value of the business".	0.738	2.079			
	4. "Managers in the renewable energy sector understand the importance of big data and its analysis in enhancing the value of the business".	0.792	1.926			
	5. "The renewable energy sector provides us with the ability to drill down into information to support root cause analysis and continuous improvement".	0.795	1.490			
GCA (Zhu *et al.*, 2023; Wu *et al.*, 2024)	1. "An environmentally conscious renewable energy sector can achieve cost advantages"	0.807	1.142	0.889	0.892	0.693
	2." By investing in the development of environmentally friendly products, the renewable energy sector can become a market leader".	0.842	2.140			
	3." The renewable energy sector can enter profitable new markets by adopting an environmentally friendly strategy".	0.818	1.442			
	4. "The renewable energy sector can penetrate the market by making existing products more environmentally friendly".	0.893	1.998			
	5. "By reducing the environmental impact of business activities, the quality of products will improve".	0.799				
GHRM (Hawela *et al.*, 2025)	1. "The renewable energy sector provides sufficient training to promote environmental management as a core value in the organization".	0.728	1.888	0.897	0.903	0.661
	2. "The renewable energy sector considers employees' commitment to environmental conservation as part of their performance evaluations".	0.793	1.857			
	3." The renewable energy sector links employees environmentally friendly behavior to rewards and compensation".	0.831	1.896			
	4. "The renewable energy sector encourages employees to submit suggestions for improving the environment".	0.844	1.896			
	5. "Employees are fully aware of the renewable energy sector's commitment to environmental policy".	0.844	1.567			
	6. "The renewable energy sector considers the compatibility between personal identity and environmental management in the recruitment and selection process."	0.818				
GSCM (Mousa *et al.*, 2025a)	1. "The renewable energy sector is implementing green procurement practices".	0.792	2.532	0.885	0.897	0.634
	2. "The renewable energy sector is implementing cross-functional collaboration practices to improve environmental performance".	0.886	2.236			
	3." The renewable energy sector is implementing information systems for the green supply chain".	0.886	1.577			
	4. "The renewable energy sector is implementing green distribution practices".	0.762	2.179			
	5. "The renewable energy sector benefits from reverse logistics systems".	0.721	1.924			
	6. "The renewable energy sector has environmental audit and complaint management programs".	0.776				

MT (Arici and Gok, 2023)	1. "Renewable energy markets are experiencing high and unpredictable price fluctuations".	0.823	2.337	0.890	0.909	0.693
	2. "Competition in the renewable energy sector has become more intense in recent years".	0.899	3.516			
	3. "Market turmoil motivates us to acquire new skills to deal with the ever-changing environment in the renewable energy sector".	0.866	3.024			
	4. "The level of demand for renewable energy products changes suddenly".	0.798	2.025			
	5. "I feel anxious about the ongoing instability in the renewable energy sector".	0.772	1.940			

Note: All constructions were specified as reflective. CR = composite reliability; AVE = average variance extracted.

discriminant validity. The confirmation of indicator reliability was achieved by ensuring that factor loadings surpassed the suggested threshold of 0.70. Internal consistency reliability was assessed using Cronbach's alpha and composite reliability (CR), with all values exceeding 0.70, indicating satisfactory reliability. Convergent validity was established by evaluating the average variance extracted (AVE), with all constructs demonstrating AVE values above 0.50. As shown in Table 2, the criteria were met with alpha coefficients above 0.70, CR values more than 0.70, and AVE values above 0.50, demonstrating convergent validity (Hair *et al.*, 2019). Table 2 demonstrates that the CR values spanned from 0.872 to 0.909, whereas the AVE values extended from 0.634 to 0.693, which confirms the presence of adequate convergent validity. Discriminant validity was assessed using the Fornell–Larcker criterion, which compares the square root of each construct's AVE with its correlations with other constructs. The findings demonstrate that the square roots of the AVE for each construct surpassed their inter-construct correlations, thereby affirming adequate discriminant validity. The results are presented in Table 2 and Fig. 2. In order to examine the potential influence of common method bias, various procedural strategies were employed during the data collection phase, such as guaranteeing respondent anonymity and alleviating evaluation apprehension. In addition, Harman's single-factor test indicated that no single factor accounted for the majority of variance, suggesting that common method bias is unlikely to significantly affect the study results. Discriminate validity was further assessed using the heterotopic-to-monotypic (HTMT) ratio, as recommended by Henseler *et al.,* (2015). As illustrated in Table 3, all HTMT values fell below the conservative threshold of 0.90, which signifies satisfactory discriminant validity among the constructs. In addition, discriminant validity was also confirmed using the Fornell–Larcker criterion, where the square root of each construct's AVE exceeded its correlations with other constructs. The low HTMT values associated with the interaction terms further suggest that there are no multicollinearity concerns in the moderation analysis. Together, these results provide strong evidence of discriminant validity for the measurement model.

Assessment of structural model

The structural model was evaluated using effect size (f^2), coefficient of determination (R^2), and predictive relevance (Q^2), following the guidelines of Hair *et al.,* (2019). The f^2 (Table 4) results indicate that BDA has a moderate effect on GHRM ($f^2 = 0.137$) and a small effect on GSCM ($f^2 = 0.116$). In addition, GHRM exhibits a large effect on GCA ($f^2 = 0.552$), whereas GSCM shows a small effect on GCA ($f^2 = 0.016$). The R^2 (Table 5) indicates that the model accounts for a significant proportion of variance in GCA ($R^2 = 0.690$), signifying robust explanatory strength. The explained variance for GSCM is also high ($R^2 = 0.598$), while the explanatory power for GHRM is relatively modest ($R^2 = 0.104$). The evaluation of Q^2 (Table 6) was conducted through the blindfolding method. The results show strong predictive relevance for GCA

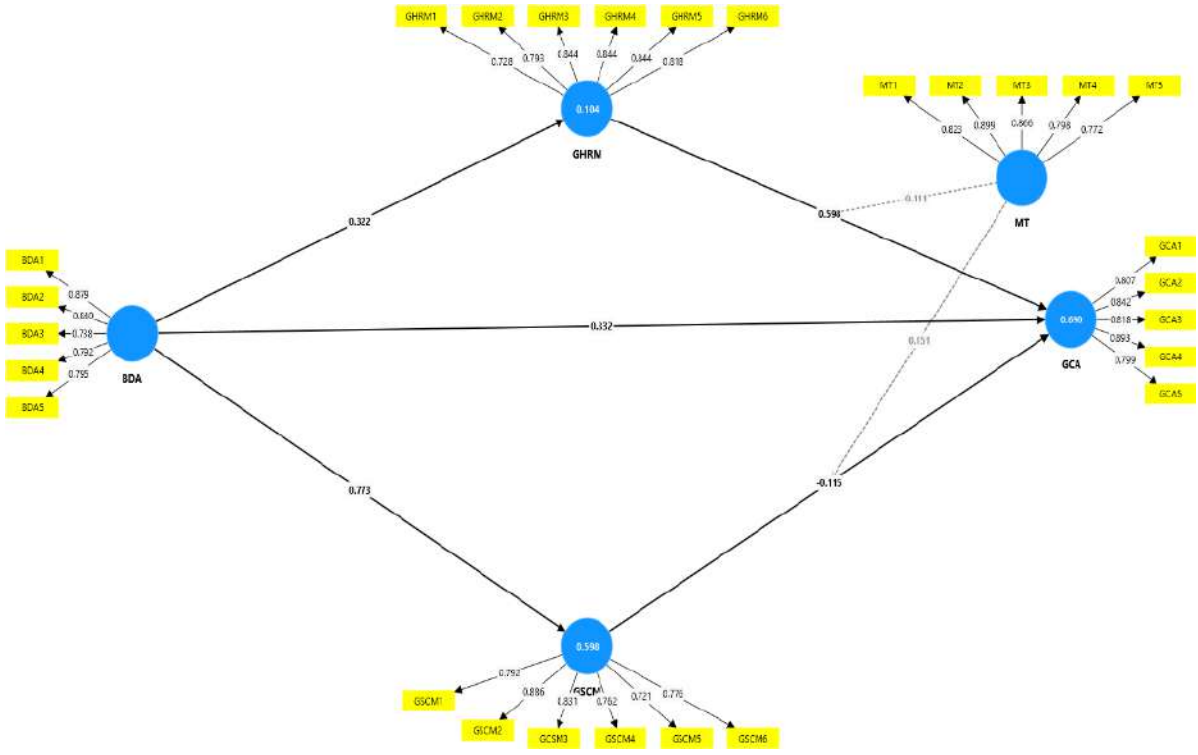

Fig. 2: Measurement model

Table 3: Heterotrait-monotrait ratio (HTMT) and discriminant validity (Fornell- Larcker criterion)

HTMT	BDA	GCA	GHRM	GSCM	MT	MT x GSCM	MT x GHRM
BDA	----						
GCA	0.495	----					
GHRM	0.363	0.871	----				
GSCM	0.866	0.391	0.385	----			
MT	0.072	0.430	0.501	0.081	-----		
MT x GSCM	0.074	0.162	0.059	0.142	0.013	----	
MT x GHRM	0.052	0.429	0.512	0.047	0.255	0.233	-----
Fornell- Larcker criterion	BDA	GCA	GHRM	GSCM		MT	
BDA	0.810	-----					
GCA	0.433	0.833	-----				
GHRM	0.322	0.786	0.813	----			
GSCM	0.773	0.352	0.334	0.796		-----	
MT	-0.050	0.390	0.459	-0.045		0.833	

Note: Diagonal values in panel B represent the square root of AVE

(Q^2 = 0.466) and good predictive relevance for GSCM (Q^2 = 0.366). However, the predictive relevance for GHRM is relatively weak (Q^2 = 0.067), suggesting that while the model explains variance in GHRM, its out-of-sample predictive capability for this construct is limited. Overall, the model demonstrates satisfactory predictive validity, especially concerning the primary outcome variable, GCA (Hair *et al.,* 2019).

Hypothesis testing results

The hypothesis testing results obtained using SmartPLS are presented in Table 7 and Fig. 3. The

Table 4: Effect size (f^2)

Predictor	GCA	GHRM	GSCM
BDA	1.489	0.137	0.116
GHRM	0.552	—	—
GSCM	0.016	—	—
MT	0.021	—	—

Table 5: Coefficient of determination (R^2)

F2							
Construct	GCA	GHRM	GSCM	Construct	R-square	R-square adjusted	Construct	Q2
BDA	0.137	0.116	1.489	GCA	0.690	0.684	BDA	0.000
GCA		-	-	GHRM	0.104	0.101	GCA	0.466
GHRM	0.552	-	-	GSCM	0.598	0.597	GHRM	0.067
GSCM	0.016	-	-	-	-	-	GSCM	0.366
MT	0.021	-	-	-	-	-	MT	0.000

Table 6: Predictive relevance (Q^2)

Construct	Q^2
GCA	0.466
GSCM	0.366
GHRM	0.067
BDA	0.000
MT	0.000

Note: Values of Q^2 greater than zero indicate predictive relevance

results indicate that BDA has a positive and significant effect on GCA (H1: β = 0.332, t = 4.719, p < 0.001). BDA also positively influences GHRM (H2: β = 0.322, t = 5.213, p < 0.001) and GSCM (H3: β = 0.773, t = 29.721, p < 0.001). Furthermore, GHRM has a positive and significant effect on GCA (H4: β = 0.599, t = 10.374, p < 0.001). In contrast, GSCM exhibits a negative but statistically significant effect on GCA (H5: β = −0.116, t = 1.975, p = 0.048). Regarding moderation effects, the interaction between MT and GSCM is positive and significant (H6: β = 0.151, t = 2.935, p = 0.003), indicating that MT strengthens the GSCM–GCA relationship. Conversely, the interaction between MT and GHRM is negative and significant (H7: β = −0.111, t = 2.678, p = 0.007), suggesting that MT weakens the GHRM–GCA relationship. With respect to mediation effects, GSCM does not mediate the relationship between BDA and GCA (H8: β = −0.089, t = 1.953, p = 0.051). However, GHRM significantly mediates the relationship between BDA and GCA (H9: β = 0.193, t = 4.672, p < 0.001). The hypothesis testing results obtained using SmartPLS are presented in Table 7 and Figure 3. The results indicate that BDA have a positive and significant effect on GCA (H1: β = 0.332, t = 4.719, p < 0.001). BDA also positively influences GHRM (H2: β = 0.322, t = 5.213, p < 0.001) and GSCM (H3: β = 0.773, t = 29.721, p < 0.001). Furthermore, GHRM has a positive and significant effect on GCA (H4: β = 0.599, t = 10.374, p < 0.001). In contrast, GSCM exhibits a negative but statistically significant effect on GCA (H5: β = −0.116, t = 1.975, p = 0.048). Regarding moderation effects, the interaction between MT and GSCM is positive and significant (H6: β = 0.151, t = 2.935, p = 0.003), indicating that MT strengthens the GSCM–GCA relationship. Conversely, the interaction between MT and GHRM is negative and significant (H7: β = −0.111, t = 2.678, p = 0.007), suggesting that MT weakens the GHRM–GCA relationship. With respect to

Table 7: Hypothesis testing results: Path coefficients and significance levels

Direct hypothesis	ß-value	SD	T values	P values	2.5%	97.5%	Decision
H1. BDA -> GCA	0.332	0.070	4.719	0.000	0.190	0.466	Supported
H2. BDA -> GHRM	0.322	0.062	5.213	0.000	0.202	0.440	Supported
H3. BDA -> GSCM	0.773	0.026	29.721	0.000	0.721	0.822	Supported
H4. GHRM -> GCA	0.599	0.058	10.374	0.000	0.482	0.708	Supported
H5. GSCM -> GCA	-0.116	0.059	1.975	0.048	-0.225	0.002	Supported (Negative)
H6. MT x GSCM -> GCA	0.151	0.051	2.935	0.003	0.047	0.250	Supported
H7. MT x GHRM -> GCA	-0.111	0.041	2.678	0.007	-0.192	-0.031	Supported (Negative)
Indirect hypothesis	**ß-value**	**SD**	**T values**	**P values**	**2.5%**	**97.5%**	**Decision**
H8. BDA -> GSCM -> GCA	-0.089	0.046	1.953	0.051	-0.177	0.002	Not supported
H9. BDA -> GHRM -> GCA	0.193	0.041	4.672	0.000	0.117	0.278	Supported

Note: Negative coefficients indicate inverse relationships

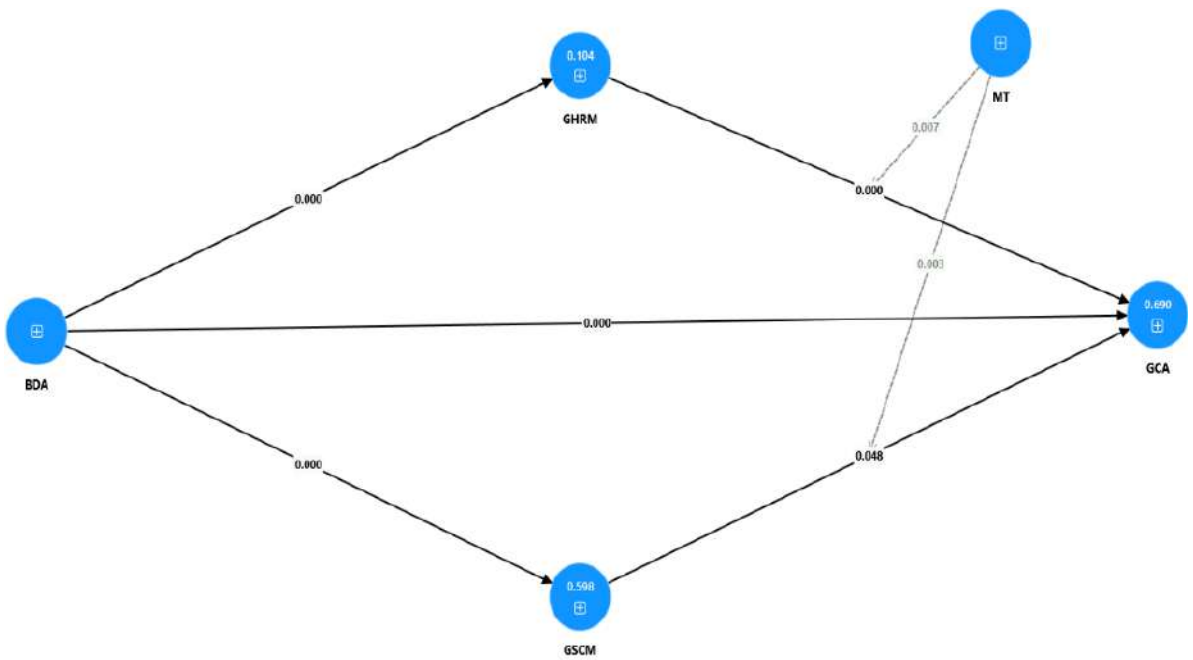

Fig. 3: Structure model

mediation effects, GSCM does not mediate the relationship between BDA and GCA (H8: β = −0.089, t = 1.953, p = 0.051). However, GHRM significantly mediates the relationship between BDA and GCA (H9: β = 0.193, t = 4.672, p < 0.001) (Table 7 and Fig. 3). Fig. 3 illustrates the estimated structural model with standardized path coefficients and significance levels. The structural equation modeling results provide strong support for the hypothesized model. The results of H1 confirm that BDA has a significant positive direct effect on GCA (β = 0.332, p < 0.001), confirming its key role as a strategic asset. The result is consistent with prior literature (Wamba *et al*., 2017; Haylemariam *et al.,* 2025; Nilashi *et al.,* 2025). Furthermore, the results of H2 reveal that BDA has a strong positive effect on GHRM (β = 0.322, p < 0.001). Similarly, the results of H3 show that BDA has a strong positive effect on GSCM (β = 0.773, p < 0.001). These results affirm

BDA's role as an essential facilitator in establishing vital green organizational capabilities, as corroborated by previous studies (Renwick *et al.,* 2013; Gallo *et al.,* 2023; Mahmood *et al.,* 2023; Yong *et al.,* 2020; Das *et al.,* 2024; Mishra *et al.,* 2021; Belhadi *et al.,* 2023; Benzidia *et al.,* 2021; Rashid *et al.,* 2024; Al-Khatib, 2023; Mousa *et al.,* 2025b; Mehmood *et al.,* 2025; Zhu and Yang, 2021). The study reveals divergent mediating pathways of GHRM and GSCM. GHRM demonstrated a strong positive direct effect on GCA ($\beta = 0.599$, $p < 0.001$, H4) and served as a significant positive mediator between BDA and GCA ($\beta = 0.193$, $p < 0.001$, H9). This conclusion is in agreement with prior studies and clarifies how BDA results in a benefit. Specifically, BDA empowers GHRM practices like data-informed green training, performance management, and culture-building. This fosters the development of human capital required to carry out data-driven sustainability strategies, consequently transforming technological capability into a competitive edge (He and Wang, 2023; Shaikh *et al.,* 2026; Mustafa *et al.,* 2024; Yong *et al.,* 2020; Abdallah *et al.,* 2024; Theeraworawit *et al.,* 2022; Gelmez *et al.,* 2024; Zhu *et al.,* 2023). In contrast, GSCM shows a significant negative direct effect on GCA ($\beta = -0.116$, $p = 0.048$, H5) and a negative mediating role ($\beta = -0.089$, $p = 0.051$, H8). This unanticipated result challenges the prevailing opinion from research in mature industries, which typically suggests that GSCM is a positive factor in achieving competitive advantage (Abdallah *et al.,* 2024; Gelmez *et al.,* 2024; Zhu *et al.,* 2023; Yu *et al.,* 2021). Within the burgeoning renewable energy sector in Saudi Arabia, GSCM initiatives discerned through BDA (for instance, green procurement and supplier environmental integration) may function as "rigid" capabilities. Their high initial costs and operational complexity can create a short-term resource drain, offsetting competitive benefits, especially if BDA is deployed primarily for operational efficiency rather than strategic green transformation (Dubey *et al.,* 2021; Awan *et al.,* 2021; Queiroz *et al.,* 2020). This result diverges from research that supports a positive GSCM-GCA link (Chen *et al.,* 2023) and contrasts with findings from other studies (Zhu and Yang, 2021; Al-Khatib, 2023). The moderating role of MT further clarifies this framework. MT significantly strengthened the GSCM-GCA relationship ($\beta = 0.151$, $p = 0.003$, H6) but weakened the GHRM-GCA relationship ($\beta = -0.111$, $p = 0.007$, H7). This dual effect is theoretically consistent, as under turbulence, the dynamic capability of an agile, data-responsive supply chain becomes paramount for resilience, thus enhancing GSCM's value (Pratono, 2024; Singh *et al.,* 2025; Rahman *et al.,* 2026). Conversely, turbulent conditions push companies to focus on short-term operations. This often leads them to deprioritize long-term green HR investments, which weakens the impact of GHRM on GCA. This finding provides a contrasting perspective to some existing studies (Zhou *et al.,* 2024; Jabbour *et al.,* 2015). Consequently, the results of the study are particularly tailored to the context of renewable energy in Saudi Arabia. The outcomes align with worldwide studies regarding BDA and GHRM, but they markedly differ concerning the function of GSCM. This suggests that the connection between technology and competitive advantage is greatly contingent upon the stage of development of the industry and the strategic aims of the organization. The results demonstrated that MT moderates the link between GSCM and GCA and does not affect the relationship of GHRM. The findings highlight the significance of employing BDA in alignment with the goals of Saudi Vision 2030 to secure growth and achieve a competitive edge that promotes both environmental and economic advancement.

The results indicate the availability of changes that affect organizational and technical issues related

to the organizations' adoption to these challenges efficiently, which assure the necessity to the need of developing digital infrastructure and enhance human capabilities to assure the competitive advantages (Amin *et al.,* 2025).

Limitations and future research opportunities

Despite its contributions, this study has several limitations. First, the study utilized a cross-sectional design based on questionnaires, which restricts the capacity to identify causal relationships and temporal changes. Future studies are encouraged to adopt longitudinal designs to examine the evolution of analytics-driven green practices. Second, the empirical context was confined to renewable energy firms operating in Saudi Arabia, which may limit the generalizability of the findings to other sectors or geographic regions. Future studies may broaden this framework to encompass additional sectors, including manufacturing, logistics, or oil and gas, along with various Middle Eastern or emerging economy settings, facilitating comparative analysis. In the third instance, the utilization of a composite measure for GSCM obstructs the investigation into how its particular dimensions (such as, green procurement and logistics) uniquely associate with BDA and GCA. Fourth, future studies may incorporate qualitative methods to gain deeper insights into organizational processes and decision-making mechanisms. Fifth, this study did not explore how factors such as firm size or ownership structure (for instance., state-owned compared to private) might affect the BDA-GSCM relationship, highlighting a significant opportunity for future research. Finally, examining additional mediating or moderating variables such as green innovation, green organizational culture, green governance, leadership styles, or green artificial intelligence (AI) applications could further enrich understanding of how digital technologies contribute to sustainable competitive advantage. Another opportunity of research is to assess how firm size and ownership structure, for example, state-owned versus private, influence the effectiveness of BDAs in GSCM and GCA.

CONCLUSION

The most prominent theoretical contributions are the introduction of a new conceptual model that links the BDA with green practices and demonstrates how technology can support sustainability and competitive advantage, especially the GCA. As previously mentioned in the literature, these factors were not analyzed in conjunction with the moderation role of MT. Additionally, this research expands the scope of RBV theory and the DC Theory by demonstrating how BDA capabilities, as an intangible resource, can enhance green practices and support the achievement of sustainable competitive advantage. It addresses a deficiency in the existing literature concerning the sustainability of Arab startup economies and environments, which currently lacks thorough studies that link BDA with environmentally friendly practices. The findings highlight the differential roles of GHRM and GSCM as underlying mechanisms linking analytics capabilities to green competitive advantage. In particular, the positive mediating role of GHRM and the non-significant mediating role of GSCM suggest that organizational capability maturity represents an important boundary condition in sustainability-oriented research. These findings enhance the expanding body of literature on green management by elucidating the circumstances and mechanisms through which analytics-driven capabilities lead to competitive advantages. From a managerial perspective, the results suggest that investments in BDA should be accompanied by strong GHRM practices to fully realize green competitive benefits. Managers in the renewable energy sector should prioritize green training, performance evaluation, and incentive systems that enable employees to

effectively utilize data-driven insights for environmental decision-making. The detrimental direct influence of GSCM on GCA implies that an early or compliance-driven adoption of green supply chain practices may lead to short-term costs without yielding immediate strategic benefits. Managers should therefore adopt a phased approach to green supply chain transformation, supported by analytics-enabled coordination and supplier capability development, particularly under turbulent market conditions. The current study provides a collection of methodological contributions that aid in the formation of integrated research samples. This includes the design and application of a multidimensional sample that includes mediating variables GHRM and GSCM to understand the mechanisms of the effectiveness of BDA on achieving GCA. It also employs PLS-SEM as an advanced analytical methodology to achieve sounding hypothesized causal connections among variables which enhances trust in results. It additionally fosters further research in applied real context of the Saudi renewable energy sector, which is a burgeoning and lively sector. The findings indicate important policy implications, as they bolster the importance of BDA in GHRM and GSCM for achieving GCA. It is essential for policymakers to increase their focus on digital transformation in the energy sector, particularly on BDA, which has the ability to promote GHRM, GSCM, and GCA, even alongside MT. Investing in BDAs could enable energy sector to achieve competitiveness and ensure business sustainability. Policymakers are encouraged to support digital infrastructure development, analytics capability building, and human capital development within the renewable energy sector. Such assistance has the potential to hasten the effective merging of advanced analytics with sustainability initiatives, which in turn enhances environmental performance and long-term competitiveness. This study examined the role of BDA in achieving GCA through GHRM and GSCM, with MT as a contextual moderator, within the Saudi renewable energy sector. Grounded in the RBV and DC theory, the findings demonstrate that BDA constitute a critical organizational capability that directly enhances GCA and indirectly contributes through GHRM. The outcomes demonstrate that although GHRM successfully converts analytics capabilities into enduring competitive results, GSCM fails to fulfill a positive mediating role in the investigated scenario. This finding suggests that green supply chain practices in the Saudi renewable energy sector may still be in an early or compliance-driven stage, limiting their immediate contribution to competitive advantage. Moreover, MT was found to strengthen the relationship between GSCM and green competitive advantage, while weakening the effect of GHRM, highlighting the contingent nature of sustainability-oriented practices under volatile market conditions. In summary, the study highlights the significance of synchronizing digital transformation efforts with both organizational and human capabilities to attain lasting competitiveness. By providing empirical evidence from a rapidly developing renewable energy market, the research offers valuable insights for organizations and policymakers seeking to integrate advanced analytics with sustainability strategies in line with national development objectives.

AUTHOR CONTRIBUTIONS

M.M. Mousa conceptualized, designed, and conducted the study, performed the formal analysis, and prepared the manuscript draft. I.N. Ayyash contributed to the theoretical framework, data interpretation, and manuscript review. Z. Azzam contributed to survey design, data curation, and manuscript review. A.M. Zamil contributed to research design, hypothesis development, and manuscript review. A.E. Abuelnasr, the corresponding author, supervised the project, acquired funding, interpreted results, and finalized the manuscript. A.E. Sobaih supervised the study, interpreted results,

and revised the manuscript. M.D. AlQahtany coordinated data collection and assisted in analysis. M. Algezawy assisted in literature review 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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During the preparation of this work, the authors used DeepSeek AI to improve the language and clarity of some specific sentences of the manuscript draft. After using this tool, the authors thoroughly reviewed, edited, and fact-checked the AI-assisted content and took full responsibility for the final publication's content, analysis, and conclusions.

ABBREVIATIONS

%	Percent
ß-value	Beta coefficient (Standardized path coefficient)
AI	Artificial intelligence
AVE	Average variance extracted
BDA	Big data analytics
COVID-19	Coronavirus disease 2019
CR	Composite reliability
DC	Dynamic capabilities
f^2	Effect size (Cohen's f-squared)
GCA	Green competitive advantage
GHRM	Green human resource management
GSCM	Green supply chain management
HTMT	Heterotrait-monotrait ratio
MT	Market turbulence
PLS-SEM	Partial least squares structural equation modeling
P values	Probability values
Q^2	Predictive relevance (Stone-Geisser Q-squared)
R^2	Coefficient of determination
RBV	Resource-based view
SD	Standard deviation
T values	T-statistic values
VIF	Variance inflation factor

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ORIGINAL RESEARCH PAPER

Integrating renewable energy based on science, technology, engineering and mathematics projects in promoting sustainable environmental solutions

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ABSTRACT

BACKGROUND AND OBJECTIVES: In environmental science and management, higher education plays a critical role in preparing future professionals capable of designing sustainable energy solutions. Nevertheless, traditional physics education frequently prioritizes theoretical understanding rather than focusing on interdisciplinary and sustainability-driven problem-solving abilities. The primary goals of the study were to analyze the effectiveness of embedding renewable energy-centered science, technology, engineering and mathematics projects into physics education in enhancing students' creativity and their competencies in innovation with an environmental focus. Specifically, the study investigates how project-based learning focused on solar and wind energy systems contributes to productivity, fluency, and originality in creative thinking within a sustainability framework.

METHODS: A quasi-experimental research design was employed involving 58 third-year physics students at Khoja Akhmet Yassawi International Kazakh-Turkish University. The participants were split into two groups: experimental (n = 29) and control (n = 29). Over a 15-week academic semester, the experimental group engaged in interdisciplinary science, technology, engineering and mathematics projects centered on renewable energy system modeling, environmental impact awareness, and applied engineering design solutions. The control group followed traditional lecture-based instruction. The creativity levels of students were evaluated prior to and following the intervention through a structured self-assessment tool that measures productivity, fluency, and originality. Statistical analyses were performed utilizing the statistical package for the social sciences software, including independent samples t-tests and Levene's test to examine group differences and homogeneity of variance.

FINDINGS: Post-intervention results demonstrated statistically significant improvements ($p < 0.05$, probability level of less than five percent) in all measured creativity dimensions among students participating in renewable energy–based science, technology, engineering and mathematics projects compared to the control group. The experimental demonstrated elevated average scores in productivity, fluency, and originality, reflecting a heightened capacity for developing innovative and environmentally sustainable solutions. The results indicate that participation in applied renewable energy initiatives enhances interdisciplinary thinking and fosters sustainability-focused problem-solving skills in physics education.

CONCLUSION: The findings indicate that project-based learning focused on sustainability can act as a powerful educational approach to cultivate the innovative thinking necessary for tackling modern environmental and energy challenges. Although limited to a single institutional context, the results support the incorporation of renewable energy projects into higher education as a pathway to developing environmentally conscious and creative professionals aligned with global sustainability goals.

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INTRODUCTION

Modern education systems in developed countries increasingly integrate economic and environmental sustainability principles into academic frameworks in line with the sustainable development goals (SDGs). In this context, the education of alternative energy has gained prominence as a crucial part of science curricula, and the adoption of science, technology, engineering, and mathematics (STEM) strategies is prevalent to support this integration. The growing climate crisis and the fact that the energy sector produces nearly three-quarters of global greenhouse gas emissions have accelerated the global transition toward renewable energy systems. Furthermore, higher education organizations are accountable not only for promoting scientific understanding but also equipping environmentally skilled individuals to create and manage sustainable energy systems (Wang and Wang, 2023). Developing future professionals in the fields of natural and engineering sciences requires a strong foundation in scientific knowledge, practical skills, and problem-solving abilities. Energy education, in particular, plays a vital role in preparing students to address global challenges in sustainability and industry (Maynard *et al.,* 2021). Renewable energy education is closely linked to the sustainable development goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). Universities are instrumental in realizing these objectives by incorporating sustainability principles into their academic curricula and advocating for environmentally responsible engineering practices. Preparing students to design and implement renewable energy systems supports the development of a skilled workforce for future energy transitions. Although there has been significant progress in renewable energy technologies, a divide persists between the evolution of these technologies and the educational strategies focused on developing sustainability competencies. Students often gain theoretical knowledge about energy systems but lack the creative and problem-solving skills needed to address real environmental challenges. This scenario underscores the necessity for educational frameworks that integrate environmental sustainability with STEM training. STEM-based education provides an effective framework for teaching energy-related subjects. In this study, renewable energy–based interdisciplinary STEM projects were integrated into physics education using principles of constructivist and experiential learning. Students enhance their comprehension by linking new information to their previous experiences and by participating in hands-on experimentation. Therefore, project-based activities in solar and wind energy were designed to involve students in modeling, prototyping, and testing engineering solutions. In this context, physics concepts are applied as tools for solving real sustainability-related problems. In this study, creativity refers to students' ability to generate numerous, fluent, and original ideas. Environmentally oriented innovation competency refers to the ability to transform creative ideas into practical and environmentally responsible solutions aligned with sustainability principles such as energy efficiency and environmental impact awareness. Studies performed in developed countries emphasize the vital contribution that renewable energy technologies will have on future energy usage and economic expansion. To accelerate the transition towards a sustainable society, there is an increasing need to focus on educating future specialists in this field (Said *et al.,* 2022). The Solar Energy Technology Office (SETO), operating under the United States Department of Energy (DOE), actively funds research and development in STEM and education to lower the costs of clean energy technologies, mitigate financial risks for private investors, and support a fair transition to a decarbonized economy (Abdurrahman *et al.,* 2023; Fabregas Villegas and Palencia Díaz, 2025). Several European countries, including Germany, Belgium, and the Netherlands, emphasize the high

energy efficiency of photovoltaic systems. A comprehensive analysis of scientific studies has revealed a statistically significant relationship between the sustained adoption of alternative energy and specialized training in its production and application (Wolniak and Skotnicka-Zasadzień, 2022), (Voss *et al.,* 2023). These studies highlight the effectiveness of problem-based learning (PBL) and design thinking (DT) as pedagogical approaches that enhance critical thinking and practical skills in renewable energy education (Colmenares-Quintero *et al.,* 2023; Shcherbak *et al.,* 2022). At the worldwide scale, many studies highlight the importance of incorporating STEM-based education into solar energy education. Evidence suggests that STEM-focused activities in alternative energy contexts positively influence students' perceptions of integrative STEM education and improve science teachers' attitudes toward STEM-based instruction (Hiğde, 2022). In a similar vein, studies employing both quantitative and qualitative analyses indicate that STEM projects centered around solar energy greatly enhance students' comprehension of STEM concepts, while also promoting meaningful and engaging learning experiences (Mayasari *et al.,* 2019). The review of the aforementioned scientific literature validates the relevance of this research topic. However, despite the growing body of literature, limited research exists on the development and assessment of research-driven and engineering-based activities in alternative energy education. This gap suggests the need for further exploration into how integrated STEM practices can effectively prepare students pursuing engineering and natural sciences. In order to remain competitive with top economies, Kazakhstan has placed a high priority on the development of alternative energy. In his Address to the Nation on September 1, 2023, President Kassym-Jomart Tokayev emphasized the country's commitment to expanding renewable energy. Over the past five years, Kazakhstan has increased the share of renewable energy sources in its total energy capacity by almost 5 percent (%). The government intends to persist in executing renewable energy initiatives, aiming to decrease energy consumption expenses by a minimum of 15% by the year 2029 (Sakibayev *et al.,* 2019). Further research conducted within the framework of the project "Development of the Potential for Innovative Training of Engineers through STEAM Education" (grant No. AP09260338) proposed a conceptual framework for STEAM education. The study emphasized the role of this approach in preparing future technical specialists and outlined strategies for integrating STEAM principles into engineering and science curricula (Jantassova *et al.,* 2022). A comprehensive meta-analysis of recent articles published in high-impact journals emphasizes the contributions of various scholars who have explored the connection between creativity and physics education. These studies have examined how innovative teaching strategies can enhance students' cognitive flexibility, problem-solving abilities, and creativity in physics-related disciplines (Malik *et al.,* 2020), (Zhou, 2012), (Gregorcic and Bodin, 2017), (Siahaan and Simamora, 2023). In the 21st century, creativity has turned into a crucial skill, as employers are increasingly in search of professionals who can think creatively and adjust to the changing demands of Industry 4.0 (Vo, 2024). Preliminary research has identified multiple challenges in this regard, including a lack of creative skills among students, insufficient motivation to engage in creative activities, and the absence of well-defined technologies designed to foster creativity in educational settings (Albishri and Blackmore, 2025). Additionally, many academic programs fail to align creativity-enhancing approaches with subject-specific curricula, limiting their effectiveness. Feedback from employers, alongside survey data, highlights the growing need to equip students with skills relevant to the Fourth Industrial Revolution, both in terms of workforce readiness and entrepreneurial capability. Annual startup contests held by global energy institutions highlight a variety of innovative initiatives designed to decrease reliance on fossil fuels and

revolutionize the worldwide energy infrastructure. Such initiatives not only stimulate research interest among young professionals and aspiring scientists but also encourage the establishment of new research centers and innovation-driven enterprises within higher education institutions (Stupnisky *et al.,* 2023; Kamolteeravit *et al.,* 2026). Nonetheless, the current study stands apart from much of the existing literature in two crucial ways. First, while many previous studies focus primarily on conceptual understanding or attitudes toward STEM learning, this research specifically evaluates creativity outcomes through structured indicators such as productivity, fluency, and originality within the context of renewable energy education. Second, the study situates creativity development within a sustainability-oriented framework, linking renewable energy STEM projects to broader environmental management objectives and sustainable development goals. In this manner, the study enhances the expanding literature that associates the cultivation of creativity in physics education with innovation motivated by sustainability. In line with this study's objectives, integrating STEM methodologies into higher education, modeling alternative energy processes, and implementing STEM projects in renewable energy research create opportunities to explore several key scientific questions:

1) What methods can be utilized to enhance creativity in physics students via an integrated STEM approach?
2) How can complex engineering and mathematical-physical problems in the field of alternative energy be effectively incorporated into academic curricula?
3) What possibilities are available for physics students to participate in classroom and extracurricular STEM projects that can enrich their creative learning experiences?

This study aims to evaluate the effectiveness of integrating renewable energy–based science, technology, engineering and mathematics projects into physics education in enhancing students' creativity and environmentally oriented innovation competencies. This study was conducted at Khoja Akhmet Yassawi International Kazakh-Turkish University in Kazakhstan during the 2024–2025 and 2025–2026 academic years.

MATERIALS AND METHODS

Research design and data collection

To confirm the relevance of the research topic and identify gaps in the existing literature, a systematic review of high-impact peer-reviewed articles was conducted using the Web of Science, Scopus, and Mendeley databases. The reliability of the sources was guaranteed by utilizing Cite Score indicators, and the studies that were collected constituted the theoretical framework for the research and the creation of the research questions. The experimental component also incorporated sustainability-oriented learning tasks, where students analyzed the environmental impact of renewable energy systems, compared solar and wind energy with fossil fuels, and performed energy efficiency and system optimization calculations. This method combined the development of creativity with the principles of environmental management instead of considering it as an isolated cognitive skill.

Research Hypotheses

The hypotheses were formulated to examine the relationship between the independent variable (the STEM approach) and the dependent variables (creativity and environmentally oriented innovation competency).

1. Hypotheses related to differences between groups

H_{01} (null hypothesis): The use of renewable energy–based STEM projects do not produce a statistically significant difference in creativity indicators between the experimental and control groups.

H_{11} (alternative hypothesis): The application of renewable energy-focused STEM initiatives leads to a statistically significant difference in creativity indicators between the experimental and control groups.

2. Hypotheses related to the direction of the effect

H_{o2} (null hypothesis): The STEM approach does not have a positive effect on the level of students' creativity and environmentally oriented innovation competencies.

H_{12} (alternative hypothesis): The STEM methodology significantly enhances students' creativity levels and their competencies in environmentally focused innovation.

Pedagogical experiment and participants

Participants were third-year physics majors enrolled in the same course at Khoja Akhmet Yassawi International Kazakh-Turkish University. The sample illustrated a convenience cohort from one particular institution. Group assignment followed a quasi-experimental approach: students were allocated to experimental and control groups based on existing class sections (non-random assignment). To minimize selection bias, baseline equivalence was assessed by analyzing pre-test creativity scores along with essential demographic factors such as gender distribution and academic cohort. Potential confounders including prior academic performance and past engineering experience, were acknowledged as limitations and are addressed in the section on internal validity (Table 1).

Intervention protocol: renewable energy STEM projects

The experimental condition consisted of a 15-week semester intervention embedded in the course "Alternative Energy Sources." The intervention integrated short lectures with laboratory-based STEM project work focusing on solar photovoltaic (PV) and wind energy systems. To support reproducibility, a written intervention protocol (weekly plan, project briefs, and assessment criteria) was used for all experimental-group teams.

The renewable energy projects were structured in three levels of complexity;

i. *Foundational level (Weeks 1–4):* guided experiments and measurements (for instance, PV short-circuit current, PV I–V characteristics, basic wind turbine output under varying load), an overview of safety protocols, instrumentation, and data logging practices;

ii. *Intermediate level (Weeks 5–9):* analytical and optimization tasks (for instance, series/parallel PV configuration to increase voltage, estimation of power/energy output, efficiency calculations, and parameter tuning);

iii. *Advanced level (Weeks 10–15):* team-based design and prototyping tasks (such as, assembling a small PV array prototype and modifying a vortex-type wind turbine generator), followed by testing, redesign, and presentation.

All teams followed a common workflow: (1) problem definition linked to a sustainability objective, (2) design and planning, (3) experimental testing, (4) data analysis and interpretation, (5) redesign/optimization, and (6) final presentation. Each team received the same project template, necessary deliverables (including schematics, calculations, experimental results), and submission deadlines. The same laboratory equipment and measurement conditions were used across groups where feasible, and the instructor used a checklist to ensure that key physics concepts and sustainability criteria were addressed consistently. Students in the experimental group primarily engaged in collaborative teams consisting of 3 to 4 students, each with specific roles.

Table 1: Detailed information about the student participating in the experiment

Group	Number		Percentage (%)	Total
1	2		3	4
Specialty	Physics			
Training course	3			
Experimental	29		50%	58 (100%)
Control	29		50%	
Gender	female (38)		65%	58 (100%)
	Control	Experimental		
	20	18		
	male (20)		35%	
	Control	Experimental		
	9	11		

Creativity assessment instrument

A self-assessment questionnaire was utilized to assess the creativity of students prior to and following the experiment. The survey consisted of 9 key questions designed to measure creativity based on three core components: Productivity Fluency (Quick Thinking) Originality Each item was rated on a 4-point Likert scale (1 = Never, 2 = Sometimes, 3 = Often, 4 = Always). The evaluation criteria are outlined in Table 2. The creativity indicators in this study were operationalized through three core dimensions: productivity, fluency, and originality, which represent widely accepted components of creative thinking in educational research. These dimensions correspond with established creativity frameworks and psychometric models that define creativity as the ability to generate numerous ideas (productivity), produce ideas rapidly and flexibly (fluency), and develop novel or unconventional solutions (originality). Because the primary objective of this study was to examine how renewable energy–based STEM projects influence students' creative ideation within physics education, these three indicators were selected as the most direct and measurable constructs associated with creativity development. Simultaneously, the authors recognize that innovation within sustainability-focused contexts encompasses a wider array of competencies, such as critical thinking, systems thinking, collaboration, and sustainability literacy. These competencies contribute to students' ability to evaluate complex environmental problems, understand interactions within energy systems, and work collaboratively to design feasible renewable energy solutions. Despite the absence of quantitative measurements for these aspects in the current study, qualitative insights during the project work suggested that students participated in collaborative decision-making, engaged in system-level reasoning, and discussed the impacts on the environment.

Creativity evaluation framework

The assessment of creativity indicators was conducted through a scoring framework that divided student responses into three essential dimensions of creativity:

- Productivity;
- Fluency (quick thinking);
- Originality;

The scoring key for the questionnaire responses is presented in Fig 1.

Creativity evaluation framework

The indicators of creativity were evaluated through a scoring framework that classified students' responses into three main dimensions of creativity: productivity, fluency, and originality.

Table 2: Self-assessment questionnaire for creativity instructions

No.	Questions	1 (Never)	2 (Sometimes)	3 (Often)	4 (Always)
1	In physics, I can implement my own and other ideas and make suggestions in the implementation of STEM projects.	☐	☐	☐	☐
2	I like to think differently in the STEM field.	☐	☐	☐	☐
3	I am ready for any changes in the implementation of STEM projects.	☐	☐	☐	☐
4	I can work independently on interesting STEM tasks.	☐	☐	☐	☐
5	I like research, invention, and production in STEM projects.	☐	☐	☐	☐
6	My ideas in the field of STEM are basic, new ideas arise quickly.	☐	☐	☐	☐
7	When I am asked a problematic question, I often offer several options for the answer.	☐	☐	☐	☐
8	When a problem situation arises in the implementation of STEM projects in physics, I think of several ways to find a solution to it.	☐	☐	☐	☐
9	It is easy for me to implement STEM projects in an interdisciplinary manner.	☐	☐	☐	☐

Indicate to what extent you agree with each statement below. Use a 4-point scale, marking the most appropriate response (1 = Never, 2 = Sometimes, 3 = Often, 4 = Always).



Fig. 1: Creativity evaluation key

Each dimension was evaluated based on specific questionnaire items.

i. Productivity was measured using items 1, 4, and 9, which reflect the students' ability to generate useful ideas and propose practical solutions during project activities.
ii. Fluency (quick thinking) was assessed through items 2, 3, 5, and 8, indicating the students' ability to produce multiple ideas and respond quickly to problem-solving tasks.
iii. The assessment of originality was conducted through items 2, 6, and 7, emphasizing the distinctiveness and innovation of the suggested ideas or engineering solutions.

This scoring framework was used to analyze the questionnaire responses and determine the level of creativity development among the participants. To quantify the results, the average score for each creativity criterion was determined using Eq. 1 (Amran *et al.,* 2021)

$$M_{av} = \frac{\sum I}{n} \quad (1)$$

where:

$\sum I$- is the total score for each criterion.

M_{av} is the mean creativity score for each component.

n represents the number of indicators assessed.

The productivity index, fluency index, and originality index were calculated using Eq. 2 (Atakaya *et al.,* 2024).

$$I_{(p),(f),(o)} = (\sum I_{maX})/n \quad (2)$$

where:

I_p - Productivity Index.

I_f- Fluency Index.

I_o- Originality Index.

Here, the amount $\sum I_{maX}$is calculated individually for each indicator $I_{(p),(f),(o)}$.

The overall creativity Index was determined using Eq. 3 (Atakaya *et al.,* 2024).

$$I_k = \frac{\mathrm{I_p} + \mathrm{I_f} + \mathrm{I_o}}{n} \quad (3)$$

where:

n represents the total number of creativity criteria.

Interpretation of results

The creativity scores were classified into the following levels:

Low creativity level: $I_{\kappa} \leq 1{,}5$

Moderate ceativity Level: $1{,}5 < I_{\kappa} \leq 3{,}0$

High creativity level: $I_{\kappa} \geq 3.0$

Reliability and validity

In order to confirm the psychometric quality of the creativity measurement instrument employed in the study, reliability and validity analyses were carried out. Internal consistency was evaluated using Cronbach's alpha coefficient, which allows assessment of the homogeneity of the scale and the consistency of the items. Distinct reliability coefficients were computed for each subscale (productivity, fluency, and originality). To evaluate construct validity, the research data were analyzed to determine their appropriateness for factor analysis. For this purpose, the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity were applied. These methods enabled the identification of the correlation structure between the variables and allowed for the validation of the empirical consistency of the theoretical three-factor model of creativity used in this study. To minimize potential subjective bias inherent in self-assessment methods, participants were informed that their responses would be processed anonymously and would not affect their academic performance. This methodological process was executed to lessen the potential effect of social desirability bias.

Objective evaluation and data triangulation

To enhance the reliability of self-assessment data, additional objective evaluation methods were employed. The project work created by students in the experimental group was assessed utilizing a specially crafted expert rubric. The evaluation criteria encompassed the feasibility of engineering, the quality of the system design, and the level of incorporation of sustainability principles into the proposed solutions. In addition, the practical feasibility of the proposed technical solutions was analyzed. This triangulation approach, which combines multiple data sources, was used to strengthen the methodological robustness and credibility of the research findings.

Statistical analysis procedure

Prior to performing statistical analyses, the necessary assumptions for parametric statistical testing were evaluated. The normality of the variables was assessed using the Shapiro–Wilk test, while the homogeneity of variances was evaluated using Levene's test. These procedures ensured the appropriateness of applying parametric statistical methods. To identify differences between groups, an independent samples t-test was applied, while paired samples t-tests were used to assess changes over time within each group. To determine the practical relevance of the outcomes, the effect size (Cohen's d) was calculated, along with the reporting of confidence intervals. The level of statistical significance was set at $\alpha = 0.05$.

Internal and External Validity Limitations

Because the study was conducted using a quasi-experimental design, full randomization was not applied, which may potentially influence internal validity. Furthermore, the study was performed at one higher education institution and included a limited sample size, potentially constraining the applicability of the results to other settings. Considering these limitations, future research is recommended to employ multi-center study designs and larger sample sizes in order to further validate and extend the findings.

RESULTS AND DISCUSSION

Theoretical Justification of Creativity Indicators in an Engineering Context

In this study, creativity was evaluated through three indicators: productivity, idea generation fluency and originality. This selection is based on

the principle of divergent thinking and recognized frameworks for evaluating creativity that are commonly utilized in educational research. Within the scope of the research, critical thinking, systems thinking, and collaboration were considered as additional moderating variables; however, creativity was selected as the primary dependent variable because the main objective of the study was to measure changes in divergent engineering thinking. The efficacy of renewable energy initiatives can be elucidated by their focus on addressing genuine socio-environmental problems. Such projects require interdisciplinary integration (physics, mathematics, engineering, and digital modeling), activate systems thinking, incorporate the engineering design cycle, and lead to the development of tangible outputs such as prototypes, models, or analytical calculations. These traits foster creativity and innovation more profoundly than numerous other types of project-based learning. The scientific problem addressed in this study arises from the dominance of theoretical content in physics curricula, the insufficient integration of applied environmental engineering tasks, and the lack of systematic approaches to the development of creativity. In order to bridge this gap, a STEM methodology centered on renewable energy is recommended, which merges disciplinary knowledge with sustainable development principles and aspires to cultivate innovation competence that is oriented towards environmental sustainability.

Conceptual model

The proposed model describes the mechanism through which renewable energy-based STEM projects influence students' environmentally oriented innovation competence and sustainable development solutions through the development of divergent thinking (Fig.2).

Creative performance in STEM education

A systematic review of scientific literature indicates that STEM education fosters an environment conducive to independent learning and creative engagement. As creative potential arises from STEM-oriented cognitive tasks, it is crucial to develop educational strategies that successfully nurture students' creativity. However, one of the key challenges lies in the organization and evaluation of the creative process. Various definitions of creativity have been proposed in scientific literature, as summarized in (Fig. 3). Several researchers interpret the concept of creativity from different perspectives. For example, Kaplan (2019) emphasizes that innovation in education and science is an important indicator of creative activity. According to Colin (2017), creativity consists of two essential components: efficiency and originality. Corazza (2016) describes creativity as engagement in activities that reflect originality within the educational process. Similarly, Abdullah and Cramond (2017) suggest that creative performance can be evaluated based on at least two criteria: originality and usefulness of an idea or product. These viewpoints illustrate that creativity is typically perceived as the capacity to produce original, valuable, and innovative concepts within educational and scientific frameworks. Building upon the literature review and comparative analysis of creativity definitions, a self-assessment questionnaire (Table 2) was developed to measure students' creativity. The primary creativity indicators assessed were productivity, fluency, and originality. In the present study, the concept of creativity in physics students is interpreted as the ability of an individual to amalgamate knowledge, distinguished by persistent motivation and involvement in research activities. This study focused on assessing how STEM-based alternative energy education enhances students' creative potential (Fig. 4).

Implementation of STEM-based alternative energy projects

The creativity of students studying in the field of physics – individual integration knowledge, which is distinguished by constant motivation in research activities during the training of the course "Alternative energy sources". This definition can be

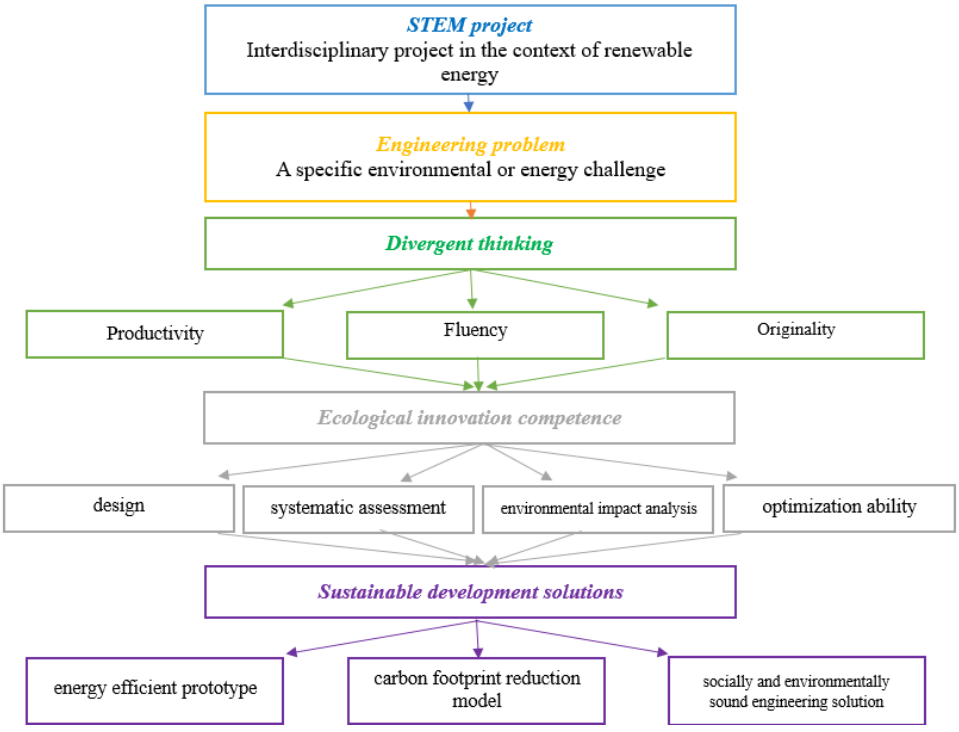

Fig. 2: Conceptual model of creativity development through renewable energy–based STEM projects

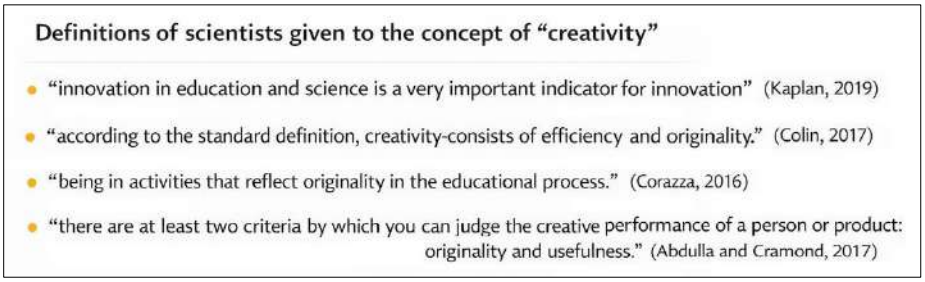

Fig. 3: Comparison of creativity definitions in scientific literature

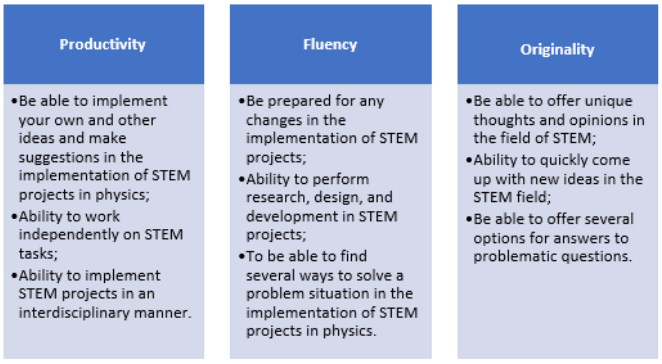

Fig. 4: Indicators of creativity of students in the field of alternative energy sources in STEM education

presented for the effective appraisal of students within the scope of just one area. The course "alternative energy sources" developed a curriculum based on the development of creativity of students through the use of STEM elements. In the program, along with the goals of training, expected results, methods used in the educational process, evaluation criteria, the content of training was developed. The curriculum's main focus on alternative energy sources encompassed solar and wind energy. In conducting lecture classes on these topics, STEM stands were used for conducting several studies in the field of solar and wind energy (Fig. 5). The STEM stand for studying the physical characteristics of solar and wind energy was used in lectures and practical classes of the course “Alternative Energy Sources.” It allowed students to investigate topics such as the current–voltage characteristics of solar cells, maximum power determination, photovoltaic system monitoring, and wind turbine performance. Through these STEM-based experiments and projects, students applied theoretical knowledge and developed their creative and research skills.

Stages and progress of the implementation of STEM projects with students in laboratory classes

During the initial stage, 29 students in the experimental group were split into seven teams and allocated STEM projects concerning solar and wind energy. Each group developed a STEM product based on theoretical knowledge and presented the results as a team project. For example, one group assembled solar panels by connecting individual cells in series, which increased the voltage from about 0.38–0.40 V to approximately 1.20 V. Through this project-based activity, students applied theoretical concepts in practice and developed their engineering and creative skills (Fig. 6). Students also implemented group projects to modify a vortex-type wind turbine generator. They constructed the magnetic holder, ensuring that the opposite magnetic poles were aligned correctly, and wrapped a copper coil consisting of approximately 500 turns around the housing to generate electricity. Through this process, students improved the main components of the wind generator and applied practical engineering skills to convert wind energy into electrical energy (Fig. 7).

Results of an experimental study

Students’ creativity was assessed using a self-assessment questionnaire developed for this study. The instrument consisted of 9 items evaluated on a 4-point Likert scale and was structured around three dimensions of creativity: productivity, fluency, and originality. Reliability analysis showed high internal consistency of the questionnaire (Cronbach’s $\alpha = 0.82$), with acceptable values for productivity ($\alpha = 0.79$), fluency ($\alpha = 0.81$), and originality ($\alpha = 0.84$). Table 3 presents the reliability indicators of the questionnaire.

To examine the construct validity, factor analysis was conducted. The Kaiser–Meyer–Olkin (KMO) measure was 0.76, indicating that the data were suitable for factor analysis. The result of Bartlett’s Test of Sphericity was statistically significant ($p < 0.001$), demonstrating that there were sufficient correlations among the variables. The findings from the factor analysis provided empirical support for a three-factor model of creativity, which encompasses productivity, fluency, and originality. The results of the factor analysis are presented in Table 4.

To reduce potential subjective bias inherent in the self-assessment method, a data triangulation approach was applied. The evaluation of students' project works was conducted by experts based on a custom-developed assessment rubric. The expert assessment included criteria such as the technical feasibility of engineering solutions, the novelty of the idea, and the practical applicability of the project. The criteria used for the expert evaluation of the projects are presented in Table 5.





Fig. 5: STEM stands focused on studying the physical characteristics of solar and wind power

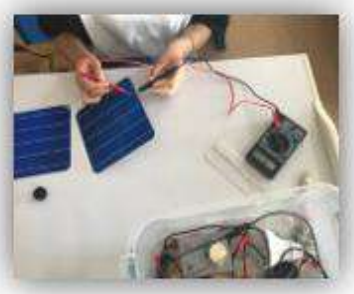



Fig. 6: Implementation of the STEM project on energy consumption with solar panels





Fig. 7: Implementation of the STEM project on the topic of wind energy use

Table 3: Reliability indicators of the student creativity assessment questionnaire (Cronbach's α)

Scale	Cronbach's α	Reliability Level
Productivity	0.79	Satisfactory
Fluency	0.81	High
Originality	0.84	High
Total Scale	0.82	High Reliability

Table 4: Results of the construct validity assessment of the creativity questionnaire (factor analysis)

Indicator	Value	Explanation
Kaiser–Meyer–Olkin (KMO)	0.76	Sufficient for factor analysis
Bartlett's Test of Sphericity	$p < 0.001$	There is a statistically significant correlation between the variables
Number of factors	3	Productivity, fluency, originality
Explained variance	>60%	Creativity structure confirmed

Table 5: Criteria for peer evaluation of students' STEM projects

Criterion	Description
Engineering soundness	The correctness of the technical solutions of the project
Innovation of the idea	The originality of the proposed solutions
Practical applicability	The potential for real application of the project
Principles of sustainable development	Consideration of environmental and energy efficiency aspects

Statistical analysis

Statistical methods for data processing were utilized to examine the information gathered throughout the study. First, the normality of the data distribution was assessed in order to determine the possibility of using parametric statistical tests. For this purpose, the Shapiro–Wilk normality test was employed. This assessment is commonly employed to determine if the data adhere to a normal distribution, especially for smaller sample sizes ($n < 50$ or $n \approx 50$–60). The results of the Shapiro–Wilk test are presented in Table 6. In addition, Levene's test was performed to determine the homogeneity of variances between groups. This examination serves to determine if the variances of the experimental and control groups are equivalent, which is essential for the utilization of the t-test for independent samples. The results of the homogeneity of variance test are shown in Table 7. During the study, several statistical analysis methods were applied to compare the results obtained before and after the experiment. First, an independent samples t-test was performed to assess the equivalence of the baseline levels of the experimental and control groups. This analysis made it possible to identify whether there was a statistically significant difference between the two groups before the experiment began. The statistical indicators of the pre-test results are presented in Table 8. After the experiment was completed, an independent sample t-test was used again to determine the impact of STEM-based alternative energy projects on students' creativity. This technique enables the comparison of the final scores achieved by both the experimental and control groups. The statistical data of the final test results are presented in Table 9. In addition, Cohen's d effect size was calculated to assess the strength of the intervention. This indicator facilitates the evaluation of the practical importance of STEM-based teaching interventions regarding students' creativity levels. To evaluate the dependability of the findings, 95% confidence intervals were computed. All statistical analyses were performed using the statistical package for the social sciences (SPSS) software. The assessment performed on the three primary aspects of creativity—productivity, fluency, and originality—revealed that all metrics improved in the experimental group. STEM-based projects contributed to the development of students' ability to generate new ideas, propose multiple solutions to problems, and design innovative engineering solutions. Based on the findings from the statistical analysis, a notable difference was observed in the post-test scores of the experimental group compared to the control groups ($p < 0.05$). Therefore, the null hypothesis (H_0) of the study was rejected, while the alternative hypothesis (H_1) was confirmed. These findings indicate that the implementation of renewable energy–based STEM projects significantly improves students' creativity levels from a statistical perspective (Table 10). These results indicate that STEM-based alternative energy projects positively influence students' creative thinking. By engaging in project-based activities, students implemented their theoretical knowledge in practical assignments, such as creating prototypes of photovoltaic systems and refining models of small wind generators. These experiences enhanced their engineering thinking, problem-solving skills, and ability to integrate interdisciplinary knowledge. Furthermore, the initiatives heightened students' consciousness regarding energy efficiency and environmental sustainability, illustrating that STEM activities foster both the development of creativity and comprehension of sustainable energy solutions.

Contextual factors and implementation possibilities

The study was conducted with Physics students at Khoja Akhmet Yassawi International Kazakh-Turkish University, where the availability of STEM stands and laboratory equipment for renewable energy research supported the effective implementation of the projects. Such facilities provided students the opportunity to merge

Table 6: Results of the Shapiro–Wilk normality test for the experimental and control groups

Group	N	Shapiro–Wilk W	p
Experimental (Pre-test)	29	0.967	0.412
Control (Pre-test)	29	0.971	0.508
Experimental (Post-test)	29	0.962	0.327
Control (Post-test)	29	0.969	0.456

Table 7: Independent samples t-test results for the pre-test comparison of the experimental and control groups

	Levene F	t	df	p (two-way)	Average difference	Standard error (SE) of difference	95% CI (lower)	95% CI (upper)
pre-test	0.001	-0.368	56	0.714	-0.069	0.188	-0.445	0.307
post test	0.262	2.060	56	0.044	0.379	0.184	0.011	0.748

Table 8: Descriptive statistics of the experimental and control groups in the pre-test

Group	N	Mean	SD	SE
Experimental	29	1.724	0.702	0.130
Control	29	1.793	0.726	0.135

Table 9: Descriptive statistics of the experimental and control groups in the post-test

Group	N	Mean	SD	SE	Cohen's d
Experimental	29	2.345	0.670	0.124	0.54
Control	29	1.966	0.731	0.136	

Table 10: Changes in creativity indicators (productivity, fluency, originality) between pre-test and post-test

Indicator	Pre-test M	Post-test M
Productivity	1.73	2.36
Fluency	1.71	2.32
Originality	1.74	2.35

theoretical understanding with practical applications in solar and wind energy. However, factors such as laboratory resources, class size, instructors' workload, and access to technology may influence the implementation of STEM projects in different institutions. In situations where equipment is scarce, renewable energy subjects can be effectively taught using straightforward experimental tools, digital simulations, or virtual laboratories, thus facilitating the adaptation of STEM education to be tailored to different learning environments.

Study limitations and future research

This study examined the impact of STEM-based alternative energy projects on students' creativity; however, several limitations should be noted. The sample size was relatively limited (N = 58) and consisted of students from just one university, potentially constraining the generalizability of the results. In addition, full randomization was not applied, and creativity was measured immediately after the intervention, without assessing long-term effects. Future studies ought to incorporate larger multi-site samples, integrate delayed post-tests, and utilize more extensive assessment techniques such as portfolio evaluation or analysis of project-based products to more effectively investigate the development of creativity in STEM education. The findings of this study align with existing research, demonstrating that STEM-based

activities in alternative energy education have a positive impact on students' knowledge acquisition and creativity development. The integration of solar and wind energy projects within STEM curricula fosters a deeper understanding of physics concepts while also enhancing students' interdisciplinary problem-solving skills. Furthermore, it has been noted that education in alternative energy based on STEM significantly impacts science teachers' views on STEM pedagogy, thereby strengthening its position as a valuable learning approach (Hiğde, 2022; Mayasari *et al.,* 2019). The results further support the notion that incorporating STEM knowledge into physics education enables the interdisciplinary application of student learning in the context of alternative energy. The capacity to create and develop STEM products within the renewable energy sector not only improves technical abilities but also fosters creativity and innovation among students. These findings are consistent with previous research, which highlights that engagement in STEM projects fosters students' ability to conceptualize, design, and implement real-world solutions (Kersánszki *et al.,* 2023). The conclusions of this study align with the broader scientific discourse on problem-based learning (PBL) and design thinking methodologies in STEM education (Rugh *et al.,* 2020). PBL is recognized as a progressive teaching method that prioritizes critical thinking and the active creation of knowledge, rendering it especially effective in the field of alternative energy education (Smyrnova-Trybulska *et al.,* 2017). Several studies suggest that integrating alternative energy sources into educational curricula enhances students' scientific literacy, preparing them to address contemporary environmental and engineering challenges. These findings reinforce the argument that exposure to renewable energy STEM projects improves creativity and equips students with industry-relevant skills. Research conducted previously demonstrates that problem-oriented learning strategies—including engaging in hands-on experimentation, developing prototypes, and participating in collaborative STEM projects—are vital for cultivating creativity, adaptability, and technological skills in students who are pursuing careers in engineering and the physical sciences.

Impact on educational and socio-economic spheres

One of the key contributions of this study is its demonstration of how STEM-based renewable energy education facilitates breakthroughs in various domains, including socio-economic, scientific, and technical sectors. Despite working with a constrained budget and design limitations, the execution of STEM initiatives in solar energy education greatly improved students' creative skills and practical knowledge. The ability to develop and implement alternative energy solutions through hands-on STEM experiences not only enhances academic performance but also prepares students for real-world applications in engineering, sustainability, and industry. This is especially pertinent in the realm of global energy transitions, where renewable energy technologies are increasingly vital for both economic and environmental sustainability. From a broader perspective, these findings contribute to the ongoing discourse on higher education reform in the context of global energy transitions. Universities are increasingly expected to function as catalysts for sustainable development, preparing graduates who can address complex environmental challenges. This study illustrates how the integration of renewable energy applications into physics education can utilize STEM-based teaching models to connect theoretical knowledge with practical solutions for

environmental issues. The results suggest that creativity development in renewable energy education is not merely an academic outcome but a foundational component of building future professionals capable of advancing sustainable energy systems.

CONCLUSION

This study examined the impact of renewable energy–based STEM projects on students' creativity within a physics education context. The evidence shows that engaging in interdisciplinary initiatives focused on solar and wind energy was linked to observable advancements in three measures of creativity: productivity, fluency, and originality. The results suggest that engaging students in hands-on engineering tasks and sustainability-oriented problem solving may support the development of divergent thinking skills within physics learning environments. The moderate effect size observed in the analysis indicates that the STEM-based instructional approach produced both statistically significant and educationally meaningful changes in students' creativity scores within the experimental group. Furthermore, qualitative assessments of student project work indicated a heightened involvement in interdisciplinary problem-solving and considerations for environmentally focused design. However, the conclusions of this study should be interpreted within the specific scope of the research design. The experiment was conducted with a relatively small sample of students from a single university, and therefore the findings cannot be generalized to all physics or engineering education contexts. In contrast, the findings indicate preliminary empirical evidence that underscores the possible advantages of utilizing renewable energy-focused STEM activities as a pedagogical strategy to promote creativity within higher education physics courses. Future studies should involve larger and more diverse samples, multi-institutional research settings, and extended observation periods to further examine the relationship between renewable energy STEM education and creativity development. Further studies could also look into how project-oriented strategies affect wider skills linked to sustainability, engineering problem solving, and interdisciplinary collaboration.

AUTHOR CONTRIBUTIONS

Y. Dossymov contributed to the implementation of the experimental intervention, data collection, statistical analysis using SPSS, and drafting of the initial manuscript. S. Ramankulov conceptualized and supervised the study, developed the research design and STEM framework, guided data interpretation. N. Genc contributed to the methodological design, and review of the theoretical background related to sustainability and renewable energy education. A. Çoruh participated in the analysis and interpretation of the results and contributed to manuscript editing and refinement. M. Nurizinova coordinated the research process, and served as the corresponding author responsible for manuscript submission and communication with the journal. N. Zhaksylyk assisted in the development of renewable energy project materials. All authors reviewed 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. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors confirm that all ethical standards have been fully observed. Issues related to plagiarism, informed consent, research misconduct, data fabrication and/or falsification, duplicate publication and/or submission, and redundancy have been carefully addressed in accordance with accepted academic and publication ethics guidelines.

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During the preparation of this work, the authors used Artificial Intelligence (AI) tools, specifically ChatGPT (OpenAI), to assist with language editing, improving clarity of expression, and refining academic phrasing. The AI tool was used solely for linguistic enhancement and structural organization purposes. After using this tool, the authors carefully reviewed, revised, and edited all generated content to ensure accuracy, originality, and alignment with the scientific objectives of the study. The authors take full responsibility for the integrity, validity, and originality of the content of this publication.

ABBREVIATIONS

%	Percent
cm	Centimeter
DOE	Department of Energy
DF	Degrees of Freedom
DT	Design Thinking
F	F-statistic (Levene's Test for Equality of Variances)
H_o	Null hypothesis
H_{o1}	Alternative hypothesis
H_1	Null hypothesis (no impact of STEM on creativity)
H_{11}	Alternative hypothesis (positive impact of STEM on creativity)
I_p	Productivity index
I_f	Fluency index
I_o	Originality index
I_k	Creativity index
M_{av}	mean creativity score for each component
p	Probability value (Two-tailed significance level)
PBL	Problem-based learning
SDGs	Sustainable development goals
SD	Standard deviation
SE	Standar error
SETO	Solar Energy Technologies Office

SPSS	Statistical package for the social sciences
STEAM	Science, technology, engineering, arts, and mathematics
STEM	Science, technology, engineering, and mathematics
t	t-statistic (Independent samples t-test value)
PV	photovoltaic
V	Volt
$\sum I$	total score for each criterion

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ORIGINAL RESEARCH PAPER

Ocean health index status and the conservation priorities associated with marine protected park

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ABSTRACT

BACKGROUND AND OBJECTIVES: Marine protected areas are critical tools for conserving biodiversity and sustaining ecosystem services. Nonetheless, their efficacy depends on the equilibrium between environmental conservation and the socio-economic advantages for coastal populations. The Savu Sea National Marine Park in Indonesia, the country's largest marine protected area, encompasses vital ecosystems, while supporting local communities reliant on marine resources. The study objectives were to utilize the ocean health index plus framework to evaluate the health of Savu Sea National Marine Park, determine conservation priorities, and emphasize the potential for ocean health index plus to emphasize Indonesia's Marine Protected Area network within the coral triangle.

METHODS: A customized ocean health index framework was applied under two scenarios. Scenario 1 ten global ocean health index objectives utilizing a preservation-oriented weighting scheme that prioritizes preservation and emphasizes conservation outcomes. Scenario 2 concentrated on five primary ecological objectives that are most pertinent to the effectiveness of Marine Protected Areas. The indicators were obtained from satellite data, government reports, and expert judgment. The status scores were calculated relative to reference points, with future status determined by trend, pressure, and resilience components

FINDINGS: The ocean health index plus score for Savu Sea National Marine Park was 69 under Scenario 1 and 87 under Scenario 2, indicating moderate to high ecological health. Ecological goals such as carbon storage (99), clean waters (96), and biodiversity (82) performed well, reflecting intact habitats and water quality. However, socio-economic goals such as artisanal fishing opportunity (30), natural products (24), and coastal livelihoods (33) showed weak performance. These circumstances underscore considerable socio-economic difficulties and reveal fundamental problems including restricted livelihood diversification, inadequate market access, and a declining fisheries value chain. The low scores for food provision (65) and livelihoods (34) suggest a direct link between the socio-economic deficits and the inability to harness the full potential of the marine resources.

CONCLUSION: Savu Sea National Marine Park demonstrates strong ecological integrity but limited socio-economic benefits. Long-term management effectiveness requires integrating livelihood development, the enhancement of fisheries value chains, and the promotion of sustainable tourism in conjunction with conservation initiatives, ensuring that ecological achievements yield significant socio-economic advantages for the local communities.

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INTRODUCTION

Healthy ocean ecosystems are vital for sustaining human wellbeing, coastal livelihoods, and climate resilience, yet they continue to face widespread degradation due to overfishing, habitat loss, pollution, and climate change (Halpern *et al*., 2012). Among key conservation strategies to halt this decline, marine protected areas (MPAs) have shown to be effective in conserving biodiversity and sustaining ecosystem services. Well-managed MPAs can enhance fish biomass, protect critical habitats, and support climate mitigation by preserving blue carbon ecosystems such as mangroves and seagrasses (Boubekri *et al*., 2025; Chirico *et al*., 2017; Sala *et al*., 2021). The Savu Sea National Marine Park (SSNMP), the largest MPA in Indonesia at 3.35 million hectares, is a critical site for evaluating how MPAs balance ecological conservation and community benefits. Located in the Coral Triangle, SSNMP protects coral reefs, seagrass beds, and mangrove forests while serving as a migratory corridor for cetaceans and other marine megafauna (The Nature Conservancy, 2015). The park is recognized as a crucial habitat for cetaceans, hosting numerous species of dolphins and whales, along with designated migration routes, and the zoning for their protection is presently under consideration (Putra and Mustika, 2020). In addition to its ecological significance, SSNMP supports coastal communities that depend on fisheries, seaweed farming, and small-scale livelihoods, making it a key site for evaluating how MPAs contribute to both ecological protection and socio-economic benefits. Its governance combines national policies with local customary practices, providing a model for co-management and multi-stakeholder participation in marine conservation (Paulus *et al*., 2023; Soemarmi and Rafsanjani, 2023; Hartoko, 2025). Despite the Ocean Health Index (OHI+) has been extensively utilized worldwide to evaluate ocean health by incorporating ecological, social, and economic factors, its implementation at specific MPA levels is still restricted due to the fact that standardized indicators might not adequately reflect local ecological diversity and governance intricacies (Turnbull *et al.,* 2021; Halpern *et al*., 2012). The OHI+ framework addresses this limitation by allowing the customization of indicators and reference points to reflect regional conditions and management priorities (Daigle *et al*., 2017; Lowndes *et al*., 2015). Unlike the standardized Ocean Health Index (OHI), which often treats MPAs as components of broader environmental goals, OHI+ enables goal-by-goal evaluation of MPA performance as a socio-ecological system that integrates ecological health, socio-economic outcomes, and governance quality (Borja *et al*., 2016; Manley *et al*., 2025; Michaels *et al*., 2026; Talubo *et al*., 2022). Localized OHI applications in Indonesia remain limited. Previous assessments in Ambon Bay and Tuban reported weak performance in water quality and biodiversity goals under persistent human pressures (Joesidawati and Suwarsih, 2022; Kesaulya *et al*., 2024). These observations underscore ongoing deficiencies in comprehending MPAs as integrated socio-ecological systems, where governance, stakeholder engagement, and community well-being are equally important as ecological results (Bennett and Dearden, 2014; Di Cintio *et al*., 2023; Pegorelli *et al*., 2024). Numerous studies continue to assess ecological and socio-economic outcomes in isolation, neglecting governance elements that are crucial for successful co-management (Picone *et al*., 2021; Susilowati *et al*., 2024). This study applies the OHI+ framework to evaluate the ocean health of SSNMP, identify conservation priorities, and demonstrate how OHI+ can strengthen Indonesia's MPA network within the Coral Triangle. By establishing a clear and reproducible scoring process that connects goal-level results to conservation and livelihood priorities, the study offers a tool for adaptive management and decision-making in marine conservation. This study aims *to apply the OHI+ framework to assess the health of SSNMP*, Indonesia, in 2024.

MATERIALS AND METHODS

Study area

This study was conducted in the SSNMP, located in East Nusa Tenggara, Indonesia and is divided into four regions as shown by Fig. 1. The marine park is divided into core, sustainable use, and traditional use zones, and exhibits dynamic oceanographic conditions, including seasonal upwelling, high primary productivity, and complex current systems. From an ecological perspective, the SSNMP fosters a variety of habitats, including coral reefs, seagrass beds, and mangroves. Additionally, it functions as an essential migratory pathway for marine megafauna, including whales, dolphins, and sea turtles. As a key area within the coral triangle, the SSNMP is globally recognized for its marine biodiversity and is a priority region for conservation and sustainable fisheries management.

The OHI+ framework

Ocean health was measured with a function of ten goals, as globally used, including ecosystem and socio-economic conditions. The OHI+ framework employed OHI scoring techniques and was modified for SSNMP to serve as the MPA area and context. The overall OHI Score and the formula used to calculate each component use the general OHI scoring method as introduced by Halpern *et al.*, 2012. The overall OHI score (I) is determined by the function of a linear weighted sum of the scores for each goal, using Eq. 1 (Halpern *et al.*, 2012; Abdurrahim *et al.*, 2020; O'Hara *et al.*, 2020):

$$I = \sum_{i=1}^{N} \alpha_i I_i \quad (1)$$

where, α_i is the weight for each goal, with the total or sum of their weights should equal 1. I_i is the score for each goal. Then the calculation for each goal score, using Eq. 2 (Halpern *et al.*, 2012; Abdurrahim *et al.*, 2020; O'Hara *et al.*, 2020; Chen and Lee, 2022; Ding and Tabeta, 2024):

$$I_i = \frac{x_i + \hat{x}_{i,F}}{2} \quad (2)$$

where, x_i is the present status and $\hat{x}_{i,F}$ is the likely future status. The current status (x_i) calculated by evaluating the current evaluation score (X_i), divided by the reference value ($X_{i,R}$) using Eq. 3 (Halpern *et al.*, 2012; Chen and Lee, 2022; Ding and Tabeta, 2024):

$$x_i = \frac{X_i}{X_{i,R}} \quad (3)$$

then, the likely future status is calculated based on the current status and the other three variables, including the trend (T_i), pressure (p_i), and resilience (r_i) in each goal, using Eq. 4 (Halpern *et al.*, 2012; Abdurrahim *et al.*, 2020; O'Hara *et al.*, 2020; Chen and Lee, 2022; Ding and Tabeta, 2024):

$$\hat{x}_{i,F} = (1+\delta)^{-1}\begin{bmatrix} 1 + \beta T_i + (1-\beta) \\ (r_i - p_i) \end{bmatrix} x_i \quad (4)$$

where, δ represents the discount rate, which is assumed to be zero, given the relatively short analysis period. The weighting parameter β is set at 0.67, implying that the trend component is given twice the influence of resilience and pressure components in projecting the future status of each goal. This value is not based on empirical estimation but is instead sourced from the OHI framework. Trend estimates were derived from the slope of the status of the earliest year, as calculated using Eq. 5 (Halpern *et al.*, 2012; Ding and Tabeta, 2024):

$$T_i = \frac{\text{slope}(y,t)k}{y_1} \quad (5)$$

where, $\text{slope}(y,t)$ is the slope of the linear regression of status against time, k is the length of the projection period (years), and y_1 is the status value in the first year of the trend period. The pressure (p_i), and resilience (r_i) in each goal were calculated using the average of the expert judgement scores.

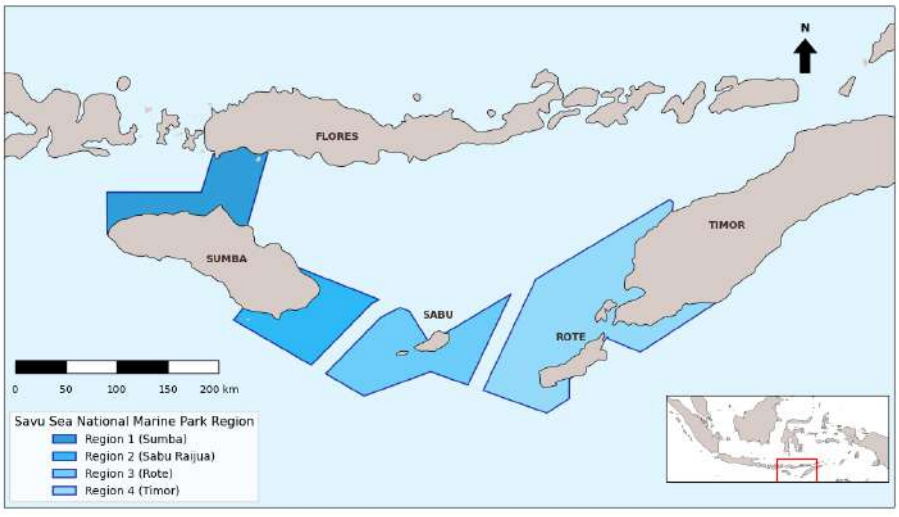

Fig. 1: Geographical location of the study area in the Savu Sea National Marine Park region in Indonesia

After calculating the trends, pressure, and resilience for each goal, the T_i, p_i, and r_i values were substituted into Eq. 4 to obtain the likely future status. For the OHI score for each goal, Eq. 3 and Eq. 4 were substituted into Eq. 2. Finally, the overall OHI score is calculated using Eq. 1 by substituting the values obtained from Eq. 2. The OHI+ for SSNMP was tailored and applied to the 2 scenarios. Scenario 1, including 10 widely accepted global goals and several sub goals (Table 1) (Halpern *et al.*, 2012; Ma *et al.*, 2016; Ding and Tabeta, 2024).

Detailed OHI+ model structure

The OHI+ framework applied in this study includes ten goals: Clean Waters (CW), Carbon Storage (CS), Food Provision (FP), Natural Products (NP), Coastal Livelihoods and Economies (LE), Coastal Protection (CP), Biodiversity (BD), Tourism and Recreation (TR), Artisanal Fishing Opportunity (AO), and Sense of Place (SP). However, some sub-goals were excluded because they were not relevant to the context of the SSNMP. As an illustration, the mariculture (MAR) sub-goal associated with FP was disregarded since mariculture is not a key focus in SSNMP, where conservation of natural habitats and sustainable fisheries are prioritized. Thus, FP was represented only by the fisheries (FIS) component without separating it as an additional sub-goal. Similarly, the iconic species (ICO) and lasting special places (LSP) sub-goals were not calculated separately under SP, as the SP goal already reflects the cultural and intrinsic value of marine ecosystems, including the importance of iconic species and special marine areas. This simplification maintains the integrity of the OHI framework while minimizing redundancy in indicators. The final sub-goals used in the analysis include Livelihoods (LIV), Economies (ECO), Habitat (HAB), and Species (SPP). Scenario 2 emphasizes a more limited range of ecological objectives that more accurately reflect the conservation nature of SSNMP as a marine protected area, including CW, CS, CP, BD, and SP. Each goal was evaluated using specific indicators and reference points. The CW goal assessed marine water quality by normalizing parameters such as Potential of Hydrogen (pH), salinity, sea surface temperature (SST), chlorophyll-a, dissolved oxygen (DO), and the Provincial Marine Water Quality Index against standards defined by Government Regulation No. 22 of 2021 and the Ministry of Environment and Forestry (KLHK) Marine Water Quality Index

methodology. The CS objective assessed the carbon storage potential of mangrove and seagrass ecosystems by utilizing weighted carbon sequestration values derived from Chen and Lee (2022). The FP goal evaluated the sustainability of marine food supply using capture fisheries production and protein consumption normalized against maximum sustainable yield (MSY) and recommended dietary intake. The NP goal evaluated the output of non-food marine resources, including seaweed and salt, in relation to national production objectives. The LE objective integrates the LIV sub-goal, which assesses employment in marine-related fields, along with the ECO sub-goal, which analyzes the economic advantages derived from fisheries and marine industries based on employment statistics and fisheries income relative to the national minimum wage. The CP goal assessed shoreline stability using End Point Rate (EPR) analysis derived from Landsat imagery from 2020–2024. The BD goal combined HAB and SPP sub-goals, where habitat condition was evaluated using the status of coral reefs, mangroves, and seagrass, while species status was determined based on The International Union for Conservation of Nature (IUCN) Red List categories (IUCN, 2025). The TR objective assessed the advantages of tourism by analyzing visitor statistics and accommodation capacity in comparison to national benchmarks. The AO goal measured small-scale fishers' access to marine resources using the number of fishers and <5 Gross Tonnage (GT) fishing vessels. Finally, the SP goal represented the cultural and conservation value of the marine environment based on the presence of protected species within the SSNMP using IUCN conservation status as a reference.

Data and limitations

Several types of data are used to determine the OHI score for each goal. These data include both status and likely future status values. The data sources used include secondary data from satellites, reanalysis and hindcast data from Marine Copernicus, as well as reports from governmental agencies and international organizations. 1) Reanalysis data and Hindcast from Marine Copernicus that combines satellite observations that are then modeled and reanalyzed; 2) Government reports from Indonesia, including periodic reports, surveys, monitoring data, and annual reports; 3) International organization annual reports and species extinction status reports, which provide global biodiversity status and trends; 4) Satellite data from Landsat 8 to which are analyzed further using geographic information system (GIS) tools; 5) Expert evaluations were collected through questionnaires that addressed the risks and opportunities for sustaining and improving conditions across the four regions of SSNMP. A detailed explanation of the data sources used for each goal can be found in Table 1. Temporal patterns were evaluated utilizing the latest available data to depict the status, pertaining to conditions in 2024. To estimate future status, trend analyses were conducted using data from the previous five years (2020–2024) when sufficient time-series data were available. In instances where multi-year datasets were restricted, year-on-year (YoY) comparisons were employed to estimate short-term trends while ensuring the relevance of indicators. Spatial patterns were evaluated across the four management regions of SSNMP and surrounding connected waters. Indicator values were compiled at the most spatially explicit scale available. However, when region-specific data within SSNMP were unavailable, provincial-level data from East Nusa Tenggara (NTT) were employed as proxies to signify more extensive environmental and socio-ecological conditions. Socio-economic data were more limited than ecological data, often relying on provincial-level estimates rather than region-specific information. This restriction is notably pertinent to objectives like livelihoods and economies, where compiled data might not

entirely reflect local circumstances. Nevertheless, these secondary datasets persist as the most trustworthy sources for analyzing broader socio-economic trends within the assessment framework.

Reference points

Reference points were applied as standardized benchmarks for all parameters to guarantee an objective assessment while considering the unique characteristics of the study area. Given the heterogeneity of goals assessed and the diversity in data sources and data quality, reference points were selected based on the guidance in OHI methods introduced by Halpern *et al* (2012) and applied in the several region such as Fiji (Selig *et al.*, 2015), Shanghai (Wu *et al.*, 2021), and Tokyo (Ding and Tabeta., 2024). The reference points combine established OHI practices with context-specific considerations. OHI+ SSNMP reference points were grouped into five main categories (Table 1): 1) Enhanced or peak values, including income levels or indicators related to fisheries that signify favorable conditions; 2) baseline or least-disturbed conditions, including natural coastal environments with minimal anthropogenic influence; 3) industry-recognized benchmarks, such as the MSY used for fisheries-related goals; 4) reference points derived from national standards and regulations, especially concerning environmental quality indicators; and (5) conditions observed in comparable regions used as relative benchmarks. Data limitations, including the temporal resolution that contain only year-on-year.

Weighting goal

In applying the OHI, four weighting schemes are used: Preservationist, Extractive Use, Non-extractive Use, and Strong Extractive Use, as outlined by Halpern *et al*. (2012). Each scheme reflects different management priorities. The Preservationist scheme emphasizes ecological conservation, whereas Non-extractive Use prioritizes ecosystem services such as tourism, recreation, and cultural values. The Extractive Use scheme emphasizes the socio-economic advantages gained from the utilization of resources, such as including fisheries and mariculture, while Strong Extractive Use assigns the highest priority to resource-based and economic outcomes. These schemes allocate weight values of high (0.15), medium (0.10), and low (0.05) for each goal, resulting in a cumulative weight of 1. In certain situations, extremely high or extremely low priorities might be applied, especially in the context of the Strong Extractive Use framework scenario, where extractive objectives are prioritized more heavily compared to ecological aims, which may be deprioritized (Ding and Tabeta, 2024). This study employs the Preservationist weighting scheme to correspond with the conservation objectives of the SSNMP. Two weighting scenarios were applied within the OHI+ framework. Scenario 1 follows a preservationist perspective, emphasizing ecological conservation while still considering socio-economic factors. Following Halpern *et al*. (2015), goals lacking relevance or sufficient data may be excluded by assigning a weight of zero. Scenario 2 adopts an ecocentric perspective that prioritizes ecological objectives, offering a more comprehensive assessment of ecosystem health. This dual-scenario approach enables a broader assessment of MPA effectiveness by examining potential trade-offs between conservation priorities and socio-economic benefits. Previous global studies show that well-managed MPAs can support significantly higher fish biomass compared to unprotected areas, particularly when complex ecosystems such as coral reefs remain intact. In contrast, habitat degradation might hinder ecological recovery, even within designated protected areas. The specific weighting scheme for each goal is detailed in Table 2.

Table 1: Details for the calculation for 10 goals and 4 sub goals that comprise the OHI

Goal	Sub goal	Parameter	Data source	Resolution	Reference point
CW	–	Salinity and SST	Marine Copernicus – Global Ocean Physics Reanalysis	Spatial: 1/12° covered SSNMP; Temporal: monthly 2020-2024	Government Regulation of the Republic of Indonesia No. 22 of 2021
		pH, Chlorophyll-a, and DO	Marine Copernicus – Global Ocean Biogeochemistry Analysis and Forecast	Spatial: 1/12° covered SSNMP; Temporal: monthly 2020-2024	
		Provincial Marine Water Quality Index	KLHK Performance Report	Spatial: NTT as Provincial data; Temporal: yearly 2020-2024	Marine Water Quality Index methodology from the KLHK
CS	–	Seagrass status and Mangrove coverage	National Marine Conservation Area Center (BKKPN) Kupang; Ocean Account 2022–2023	Spatial: SSNMP; Temporal: yearly 2020-2024	Ministerial Decree of Environment No. 4 of 2001
FP	–	Capture fisheries production	Ministry of Marine Affairs and Fisheries (KKP) Data Portal	Spatial: NTT; Temporal: yearly 2020-2024	MSY
NP	–	Protein consumption	Statistics Indonesia (BPS)	Spatial: NTT; Temporal: yearly 2024	Recommended Protein Adequacy Level
		Seaweed production	KKP Data Portal	Spatial: NTT; Temporal: yearly 2024	National production
		Salt production (tons)			Provincial production target
LE	LIV	Total number of fisheries business actors	KKP Data Portal	Spatial: NTT; Temporal: yearly 2020-2024	30 percent (%) of total workers in East Nusa Tenggara
	ECO	Income of fisheries business actors in East Nusa Tenggara	Agency for Extension and Human Resources Development (BPPSDM) Social Welfare Survey 2024		National minimum wage
		Fishermen's Exchange Rates (NTN)	BPS	Spatial: NTT; Temporal: yearly 2019-2024	National NTN Target
CP	–	EPR by region in the SSNMP	Landsat imagery	Spatial: SSNMP; Temporal: yearly 2016, 2020, and 2024	Erosion and accretion rates based on the Research and Development Center for Water Resources, Ministry of Public Works (1993).
BD	HAB	Coral reef cover, Seagrass status, and Mangrove cover	BKKPN Kupang	Spatial: SSNMP; Temporal: yearly in 2020-2024	Ministerial Decree of Environment No. 4 of 2001
	SPP	Number of species occurrences based on the IUCN status improvement			IUCN conservation status 2004-2024
TR	–	Total tourist visits	BPS	Spatial: Provincial data; Temporal: yearly 2019-2024	Average national value
		Number of tourism accommodations			Maximum national value
AO	–	Number of fishers and Number of small-scale fishing vessels <5 GT	KKP Data Portal	Spatial: NTT; Temporal: yearly 2020-2024	Maximum national value
SP	–	Number of protected species observed in the Savu Sea waters	BKKPN Kupang	Spatial: NTT; Temporal: yearly 2024	IUCN conservation status (2004-2024)

Table 2: The weight for each goal

Goal	Weight		Rationale
	Scenario 1 (Preservationist)	Scenario 2 (Ecocentric Framework)	
CW	0.15	0.2	Essential for ecosystem health; more emphasized in Scenario 2 for ecological balance.
CS	0.15	0.2	Important for climate mitigation and ecosystem services in both scenarios.
FP	0.05		Minor role in Scenario 1 for conservation, excluded in Scenario 2.
NP	0.05		Excluded in Scenario 2; minimal relevance for ecological assessment.
LE	0.10		Socio-economic relevance in Scenario 1, excluded in Scenario 2.
CP	0.10	0.2	Coastal protection is vital in maintaining ecosystem resilience, particularly in the face of climate change. It is highly relevant to both scenarios but receives slightly more weight in Scenario 2, as it directly contributes to ecological health.
BD	0.15	0.2	Core to both scenarios; central for maintaining ecosystem function.
TR	0.10		Socio-economic benefit in Scenario 1, excluded in Scenario 2.
AO	0.05		Relevant in Scenario 1 for socio-economic benefit, excluding in Scenario 2.
SP	0.10	0.2	Cultural and ecological value in both scenarios, with higher emphasis in Scenario 2.

Trend, pressure, and resilience

Trend represents changes in status over the previous five-year period and is used to estimate the likely future condition of each goal within the OHI framework. In assessing probable future conditions, the trend component is given twice the weight of the disparity between resilience and pressure, highlighting its significant influence on forecasting future ecosystem performance. Trends quantify proportional changes in status and generally range from −100% to +100% (−1.0 to +1.0), with values constrained within this range to ensure comparability across indicators. Trend calculations typically rely on data covering at least five years to provide a reliable basis for assessing long-term ecological and socio-economic dynamics. Nevertheless, in numerous instances, year-on-year (YoY) data were utilized because of the restricted availability of long-term data. For instance, protein consumption under the FP goal and the income of fisheries business actors in East Nusa Tenggara under the ECO sub-goal were derived from annual datasets. These indicators were analyzed using shorter temporal scales because they reflect more immediate fluctuations, such as seasonal variations or yearly economic performance. Even though this results in certain temporal inconsistencies, the application of shorter-term trends continues to be important for recognizing recent developments in food security and fisheries economics relevant to SSNMP management. Future assessments may benefit from more standardized multi-year datasets as they become available. The Pressure and Resilience components were evaluated using a structured questionnaire administered to five representatives from BKKPN Kupang responsible for managing the four regions of the SSNMP. The survey was based on expert assessment derived from management experience and field observations, incorporating both ecological and socio-economic considerations within the MPA. Responses were recorded using a Likert scale ranging from “strongly disagree” to “strongly agree” and converted into a numerical scale of 0–100. The participants included four regional supervisors and one head supervisor, all of whom possess significant expertise in ecosystem monitoring, fisheries management, and conservation practices in SSNMP. Final pressure and resilience values were calculated by averaging the scores from the five experts. Although the sample size was limited, this approach was intended to capture informed qualitative insights from experienced managers. The resulting values consequently reflect a comprehensive estimate of pressure and resilience, based on the collective knowledge of SSNMP management personnel.

Sensitivity test

The Monte Carlo (MC) methodology used for the sensitivity and uncertainty analysis of the OHI+ model for the SSNMP involved the application of random sampling techniques to account for uncertainties in goal weights, pressure, and resilience scores. commenced with the adjustment of goal weights according to a normal distribution to incorporate random variations, where the 50% uncertainty factor facilitated a wide array of weight values. Similarly, pressure and resilience scores were modified using log-normal distributions, which were derived from expert judgment to reflect the uncertainty in these parameters. After applying these variations, the OHI+ score for each simulation was determined by averaging the values of the current status alongside the anticipated future status of each goal. The Preservationist and Ecocentric scenarios were evaluated by adjusting the weights in accordance with management priorities, allowing the simulation to capture the impact of different scenarios on marine ecosystem health. The procedure entailed executing 1,000 simulations for every scenario to guarantee a thorough examination of variability and stability within the model. This method facilitated an investigation into the variety of potential results, providing a solid structure for comprehending the uncertainty inherent in the OHI+ scoring system (Zhang, 2020; McFarland and DeCarlo, 2020).

OHI workflow

The workflow for ensuring reproducibility of the OHI+ framework follows the methodology proposed by Halpern *et al*. (2012), focusing on the calculation of status, likely future status, and the overall OHI score. The process initiates with the selection of pertinent goals and subgoals, taking into account the ecological and socio-economic context of the study area. Indicators are then identified using available data sources, including satellite observations, government reports, and expert judgment. Indicator status is assessed by evaluating observed values in relation to established reference points, which helps in determining the current performance of the ecosystem. The likely future status is subsequently estimated by incorporating trends, pressures, and resilience factors that may influence future ecosystem conditions. The overall OHI score is calculated through a weighted combination of goal scores utilizing the OHI formula, which can be modified to align with local conservation priorities. To support transparency and reproducibility, the methodology is presented using clear workflow diagrams and comparative analyses with previous OHI applications.

RESULTS AND DISCUSSION

Ocean health status of SSNMP

The case study of SSNMP resulted in a score of 69 for Scenario 1 and 87 for Scenario 2. These results are comparable to the global OHI assessment for Indonesia, which reported a score of 66 (Halpern *et al*., 2012). Detailed results of the OHI measurement for SSNMP are presented in Table 3 and Figs. 2 and Fig. 3. The scores are primarily influenced by two factors: the selection of goals and the weighting scheme applied. Scenario 1 employs a preservationist strategy that emphasizes ecological objectives, including CW, CS, and BD, while also integrating socio-economic factors to offer a more thorough assessment of MPA effectiveness. In contrast, Scenario 2 focuses exclusively on ecological goals, producing a higher score of 87. This reflects the strong ecological condition of SSNMP, particularly in terms of carbon storage and biodiversity. High scores for CW, CS, and BD indicate strong ecological performance, supported by the presence of key coastal habitats such as mangroves, seagrass meadows, and coral reefs, as well as generally good water quality conditions. Robust governance and zoning strategies further bolster ecosystem resilience through the facilitation of biodiversity preservation and carbon sequestration. These findings align with previous studies highlighting

Table 3: OHI Measurement for SSNMP

Goal	Subgoal	Score	Current status	Likely future status	Trend	Pressures	Resilience
CW		96	98	94	0.194	55	40
CS		99	97	100	0.307	50	80
FP		65	48	83	1	50	75
NP		24	25	23	-0.138	45	55
LE		34	33	34	-0.038	55	70
	LIV	19	19	19	-0.065	55	70
	ECO	48	47	50	-0.012	55	70
CP		71	73	70	-0.090	65	70
BD		82	75	90	0.167	55	75
	HAB	91	83	99	0.29	55	75
	SPP	74	67	80	0.04	55	75
TR		25	23	27	0.163	60	75
AO		30	27	33	0.199	50	80
SP		87	73	100	0.8	45	75
Overall index for scenario 1					69		
Overall index for scenario 2					87		

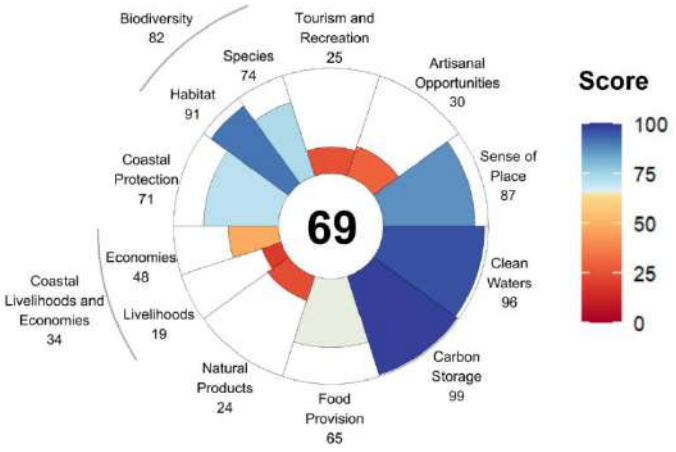

Fig. 2: Goal and Sub Goal for the SSNMP (Scenario 1)

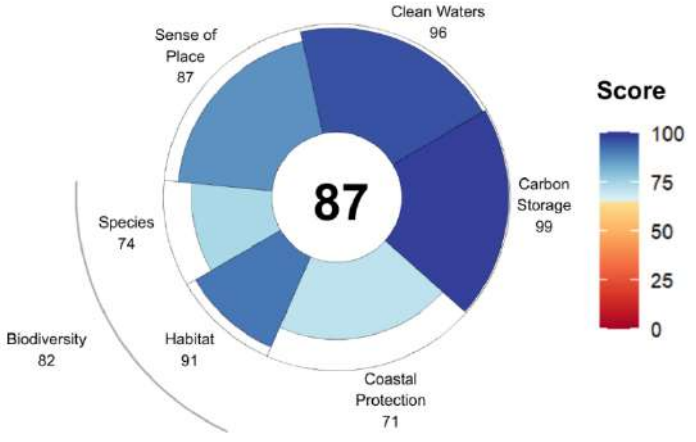

Fig. 3: Goal and sub goal for the SSNMP (Scenario 2)

the importance of well-maintained ecosystems for successful MPAs. However, lower scores for AO, NP, and LE indicate challenges within the fisheries value chain, including post-harvest handling, market access, and infrastructure limitations. These challenges are additionally affected by restricted livelihood diversification and governance capacity. Previous studies emphasize that governance quality, staff capacity, and adequate funding are crucial for achieving both ecological and socio-economic outcomes in MPAs (Picone *et al*., 2021; Susilowati *et al*., 2024). Confronting these obstacles through strategic interventions could lead to improved local economic outcomes and bolster community-driven resource management. The dual-scenario approach provides a nuanced perspective on SSNMP performance. Scenario 2 highlights the park's ecological strengths, while Scenario 1 emphasizes the need to improve socio-economic outcomes to enhance conservation effectiveness. Nevertheless, this approach has several limitations. Scenario 2 excludes socio-economic goals, which may artificially increase the score and represent ecological potential rather than a comprehensive measure of ecosystem health. Furthermore, the weighting schemes rely on normative viewpoints instead of stakeholder preferences that are derived from empirical evidence. Future studies could incorporate participatory weighting approaches (Daigle *et al*., 2017). Ultimately, the analysis addresses ecological and socio-economic objectives independently, even though they interact dynamically, for instance, how enhancing artisanal fishing opportunities may influence biodiversity outcomes. These limitations suggest that scenario-based assessments should be interpreted as diagnostic tools rather than definitive management decisions.

Sensitivity Analysis and Uncertainty Assessment

The MC simulations for the OHI+ sensitivity analysis of SSNMP reveal that the model is robust to uncertainty in goal weights, pressure, and resilience scores. In the Preservationist scenario, the mean OHI+ score was 76.3, significantly higher than the base score of 69, with a 95% confidence interval (CI) of [73.1, 79.7], indicating an improvement under conservation-focused management. Similarly, the Ecocentric scenario produced a mean score of 96.3, with a 95% CI of [93.7, 98.7], confirming that ecological goals lead to higher and more stable outcomes. The coefficient of variation (CV) for most ecological objectives (for instance, 0.022 for CW and 0.020 for CS) was low, signifying minimal variability in the results. However, socio-economic goals (such as NP and TR) showed higher CVs, indicating greater sensitivity to changes in goal weights (Borgonovo and Plischke, 2016). Table 4 presents a summary of the results from the sensitivity analysis, illustrating the stability and variability observed in both the Preservationist and Ecocentric scenarios.

The uncertainty assessment further emphasizes that weights contribute the most to the total uncertainty (45%), followed by pressure (25%) and resilience (15%). This discovery emphasizes the considerable influence that differences in goal weight distribution exert on the OHI+ score, stressing the importance of meticulous management of goal weights in the decision-making process. MC simulations, widely used for uncertainty quantification (UQ) in computational models (Zhang, 2020), have proven effective in propagating uncertainty through nonlinear models. These methods are also applied in risk assessment and instrumentation (McFarland and DeCarlo, 2020) which underscores the significance of MC simulations in evaluating uncertainty for intricate models such as OHI+. These insights are clearly illustrated in Fig. 4.

Key environmental and ecological factors

The ecological state of the marine ecosystem in SSNMP is influenced by the interplay of physical environmental characteristics, habitat structure, and human-induced influences. Within the OHI

Table 4: MC Simulation Results for OHI+ Sensitivity Analysis

Goal	Base Score	Mean Score		95% CI		CV		Weight Sensitivity
		Preservationist	Ecocentric	Preservationist	Ecocentric	Preservationist	Ecocentric	
CW	69	76.3	96.3	[73.1, 79.7]	[93.7, 98.7]	0.022	0.013	High
CS	69	76.6	96.8	[73.0, 79.7]	[93.7, 98.7]	0.020	0.014	High
FP	65	62.1	74.2	[60.0, 64.4]	[72.0, 76.0]	0.022	0.017	Medium
NP	24	31.2	45.0	[27.9, 34.5]	[43.5, 47.5]	0.087	0.026	High
LE	33	35.8	49.5	[32.5, 39.0]	[47.5, 51.5]	0.025	0.019	Medium
CP	73	74.1	89.3	[71.9, 77.0]	[87.0, 91.5]	0.018	0.014	Low
BD	75	78.1	96.0	[74.9, 81.3]	[94.0, 98.0]	0.019	0.013	High
TR	23	30.0	45.0	[27.5, 32.0]	[43.5, 46.0]	0.040	0.03	High
AO	27	29.6	35.8	[27.0, 32.0]	[34.5, 37.0]	0.047	0.025	Medium
SP	73	77.0	93.5	[74.0, 80.0]	[92.0, 95.0]	0.019	0.015	Medium

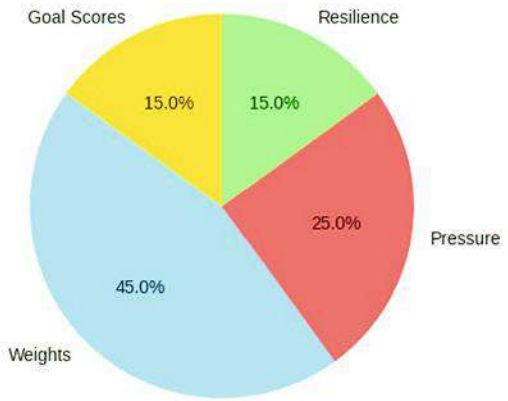

Fig. 4: Uncertainty Decomposition (Approximate)

framework, ecological performance is influenced by several environmental drivers, including water quality, habitat condition, carbon storage capacity, biodiversity support, coastal stability, and cultural ecosystem values associated with coastal landscapes. These drivers are represented through five ecological goals: CW, CS, BD, CP, and SP. Collectively, these indicators connect environmental conditions and ecosystem services to the overall ecological performance of the marine protected area. The high CW score of 96 indicates that water quality in SSNMP remains generally favorable for marine ecosystems. Most physicochemical parameters, including pH, salinity, SST, chlorophyll-a, and DO, remain within ecologically suitable ranges. To verify the parameters obtained from satellite data, remote sensing information was contrasted with in-situ measurements gathered from multiple sampling sites throughout SSNMP. These measurements, conducted by local authorities such as the NTT Forestry and Environmental Agency, provide ground-truth data for evaluating satellite observations. Sampling data from June and August 2023 recorded pH values between 7.8 and 8.4, salinity ranging from 27.4 to 33.3 practical salinity unit (PSU), and SST between 28.2°C and 32.5°C. These values correspond closely with satellite-derived reference ranges for the same period (SST: 28–30°C, salinity: 33–34 PSU, and pH: 7.5–8.5). Despite the observation of minor discrepancies, especially with slightly elevated salinity levels noted in satellite data, the analysis suggests that remote sensing offers a dependable estimation of marine environmental conditions. Monitoring data between 2020 and 2024 show that water

quality remains within acceptable thresholds defined in Government Regulation of the Republic of Indonesia No. 22 of 2021, suggesting that current conditions remain suitable for marine ecosystem health. However, spatial analysis using Marine Copernicus data revealed slight declines in pH in some coastal areas, which may reflect localized environmental variability related to pollution inputs or climate-related oceanographic processes (Selig *et al*., 2015). These variations illustrate hydro-biogeochemical alterations that arise from the interplay between hydrological circulation, the chemical characteristics of seawater, and biological ecosystem processes, which together govern ecosystem productivity and habitat stability. Changes in parameters such as pH, salinity, DO, and nutrient dynamics can influence ecosystem functioning by affecting carbonate chemistry, primary productivity, and habitat conditions. Reduced pH may affect carbonate saturation states required for coral calcification, while declining salinity may indicate increased freshwater input from precipitation, runoff, or hydrodynamic variability. The simultaneous increase in freshwater input has led to a decrease in tidal mixing, localized surface freshening, and reduced flushing efficiency, indicating that freshwater forcing may be a potential driver of these environmental changes (Kudela *et al*., 2023). Such variability may influence turbidity, nutrient availability, and habitat quality, potentially affecting seagrass productivity and coral reef stability. Habitat condition represents another key driver influencing several ecological goals, particularly BD, CS, CP, and SP. Coral reefs, mangroves, and seagrass meadows form the structural foundation of marine ecosystems in SSNMP. Within the BD goal, the HAB sub-goal reflects the condition and spatial extent of these ecosystems. Coral reef conditions remain relatively moderate but still require continued restoration following disturbances such as Cyclone Seroja in 2021 (Toruan *et al*., 2024). Mangrove cover remained relatively stable at 68.7% in 2024, although fluctuations in density occurred due to environmental pressures. Seagrass beds have exhibited enhancement, with a present status of 57.64% in 2024 subsequent to a considerable drop in 2021, implying that restoration efforts are playing a role in the recovery of the ecosystem (Fourqurean *et al*., 2012). Mangrove forests and seagrass ecosystems also contribute significantly to CS as key blue carbon ecosystems that store large amounts of organic carbon in coastal sediments (Fourqurean *et al*., 2012). Alongside carbon sequestration, these ecosystems fulfill important ecological functions, providing nursery grounds, feeding habitats, and protection for marine organisms. These functions support the SPP sub-goal under BD by maintaining habitats that allow marine species to persist and maintain stable populations. Healthy coral reefs and seagrass ecosystems also support reef-associated fish assemblages and marine biodiversity, reinforcing the ecological performance of SSNMP. Prior studies indicates that healthy and diverse coastal ecosystems are strongly linked to higher fish biomass and enhanced ecosystem performance within marine protected areas (Clausius *et al*., 2025). SP was assessed based on the presence of protected and conservation-relevant marine species within the park, using their conservation status according to the IUCN Red List as the reference. The occurrence of species with higher conservation importance contributes to the cultural and conservation value of SSNMP as a marine protected area preserving species of ecological and societal significance. CP denotes another environmental objective that is affected by both the state of the habitat and the movements of the shoreline. Mangrove forests, seagrass beds, and coral reefs function as natural barriers that reduce wave energy, stabilize sediments, and protect shorelines from erosion. In SSNMP, shoreline dynamics vary across regions based on EPR analysis. Region 1 (Sumba Barat and Manggarai Barat) showed relatively stable shoreline conditions with light accretion (EPR 0.94 m/y), indicating effective natural coastal

protection. In contrast, Region 2 (Sumba Timur and Sabu Raijua) and Region 4 (Rote Ndao and Kupang) experienced significant erosion with negative EPR values, indicating increased vulnerability to coastal abrasion. The current OHI score for CP is 73, reflecting moderate protection but also highlighting potential degradation if erosion pressures persist. Overall, the ecological performance of SSNMP is influenced by external pressures such as pollution, overfishing, and climate-related environmental variability. Effective governance, which encompasses the creation of no-take zones, the promotion of ecological connectivity among protected areas, and the management of external pressures, is crucial for preserving ecosystem integrity and resilience (Dunham *et al*., 2024). Marine protected areas characterized by good water quality, intact coastal habitats, and relatively low anthropogenic pressures tend to demonstrate stronger ecological performance. The aforementioned conditions are instrumental in the notably high ecological scores recorded in SSNMP, which accentuates the importance of persistent monitoring and a unified ecosystem-based management framework to uphold long-term ecological resilience.

Socioeconomic factors

The OHI framework is uniquely positioned to evaluate marine management by treating the ocean as an integrated socio-ecological system. By assessing both ecological and socio-economic factors, OHI highlights significant trade-offs and synergies in resource management, progressing beyond mere ecological analyses (Halpern *et al*., 2017). Application of the OHI+ framework to SSNMP illustrates this dynamic by uncovering socio-economic deficits that may threaten the long-term ecological success of the MPA. Although the region possesses high natural capital, these assets have not been fully translated into sustainable human well-being, a challenge often observed in conservation areas that do not sufficiently address local livelihoods (Ma *et al*., 2016; Gulseven, 2020). The analysis points out two primary concerns: a faltering fisheries value chain and inadequately developed alternative economic sectors. First, low scores for LE (34), FP (65), and AO (30) indicate structural weaknesses within the fisheries system. Low NTN (89.49) and incomes below the provincial minimum wage suggest that fishing alone is not a viable livelihood, which can discourage sustainable practices. This vulnerability is exacerbated by relatively low fish production 137,029.90 tons, which is significantly below the target of 400,000 tons, and the restricted community nutrition characterized by a protein intake of 8.32 g/d. Collectively, these elements create a cycle where economic pressure contributes to unsustainable resource use. Similar patterns have been reported in other developing regions where limited post-harvest infrastructure and market access constrain the economic potential of small-scale fisheries (Elfes *et al*., 2014). Second, the low NP (24) and TR (25) scores highlight limited diversification in the local economy. Shortfalls in seaweed and salt production, together with the large gap in tourism potential (less than 8 million visits compared to a target exceeding 52 million), represent missed opportunities. These sectors might mitigate the stress on fish stocks by creating more employment opportunities and generating additional income. The limited availability of accommodation units and the low volume of tourist visits indicate that the region's natural resources are not being fully utilized. Investing strategically in sustainable tourism and enhancing marine products could bolster economic resilience, as evidenced in other Marine Protected Area (MPA) scenarios (Sala *et al*., 2021). The socio-economic landscape of East Nusa Tenggara, particularly in the Savu Sea region, reflects a diversified livelihood structure. Although communities maintain strong cultural ties to fishing, many households rely primarily on inland agriculture, small businesses, or wage labor. Fishing remains important for food security and cultural identity, but its economic contribution is often supplementary. Studies on small-scale fisheries in SSNMP describe the fishing economy

as "poor," with households facing financial vulnerability and relying on additional income sources (Ninef *et al*., 2018). This livelihood framework elucidates the reason behind the lower scores in socio-economic indicators during the OHI+ assessment, even in the presence of robust ecological conditions. Limited development of the fisheries value chain and alternative sectors such as tourism or mariculture has restricted the translation of ecological success into economic benefits. Addressing these gaps requires improved market access, stronger community-based management, and sustainable livelihood opportunities aligned with local capacities. These issues illustrate larger patterns observed in small-scale fisheries worldwide, where financial instability may result in the unsustainable resource utilization (Fabinyi *et al*., 2022; Sulu *et al*., 2015). Increasing resilience therefore requires livelihood diversification, improved governance, and stronger institutional support (Stacey *et al*., 2021; Ateweberhan *et al*., 2018). Integrating ecological conservation with socio-economic development will be essential to ensure long-term benefits for both marine ecosystems and coastal communities in SSNMP.

Comparison with other OHI assessments

The comparative OHI assessment of Fiji, SSNMP, and the Tokyo Metropolitan Area highlights a pronounced socio-ecological gradient, illustrating diverse approaches to marine resource management. The analysis for each objective is illustrated in Fig. 5, highlighting the variations among the three regions. Fiji exhibits elevated OHI scores in both ecological (for instance, BD, CW) and socio-economic (such as, TR, LE) aspects, indicating a comprehensive management strategy. In Fiji, ecological health supports economic prosperity through community-based co-management and a strong tourism sector (Halpern *et al*., 2015; Gazioğlu, 2018). In contrast, the Tokyo Metropolitan Area exhibits low biodiversity and carbon storage scores, reflecting the impacts of urban and industrial development. Economic pressures and rapid urbanization have led to significant ecological degradation and depletion of natural resources (Wu *et al*., 2021; Ding and Tabeta, 2024). This contrast underscores the necessity of blending ecological and socio-economic aspects in the management of marine resources. SSNMP occupies an intermediate position, with moderate ecological health but notable socio-economic limitations. Ecological indicators such as CW and BD perform relatively well, yet low scores for AO and FP indicate limited translation of conservation outcomes into benefits for local communities (Gill *et al*., 2017). This disparity poses difficulties in harmonizing ecological benefits with the welfare of the community, especially in situations where economic fragility might promote unsustainable utilization of resources (Fabinyi *et al*., 2022; Sulu *et al*., 2015). This comparison demonstrates the value of the OHI framework in identifying trade-offs between ecological integrity and socio-economic development. For SSNMP, management strategies should focus on strengthening artisanal fisheries value chains, promoting sustainable tourism, and ensuring that conservation policies support local livelihoods. The implementation of adaptive governance and sustained monitoring will be vital for upholding ecological integrity and simultaneously boosting community benefits (Halpern *et al*., 2017; Gulseven, 2020; Lowndes *et al*., 2015). Fiji's integrated approach offers a model of sustainable management, with OHI scores generally ranging from 70 to 90 across categories such as CW, BD, and TR. In comparison, SSNMP shows moderate scores between 50 and 80, indicating relatively healthy ecosystems but weaker socio-economic outcomes. The Tokyo Metropolitan Area, which has scores ranging from 15 to 55, exemplifies the difficulties of reconciling urban growth with marine conservation. These differences emphasize the need for context-specific management strategies to bridge ecological sustainability and socio-economic well-being. Detailed comparisons are presented in Table 5.

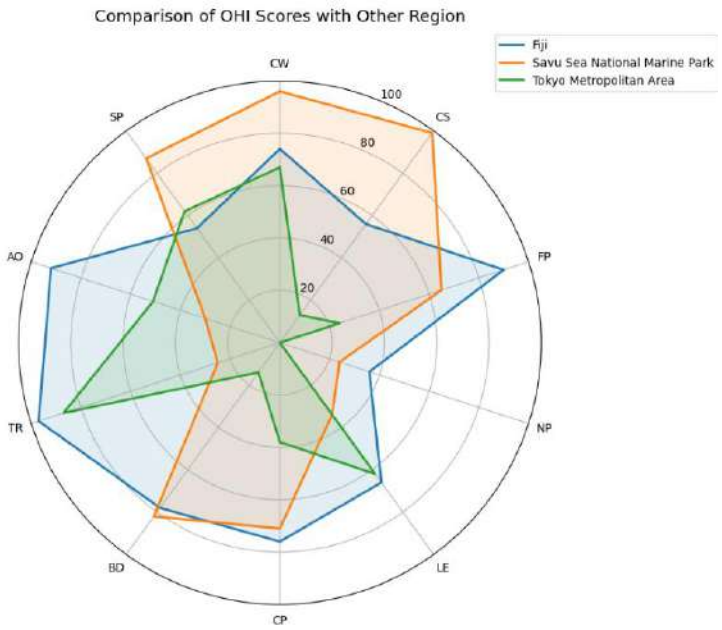

Fig. 5 Comparison of OHI scores with other countries and areas

Table 5: OHI+ SSNMP Comparison from other countries and areas (Fiji and Tokyo Metropolitan Area)

Aspect	Fiji	Tokyo Metropolitan Area	SSNMP
Ecological Performance	High OHI scores across both ecological and socio-economic dimensions, such as CW and BD.	Low scores in BD, CS, and AO, indicating significant ecological degradation.	Moderate ecological health with strong scores for CW and BD.
Socio-Economic Performance	Balanced socio-economic growth through community-based co-management and thriving tourism linked to ecosystems.	Moderate TR but a focus on urban-industrial development at the expense of environmental sustainability.	Low socio-economic outcomes (AO and FP).
Governance and Co-Management	Community-based co-management strategies.	Fragmented governance and lack of integration between urban development and ecological management.	Weak governance, lack of community participation, leading to socio-economic deficits.
Key Lessons for MPA Management	Integrated management that balances ecological protection and socio-economic development, with community involvement in decision-making.	Importance of avoiding overdevelopment and balancing ecological protection with socio-economic growth.	Need for strengthening governance, integrating sustainable livelihood development, and improving community involvement.
OHI Scores	CW = 96, BD = 90, TR = 85, LE = 80	CW = 75, BD = 40, CS = 20, AO = 10	CW = 87, BD = 85, FP = 45, AO = 30
Similarities	All three areas emphasize the importance of marine conservation and community-based management strategies.	Like Fiji, SSNMP and Tokyo are both MPA models, though Tokyo's model leans toward urban development, while SSNMP struggles to achieve balance.	SSNMP shares similarities with Fiji in terms of strong ecological health but lacks the same socio-economic outcomes.
Differences	Fiji integrates socio-economic development with ecological protection effectively.	Tokyo shows high ecological degradation due to urban pressures and industrialization, focusing on economic growth over conservation.	SSNMP has moderate ecological health but significant socio-economic deficits, a "paper park" issue.

In terms of conservation priorities, the study highlights the importance of balancing biodiversity conservation with socio-economic development. Given the MPA's relatively high ecological health, particularly in CW and CS, conservation efforts should focus on maintaining these areas. It is crucial, however, to also focus on the socio-economic factors that are currently not performing well. The main priorities should encompass safeguarding essential habitats for marine biodiversity, while ensuring that local communities reap the benefits of sustainable resource management. Emphasis should be placed on improving artisanal fisheries, which remain a central livelihood for coastal communities, and addressing food security through improved fisheries management and sustainable practices. Prioritizing ecosystem-based management that incorporates socio-economic factors will be key to aligning conservation goals with community development.

CONCLUSION

The OHI+ analysis of SSNMP reveals a marked disparity between ecological success and socio-economic outcomes. While the area shows strong ecological performance, with high scores for indicators like CW = 96 and CS = 99, socio-economic indicators such as AO = 30 and FP = 34 suggest significant challenges. This disparity illustrates a wider global trend, wherein community-driven conservation initiatives frequently meet ecological objectives yet struggle to deliver stable socio-economic advantages. Despite strong ecological protection, local communities continue to face issues such as unsustainable fishing practices, limited market access, and inadequate post-harvest infrastructure. These socio-economic challenges highlight the limitations of a conservation strategy that prioritizes ecological outcomes alone, echoing findings from global studies that governance design and benefit distribution are key factors in bridging this gap. To address this imbalance, it is crucial to implement a paradigm shift in the management approach at SSNMP. While the ecological accomplishments shown by the OHI+ framework are important, the detected socio-economic gaps reveal a pressing requirement for specific interventions. Future management strategies must focus on strengthening the fisheries value chain, fostering alternative livelihoods such as sustainable tourism, and enhancing community-based governance. These initiatives would ensure that conservation efforts are not only ecologically successful but also translate into meaningful socio-economic improvements for local communities. Moreover, future investigations should examine the influence of integrated socio-ecological strategies on conservation effectiveness and human well-being, specifically concentrating on how governance arrangements and benefit-sharing practices can be refined to establish more inclusive communities in marine protected areas. The long-term sustainability of large-scale MPAs, such as SSNMP, depends on an integrated management paradigm that aligns ecological resilience with community-centered economic development. This study underscores the necessity of establishing long-term monitoring systems that link ecological indicators with socio-economic outcomes, enabling holistic assessment of ecosystem health and human well-being. Effective monitoring ought to yield clear, policy-relevant indicators that represent economic and social value. This includes establishing connections between plankton dynamics and fish stocks, as well as catch yields, while also tracking long-term trends to assess climate change and

management interventions. Such systems should prioritize socially and economically valuable components including fisheries, tourism, and coastal protection within broader ecosystem assessments. The collaboration between national and regional monitoring networks, facilitated by standardized indicators and open-access data platforms, can significantly improve evidence-based decision-making across jurisdictions. In the context of SSNMP, strategic interventions must prioritize strengthening the artisanal fisheries value chain, improving market access, and fostering sustainable tourism under a robust governance framework. Integrating fisheries management, habitat protection, and tourism development ensures that ecological conservation and socio-economic objectives are mutually reinforcing. An integrated management model rooted in ecosystem-centric methods and engaged community participation is vital for transforming conservation investments into durable benefits. Ultimately, the success of SSNMP rests on its ability to bridge the gap between ecological integrity and socio-economic prosperity, securing a resilient future for both marine ecosystems and the coastal communities that depend on them.

AUTHOR CONTRIBUTIONS

F.Y. Arthatiani was responsible for the conceptualization of the study, drafting the manuscript, and editing the final version. M.R. Putri provided supervision and contributed to the manuscript's editing, while L.I. Bernawis developed the methodology. N.F. Gusmawati contributed to the manuscript by adding relevant references, and K. Kasim was involved in both editing and writing sections of the manuscript. F. Hidayat conducted field investigations and collected data. S.W. Trenggono provided overall supervision, and T. Yuwono contributed to the administration of the project. All authors participated in the interpretation of the results, critically reviewed the manuscript, and approved the final version. The specific contributions of each author have been individually recognized and acknowledged.

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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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☑ **Negative AI Statement**

The author(s) declared that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
AO	Artisanal fishing opportunity
BD	Biodiversity
BKKPN	Regional Office for Marine Protected Areas
BPPSDM	Agency for Extension and Human Resources Development
BPS	Statistics Indonesia
CI	Confidence interval
CV	Coefficient of variation
CP	Coastal protection
CS	Carbon storage
CW	Clean waters
DO	Dissolved oxygen
ECO	Economies
EPR	End point rate
FP	Food provision
g/d	Grams per day
GIS	Geographic Information System
GT	Gross tonnage
HAB	Habitat
i	**Index (subscript) indicating each goal**
I	Overall ocean health index score
I_i	Score for each goal
IUCN	The International Union for Conservation of Nature
k	The length of the projection periods (years)
KKP	Ministry of Marine Affairs and Fisheries
KLHK	Ministry of Environment and Forestry
LE	Coastal Livelihoods and Economies
LIV	Livelihoods
MC	Monte Carlo
MPA	Marine protected area
MPAs	Marine protected areas
MSY	Maximum sustainable yield
N	Number of goals
NP	Natural products
NTN	Fishermen's exchange rates
NTT	East Nusa Tenggara
OHI	Ocean health index
OHI+	Ocean health index plus
p_i	Pressure per goal
pH	Potential of Hydrogen
PSU	Practical Salinity Units
r_i	Resilience per goal
$Slope(y,t)$	Slope of the linear regression
SP	Sense of place
SPP	Species
SSNMP	Savu Sea National Marine Park
SST	Sea surface temperature
T_i	Trend
TR	Tourism and recreation
UC	Uncertainty quantification
w	Weight
x_i	Present status
X_i	Current evaluation score

$X_{i,R}$	Reference value
$\hat{x}_{i,F}$	Likely future status
YoY	Year-on-year
α_i	Weight per goal
β	The weighting parameter
δ	Discount rate
$\sum$	Sigma

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ORIGINAL RESEARCH PAPER

Carbon footprint assessment for university campuses using corporate accounting and reporting standard protocol

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ABSTRACT

BACKGROUND AND OBJECTIVES: In the context of the intensifying global climate crisis, higher education institutions have become crucial participants in the cross-sectoral shift towards achieving carbon neutrality. The study objectives were to present a comprehensive carbon footprint assessment for Phase I of a multi-campus initiative at the Universidad Cooperativa de Colombia. It involved emissions across seven urban campuses from 2019 to 2022 to ensure alignment with national sustainability targets and global climate action goals.

METHODS: Following the Corporate Accounting and Reporting Standard Protocol -2005, the research quantified Scope 1 (direct), Scope 2 (indirect electricity), and selected Scope 3 (staff air travel) emissions for the period 2019–2022. Data collection used standardized virtual forms to assemble institutional records, including fuel receipts, utility bills, and air travel logs provided by the Aviatur travel agency. Emissions were assessed by taking the activity data and multiplying it by both city-specific and international emission factors, ensuring that all values are expressed in tons of carbon dioxide equivalents.

FINDINGS: For campuses in cold climatic zones, 2022 CF values were 174.9- ton carbon dioxide equivalents (0.0143- ton carbon dioxide equivalents/person) in Bogotá and 75.4- ton carbon dioxide equivalents (0.0152- ton carbon dioxide equivalents/person) in Pasto, representing reductions of 15.93 percent and 27.72 percent relative to 2019. In mild climatic zones, 2022 emissions were 147.5 ton carbon dioxide equivalents (0.0163 ton carbon dioxide equivalents /person) for Ibagué–Espinal, 200.8 ton carbon dioxide equivalents (0.0270 ton carbon dioxide equivalents/person) for Medellín, 258.8-ton carbon dioxide equivalents (0.3839 ton carbon dioxide equivalents/person) for National, 239.1-ton carbon dioxide equivalents (0.1111-ton carbon dioxide equivalents/person) for Pereira–Cartago, and 67.7 ton carbon dioxide equivalents (0.0375-ton carbon dioxide equivalents /person) for Popayán, with percentage variations of +8.78 percent, +33.06 percent, +60.75 percent, +5.18 percent, and +37.56 percent from 2019 baselines, respectively.

CONCLUSION: Across all campuses, Scope 2 electricity consumption was identified as the primary emission source, followed by Scope 1 fugitive emissions and Scope 3 staff travel. Key mitigation efforts encompassed the installation of solar-powered luminaires in Bogotá and energy-efficient light-emitting diode in Pasto. The outcomes emphasize the importance of implementing energy-efficiency programs, better upkeep of air-conditioning units, and minimizing travel to mitigate emissions. These findings provide Universidad Cooperativa de Colombia with actionable insights for its 2025 carbon neutrality goal and offer a replicable model for higher education institutions to standardize carbon accounting frameworks in alignment with international protocols.

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INTRODUCTION

Greenhouse gas (GHG) emissions have accelerated climate change faster than previously anticipated (Bamniya *et al.,* 2024; Poddar, 2024). Thus, mitigating GHG emissions is among the most critical measures to combat climate change (IPCC, 2014). Mitigating global warming could assist in lessening its negative impacts, such as wildfires, hurricanes, droughts, floods, and water shortages (Tanjeela and Billah, 2022; Nordhaus, 2010; Kim *et al.,* 2023). Colombia is particularly vulnerable to climate change owing to two major climatic phenomena: El Niño and La Niña (Hoyos *et al.,* 2013; Vargas *et al.,* 2018). In this region, climate change not only heightens temperature spikes but also contributes to the deterioration of water quality (Barrucand *et al.,* 2017; Rios *et al.,* 2022). Consequently, Colombia has set a national target to reduce its GHG emissions by 51 percent (%) by 2030, ultimately aiming to achieve carbon neutrality by 2050 (Acevedo *et al.,* 2023). Carbon neutrality refers to balancing anthropogenic carbon dioxide (CO_2) emissions with their removal from the atmosphere (Chen *et al.,* 2024; Ren *et al.,* 2024). Nonetheless, contemporary approaches aimed at minimizing carbon footprints (CFs) now focus on attaining negative carbon footprints (NCFs) (Kharissova *et al.,* 2024). Achieving an NCF goes beyond net-zero by removing more CO_2 than is emitted (Salvia *et al.,* 2021). Proposed pathways include carbon-negative and carbon-storing materials and other mitigation strategies (Kharissova *et al.,* 2024). Consequently, effective CF reduction necessitates a collaborative, multi-sectoral effort that includes governments, industries, and higher education institutions (HEIs). Following this approach, many HEIs worldwide aim to develop sustainable buildings and infrastructure designed to conserve energy and water, enhance indoor environmental quality, facilitate access to public transportation, and implement recycling programs (Biancardi *et al.,* 2023; Leal Filho *et al.,* 2018). A multitude of peer-reviewed studies have explored various methods and strategies aimed at quantifying and minimizing CFs at HEIs, providing significant insights for climate change mitigation (Yañez *et al.,* 2019; Varón-Hoyos *et al.,* 2021; Cano *et al.,* 2022). These studies typically focus on four key areas: 1) fundamental concepts and definitions (Peng *et al.,* 2024; Pan *et al.,* 2024); 2) evaluation methodologies and their advantages in lowering CFs (Ma *et al.,* 2023; García-Alaminos *et al.,* 2022); 3) impact of campus sustainability on different societal sectors (Dawodu *et al.,* 2022; Puertas *et al.,* 2023); and 4) policy and regulatory frameworks (Naz *et al.,* 2024; Nketiah *et al.,* 2024). To facilitate quantification, CF calculations are categorized into three scopes (WRI and WBCSD, 2005): Scope 1 encompasses emissions resulting from the combustion of stationary fuels, the use of refrigerants, and the operation of vehicle fleets. Scope 2 includes emissions from purchased electricity and on-site electricity generation. Scope 3 accounts for indirect emissions from water consumption, paper usage, food production, laboratory chemical usage, electronic equipment usage, fertilizer application, business travel, commuting, procurement activities, waste management, wastewater treatment and construction activities (Valls-Val and Bovea, 2021). In Colombia, the availability of peer-reviewed evidence regarding HEI carbon footprints is still limited and frequently centers on individual campuses. Additionally, methodological diversity—encompassing boundaries, scopes, emission factors, and denominators—restricts the ability to make comparisons (Varón-Hoyos *et al.,* 2021; Cano *et al.,* 2023; Osorio *et al.,* 2022). In this context, scientific evidence on university carbon footprints in Colombia remains scarce in peer-reviewed journals, which limits methodological traceability and the external validity of national benchmarking efforts. Although the GHG Protocol is well established, its usefulness for HEIs depends on consistent boundaries, normalization, and interpretation across heterogeneous campuses. Consequently, this study utilizes a unified

organizational boundary and standardized accounting principles throughout the campuses of Universidad Cooperativa de Colombia (UCC) campuses. Therefore, beyond reporting a single-campus footprint, the multi-campus design adopted in this study applies a single harmonized organizational boundary and consistent accounting rules across heterogeneous climatic and functional contexts. This facilitates a methodical analysis of the fluctuations in both absolute emissions and intensity metrics between campuses and from year to year, while differentiating (to the extent feasible based on the available activity data) contextual influences like climate-driven energy demand, types of operations, changes in enrollment and staffing, and external modifications in the national grid emission factor. In doing so, this study contributes a harmonized, multi-campus GHG inventory with explicit boundaries, transparent emission-factor selection, and uncertainty-informed interpretation, providing a replicable baseline for HEIs operating in data-constrained contexts. Importantly, this is UCC's first institution-wide exercise to establish a measurement–reporting–verification (MRV)-ready emissions baseline that informs its decarbonization roadmap and carbon-neutrality planning, while enabling systematic expansion to additional campuses and material Scope 3 categories as data systems mature. Therefore, the main objective of this study is to evaluate the CF at UCC based on scopes 1, 2, and 3. The UCC is a private HEI with 16 campuses located throughout Colombia, and its diverse campuses are dedicated to sustainability. Sustainability principles are embedded within UCC's institutional policies, and the university actively advocates for environmental responsibility and sustainable initiatives. One of its key objectives is to achieve carbon neutrality across all campuses by 2025. To track its progress toward this goal, the UCC conducted a comprehensive CF assessment covering the years 2019, 2020, 2021, and 2022. In light of the geographical spread and the dimensions of its campuses, the study was divided into two phases. The current study evaluates the findings from phase 1, covering Scope 1, Scope 2, and Scope 3 emissions for seven campuses. Additionally, UCC's National Structure, headquartered in Medellín, is treated as a separate campus, referred to as Campus National, owing to its administrative role within the university. This study reports Phase I results for seven urban campuses (2019–2022) and frames them for MRV-oriented decision support.

MATERIALS AND METHODS

As part of the update to the National Strategic Plan 2022–2025—which outlines the roadmap for the university's carbon neutrality goal in alignment with the 2030 Agenda and the transition to a sustainable multi-campus model—UCC conducted a two-phase institutional CF assessment across its campuses. This study outlines the findings from the initial phase, which encompassed six out of the 16 campuses, in addition to the National Structure: Bogotá, Ibagué–Espinal, Medellín, National Structure (in Medellín), Pasto, Pereira - Cartago, and Popayán. While the Espinal campus falls under the hot-dry climate category, it is grouped with Ibagué - Espinal as a single entity and was therefore included in the first phase. Furthermore, the National Structure is regarded as an independent campus—designated as the National campus—owing to UCC's organizational framework. The campuses in the first phase of the analysis were classified into two climate categories, based on Colombia's climate classification map, which considers temperature and relative humidity: mild (Medellín, National, Pereira - Cartago, Popayán, and Ibagué-Espinal) and cold (Bogotá and Pasto). This classification follows the Decree 0549 of 2015 (Minvivienda, 2015), a regulation supported by the International Finance Corporation. To maintain uniformity, the Decree 0549 'temperate' category is designated as 'mild' throughout the

manuscript, while the term 'cold' is used without alteration. Although Espinal is classified as hot-dry, it is operationally reported as part of the Ibagué–Espinal unit in Phase I; therefore, all results, tables, and figures retain the two-category reporting structure (cold vs. mild/temperate) for internal comparability.

Activity data collection

The inventory was developed using the GHG 2005 and its 2015 update (WRI and WBCSD, 2005). A detailed assessment of the university's operations, procedures, equipment, and resource usage was performed to pinpoint the emission sources that should be incorporated into the analysis, contingent upon the accessibility of data. Once these activities were identified, UCC personnel proceeded with data collection. Data collection was led by UCC's Social Projection function in collaboration with campus focal points, using standardized virtual forms and coordination meetings to ensure that the information was completed as accurately and precisely as possible. Activity data were collected obtained from all campuses involved for Scopes 1, 2, and 3, and each campus contributed the full annual consumption data necessary for the analysis. All campuses provided complete annual consumption data required for the analysis, resulting in a high level of data completeness across all included categories and reporting years. Scope 2 electricity consumption was obtained from monthly utility bills for all campuses and reporting years (100% completeness). For Scope 1, the annual amounts for refrigerant recharge and fire-extinguisher refill quantities were gathered from maintenance and service records. In instances where direct fuel consumption data for mobile sources were not consistently available, fuel volumes (liters) were reconstructed from expenditure records by applying city-specific annual reference prices from the national fuel information system (SICOM). Internal quality-assurance and quality-control (QA/QC) procedures encompassed cross-validation of annual totals with the orders of magnitude from the previous year, along with follow-up communications with campus focal points to examine and address any outliers. In cases where discrepancies could not be reconciled, conservative assumptions were applied to prevent underestimation of emissions. Scope 1 emissions encompassed mobile and stationary fuel combustion, as well as fugitive emissions from refrigerant losses and fire-extinguisher refills associated with the institution's internal operations. For fossil utilized by mobile sources, the compiled data encompassed vehicle type, model, license plate, propulsion type, and total annual fuel cost. Fuel volume in liters was estimated based on the annual average reference prices sourced from the fuel distribution chain information system (SICOM) of the Ministry of Mines and Energy (MME, 2024). City-specific fuel prices were applied to the Ibagué-Espinal, Medellín, National (in Medellín), Pereira - Cartago, Popayán, and Bogotá campuses. For Pasto, owing to the unavailability of SICOM data (MME, 2024), the average price calculated from the data of other campuses was used. The report recorded the brand and type of equipment, the refrigerant gas utilized, the date of maintenance, and the total annual amount of refrigerant recharged for fugitive emissions from refrigerant gas used in air conditioning systems. Similarly, for fire extinguisher refills, the report included the brand, type of gas used, and total annual gas replenishment. For fossil fuels consumed by stationary sources, the report specified the brand, type, quantity of fuel used, and its functional purpose. For Scope 2 emissions, electricity consumption data were obtained from monthly utility bills. Specialized facilities that are located within the campus confines (including dental or veterinary clinics, laboratories, and psychological clinics) were considered to the degree that their energy and fuel consumption was recorded in aggregated utility bills and institutional fuel/refrigerant records. Separate treatment by facility type was not feasible because submetering and standardized activity logs were

not consistently available across campuses during 2019–2022; this limitation is acknowledged and is identified as a priority for improving granularity in future inventory cycles. Scope 3 screening identified several potentially material categories (e.g., commuting, waste, procurement), but due to limited and non-comparable activity data in this first institution-wide exercise, Phase I quantifies only staff business air travel. The university issued a report obtained from the Aviatur SAS travel agency, which documented the travel routes of every campus member on an annual basis. For flights with multiple layovers, emissions from each segment were calculated separately and then aggregated in the final report. Since this represented the first comprehensive GHG inventory across the institution at Universidad Cooperativa de Colombia (UCC), various potentially significant Scope 3 categories (including waste, purchased goods and services, water, food services, construction/capital goods) were assessed but were not included due to inadequate consistency activity data across campuses and/or uncertainty levels that exceeded the predetermined acceptability threshold (target <30% relative uncertainty for robust reporting). Accordingly, the Scope 1–2 plus staff-air-travel Scope 3 inventory reported here should be interpreted as a conservative (minimum) estimate of the university's full value-chain emissions rather than a complete Scope 3 profile. In HEI inventories, categories including commuting, purchased goods and services, and waste typically serve as major contributors to Scope 3 emissions. Thus, Phase I is designed to create a unified methodological baseline and a framework for the incremental expansion of Scope 3 in later reporting periods, emphasizing the most critical categories as data systems mature and uncertainty can be reduced to acceptable levels.

Uncertainty of the activity data

The uncertainty percentages assigned to the activity data (±5% to ±30%) were determined based on the Intergovernmental Panel on Climate Change (IPCC) Tier 1 and Tier 2 methodological approaches. Lower uncertainties, such as ±5% for fire extinguishers and ±7% for grid electricity, were associated with externally sourced data, including utility bills and contractor reports. Conversely, greater uncertainties (±15%) for mobile fuels and (±25%) for stationary fuels were assigned to data estimated from fuel receipts and partial submetering. The most significant uncertainty (±30%) was designated to refrigerant emissions, which depended on maintenance/service records of annual refrigerant recharges (acting as a proxy for leakage) instead of direct leak measurements (for instance., continuous monitoring), hence the higher assigned uncertainty. Uncertainty assignments follow IPCC guidance (IPCC, 2019), with higher values used where activity data rely on proxies rather than direct measurement. This approach ensures alignment with international reporting standards while transparently communicating the limitations inherent in each dataset. To propagate uncertainty from activity data and emission to the total aggregated Scope- and campus-level figures, a first-order error propagation method aligned with IPCC guidance was utilized, presuming independent uncertainties and merging relative uncertainties in quadrature. For each emitting activity, the relative uncertainty of emissions was calculated as the square root of the sum of squares of the relative uncertainties of activity data and emission factors; Scope and campus uncertainties were consolidated following the same methodology. The uncertainty ranges that result are documented next to the totals in the results to aid in transparent interpretation and to prioritize initiatives aimed at enhancing data quality.

Baseline year, boundaries, and scopes

Organizational boundaries followed the GHG Protocol operational control approach, accounting

for 100% of emissions from operations under UCC's authority to implement operating policies. The operational control approach of the GHG Protocol Corporate Standard was employed to define organizational boundaries, whereby UCC is accountable for the entirety of emissions from operations over which it possesses the authority to introduce and execute operating policies. Operational boundaries included (i) Scope 1: stationary and mobile fuel combustion within UCC-controlled assets, fugitive emissions from refrigerants reported in maintenance/service logs, and emissions associated with fire-extinguisher refilling; (ii) Scope 2: purchased electricity for all buildings within each campus' spatial boundary; and (iii) Scope 3 (selected): staff business air travel booked through the institutional travel agency. Emission sources that are beyond operational control (such as energy consumption managed by tenants in leased areas, shared infrastructure not overseen by UCC, and outsourced services lacking verifiable activity data) were omitted from Phase I and are prioritized for future expansion where data quality allows. The temporal boundaries of the CF data span from January to December each year between 2019 and 2022. Meanwhile, the spatial boundaries, outlined in Table 1, correspond to the buildings within each campus. Notably, some campuses such as Bogotá and Medellín consist of multiple buildings distributed across their respective municipalities. Furthermore, Table 2 illustrates the population distribution across each campus, segmented into faculty, administrative personnel, and students, to report the per capita CF. The faculty group includes both tenured and adjunct professors. The administrative category comprises apprentices, facilities personnel, welfare department employees, and retired staff who maintain affiliations with the campus. The student population includes both undergraduate and graduate students. Per capita indicators were calculated using the annual campus population (students, faculty, and administrative staff) reported in Table 2 for each year, thereby capturing enrolment and staffing variability through time. To prevent misinterpretation during unusual periods such as the restrictions imposed by Coronavirus-2019 (COVID-19) or when the effects of the denominator are significant, the manuscript presents absolute emissions as metric tons of carbon dioxide equivalent (tCO_2e) alongside intensity indicators (tCO_2e/person). It also explicitly addresses how changes in population can influence per-capita trends, even when absolute emissions are moving in the contrary direction.

Emissions calculation

The CF assessment focused on mandatory Scopes 1–2 and voluntary Scope 3 (specifically air travel), as this represented the only consistently quantifiable Scope 3 emission source during the study period. Colombian-specific emission factors were prioritized whenever feasible to accurately represent the national conditions. In sectors where local data is scarce, such as aviation, these factors were supplemented with internationally recognized datasets, thereby ensuring methodological robustness while also recognizing the limitations of regional data. In addition, all emission values are reported in carbon dioxide equivalents (CO_2e), which incorporates the global warming potential (GWP) of non-CO_2 greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) relative to CO_2 over a 100-year timeframe. Global warming potentials correspond to GWP100 values from the IPCC Sixth Assessment Report to ensure consistent conversion of non-CO_2 gases to CO_2e across scopes. Emission factors were selected to be region and year-appropriate wherever possible: Colombian sources were prioritized for fuels (FECOC) and electricity, using annually updated Colombian National Interconnected System (SIN) grid emission factors for 2019–2022,

Table 1: Spatial boundaries of the campuses under investigation

Campus	Climatic zone	Properties and descriptions			
		Block	Description	Block	Description
Bogotá	Cold	Block 1	Classroom and basement library block	Block 19	Cesde
		Block 2	Human management, School of Communications, Communications Support Unit	Block 23	Marketing classrooms
		Block 3	School of Law/Library (right-wing section)	Block 24	Engineering classrooms
		Block 4	School of Economic and Administrative Sciences	Block 25	Warehouse (fixed assets), Union
		Block 5	Multilingual offices	Block 26	International trade classrooms
		Block 6	Dental clinics	Block 27	Legal Clinic, School of Law
		Block 6A–B	Apartment—Garage	Block 28	AOG 4
		Block 6C	Parking lot	Block 30	Wellness house
		Block 8	School of Accounting	Block 31	School of Psychology
		Block 9	Accounting and administration	Block 34	Office classrooms and administrative offices on the top floor
		Block 10	Extension offices	Block 35	Multilingual classrooms
		Block 12	System room	Sports field/court	Sports field/court
		Block 13	New CAVIPETROL lease—8th floor (National Structure)	Room 227	Not used
		Block 14	Administrative offices	Room 226	Not used
		Block 15	Laboratories	Block 20—House of Culture	Welfare
		Block 16	School of Engineering	AOG4 Camp	AOG4 Camp
		Block 17	The land is owned by Pensamiento Liberal, while the building is owned by the University	Lot 170	Lot 170
		Block 18	Quiroga—Not in use		
Pasto	Cold	Legal clinics	Only	Courts and parking lots	Sports facilities and parking lot
		Block A Block B, Block B	Torobajo Campus		
Ibagué–Espinal	Mild	Engineering building	Engineering building	Main building	Block 4
		Casa Urrutia	Casa Urrutia	El Salado Campus	El Salado
		El Pensil Farm (Totumo)	Large animal clinic, Veterinary medicine	Legal Clinic and Conciliation Center	Legal Clinic and Conciliation Center
		Espinal Campus	Block 8		
Medellin–National	Mild	Envigado	Envigado	Block 1	Block 1
		Block 2	Block 2	Legal Clinic and Conciliation Center	Legal Clinic and Conciliation Center
		Block 4	Block 4	Block 8	Block 8
		Block 5	Block 5	Block 9	Block 9
		Block 6	Block 6	La Playa Lot	La Playa Lot
		Block 7	Block 7	Block 3	Block 3
Pereira–Cartago	Mild	Blocks A, B, C, D, E, F, G, H	Campus	Block 1	Block 1
		Psychological Clinic	ICONO Block (Pereira)	Block 2	Block 2
		Lot	Lot	Block 3	Block 3
Popayán	Mild	Block 1	Administrative block	Block 3	Block 3
		Block 2	Block 2		

Table 2: University community by role, campus, and year

Campus	Weather	2019				2020				2021				2022			
		S	F	As	T	S	F	As	T	S	F	As	T	S	F	As	T
Bogotá	Cold	16.447	813	357	17.617	13.997	788	312	15.097	12.780	685	278	13.743	11.309	651	297	12.257
Pasto		4.159	536	136	4.831	4.016	466	115	4.597	4.151	562	99	4.812	4.254	603	94	4.951
Ibagué-Espinal		9.477	493	221	10.191	8.838	427	164	9.429	8.613	426	132	9.171	8.415	491	136	9.042
Medellín		6.974	906	232	8.112	6.727	811	193	7.731	6.683	788	173	7.644	6.398	861	173	7.432
National	Mild	0	0	334	334	0	0	306	306	0	197	302	499	0	337	337	674
Pereira-Cartago		1.979	137	73	2.189	1.964	129	49	2.142	2.067	122	45	2.234	1.945	158	50	2.153
Popayán		1.987	147	66	2.200	1.787	128	51	1.966	1.677	132	48	1.857	1.578	175	50	1.803

Note: S: Students, As: Administrative Staff, F: Faculty and T: Total

while internationally recognized datasets were used for air travel where national factors are not available. The method employed for the emission calculations included the multiplication of the activity data by an emission factor that aligns with the measured activity.

Scope 1

For Scope 1 emissions from fuel consumed by mobile and stationary sources, emission factors were sourced from the 2016 FECOC Colombian report, and emissions were calculated (CO_2e) based on direct and mobile sources (Arrieta *et al.,* 2016). The following values were used: 2.013 as kilograms of carbon dioxide equivalent per liter (kg CO_2e/L) for E10 gasoline, 2.715 kg CO_2e/L for B10 diesel, 2.327 kg CO_2e/L for motor gasoline, 2.682 kg CO_2e/L for diesel, 1.980 as carbon dioxide equivalent per cubic meter (kg CO_2e m^3) for generic natural gas, and 3.051 as kilograms of carbon dioxide equivalent per kilogram (kg CO_2e/kg) for liquefied petroleum gas. According to Colombian regulations, emissions from liquid fuel utilized by mobile and stationary sources are required to include mandatory blends of ethanol in motor gasoline and palm biodiesel in diesel. Based on the information provided by the Colombian National Biofuels Federation (Fedebiocombustibles), the ethanol blend E10 was reported in 2018 and 2021, while E6 was reported (January to March and April to June) in 2022. For palm biodiesel, the following blends were reported: B12 (September), B6 (October), B8 (November), and B10 (December) in 2018; B10 in 2020; B12 (April) and B10 (August) in 2021; and B11 (January to February) and B10 (March to July) in 2022 (Fedebiocombustibles, 2024). For the calculations, it was assumed that gasoline E10 (10% ethanol) and diesel B10 (10% palm biodiesel) would be utilized, depending on the availability of data. Refrigerant emissions were estimated using the annual quantities of refrigerant recharged (kg) documented in maintenance and service records as a proxy for annual leakage (mass-balance approach); no no generic/default leakage rates were incorporated into the emissions calculation. For emissions resulting from refrigerant gas use in air conditioning systems, the emission factors specified in the IPCC Sixth Assessment Report (IPCC, 2021) were used for the following gases: 2,2-dichloro-1,1,1-trifluoroethane ($CHCl_2CF_3$, R-123); 1,1,1,2-tetrafluoroethane (CH_2FCF_3, R-134a); chlorodifluoromethane ($CHClF_2$, R-22); and a 50/50 blend of difluoromethane (CH_2F_2, R-32) and pentafluoroethane (CHF_2CF_3, R-125), known as R-410A. The corresponding emission factors were as follows: R-123 = 90.40 kg CO_2e/kg, R-134a = 1,530.0 kg CO_2e/kg, R-22 = 1,960.0 kg CO_2e/kg, and R-410A = 2,255.5 kg CO_2e/kg. For emissions resulting from the refuelling of fire extinguishers, the emission factors specified in the IPCC Sixth Assessment Report (IPCC, 2021) were used for the following gases: CO_2 and 2,2-dichloro-1,1,1-trifluoroethane ($CHCl_2CF_3$, HCFC-123). Notably, other types of extinguishers, such as ABC multipurpose extinguishers and pressurized water extinguishers, lack defined emission factors. The emission factor for CO_2 was 1.0 kg CO_2e/kg, while that for HCFC-123 (SOLKAFLAM) was 90.40 kg CO_2e/kg.

Scope 2

For Scope 2 emissions related to electricity usage, the cumulative annual amount of the monthly electricity invoices for each campus was utilized. Indirect emissions were determined based on the emission factor for Colombian electric power, as supplied by the Colombian National Interconnected System (SIN), as follows: 2019: 0.166 kilograms of carbon dioxide per kilowatt-hour (kg CO_2/kWh) (UPME, 2020), 2020: 0.203 kg CO_2/kWh (UPME, 2021), 2021: 0.126 kg CO_2/kWh (UPME, 2022), and 2022: 0.112 kg CO_2/kWh (UPME, 2023). Because Scope 2 emissions are the product of electricity consumption and the annual grid emission factor (EF), year-to-year changes in reported Scope 2 emissions may reflect not only changes in campus demand but also exogenous variations in the national grid EF. Consequently, the results report provides an analysis and interpretation of consumption trends in conjunction with EF trends, and causal attribution to mitigation is only made when a specific intervention is documented and is consistent in timing with the observed change.

Scope 3

For Scope 3 resulting from air travel, the MyClimate.org calculator (Myclimate, 2024) a Swiss-based non-profit organization specializing in CO_2 offsetting projects and accredited by the United Nations Framework Convention on Climate Change (UNFCCC) was used. This tool was selected for its methodological rigor, alignment with the GHG Protocol boundaries, and widespread adoption by comparable academic institutions (Hoffmann *et al.,* 2024; Iken and Aguessy, 2022; Montlaur *et al.,* 2021). Upon the identification of the origin and destination, every trip was designated as one-way or round-trip, and the number of passengers as well as the travel class (economy) were specified. The results were reported directly in tonnes of CO_2. The variables ultimately used from the AVIATUR SAS travel agency report included the name of the cost center (i.e., campus name), year, and travel route.

RESULTS AND DISCUSSION

Beyond institutional benchmarking, the multi-campus design enables an interpretation of how climate zone, operational typology, and temporal drivers shape both absolute and intensity-based emissions under a single harmonized accounting boundary. Consequently, variations between campuses are analyzed through (i) climatic conditions (e.g., demand for electricity related to cooling), (ii) alterations in grid emission factors, (iii) shifts in activities such as decreased travel, and (iv) "denominator effects" linked to enrollment and staff dynamics. This comparative lens generates transferable insights on the main drivers of variability and helps prioritize mitigation levers and data-improvement needs for HEIs operating across heterogeneous climatic and functional contexts. In order to ensure interpretive consistency across various campuses and academic years, absolute emissions (tCO_2e) and intensity indicators (tCO_2e/person) are reported and analyzed together in this section, especially in instances where changes in enrollment and staffing significantly affect the per-capita denominator. Within this interpretive framework, temporal changes are analyzed by distinguishing between i) structural/external drivers (including COVID-19 restrictions, variations in enrollment/staff, and annual changes in the national grid emission factor), and ii) campus-level mitigation actions (such as lighting retrofits and on-site energy measures) documented by UCC. While the inventory presents a thorough diagnostic of trends, it does not perform a formal counterfactual impact evaluation (such as weather-normalized baselines, decomposition, or difference-in-differences). Therefore, changes are discussed as consistent with observed drivers, and mitigation “impact” is stated conservatively unless supported by intervention timing and corroborating activity data. This structure underpins a roadmap centered on MRV for future inventories, designed to separate operational modifications from external factors.

From a theoretical perspective, university decarbonization can be interpreted as a socio-technical and organizational change process in which infrastructure (buildings and energy systems), institutional practices (mobility, procurement routines), and governance mechanisms (data ownership, accountability, and MRV cycles) co-evolve. From this perspective, the inventory transcends a simple accounting function and acts as a diagnostic instrument that (i) highlights significant leverage points (e.g., electricity demand and refrigerants), (ii) clarifies the extent to which observed changes are attributable to external drivers versus campus actions, and (iii) supports translation into implementable portfolios through stable indicators and iterative MRV.

Cold climate campuses

Fig. 1 displays the CF per capita for (a) 2019, (b) 2020, (c) 2021, and (d) 2022, categorized by the scopes for campuses in cold climates. The total and per capita CF values in 2022 were 174.9 tCO_2eq and 0.0143 tCO_2eq/person for campus Bogotá and 75.4 tCO_2eq and 0.0152 tCO_2eq/person for campus Pasto, respectively. These indicate reductions of 15.93% and 27.72%, respectively, relative to their 2019 baselines. Following the GHG Protocol's recommendation to report biogenic (b) emissions separately, the emissions in cold climates in 2022 were 0.9216 tCO_2eq and 0 tCO_2eq, for Bogotá and Pasto, respectively. A detailed comparison of the net percentage change (%) in per capita CO_2 emissions from 2019 to 2022 by campus for a) Scope 1, b) Scope 2, and c) Scope 3, along with a summary of consumption for 2019, 2020, 2021, and 2022 categorized by emitting activity, is presented in Fig. 2 and Table 3. The Bogotá campus experienced a 32.1% increase in Scope 1 emissions between 2019 and 2022 due to stable resource consumption coupled with a decline in the total number of administrative staff, faculty, and students. In contrast, Scope 2 emissions decreased by 35.7% during the same period, as electricity consumption dropped from 1,122,935.0 kilowatt-hour (kWh) to 744,599.7 kWh. This reduction indicates a decline in electricity usage as well as a diminished national grid EF throughout the study duration; the implementation of solar-powered luminaires is mentioned as a recorded action that aligns with the noted decrease in electricity demand on campus. In contrast, the Pasto campus achieved a 3.2% reduction in Scope 1 emissions due to a decrease in the use of pipeline natural gas for stationary food service equipment, primarily institutional stoves and ovens. Scope 2 emissions also declined by 35.9%, as electricity consumption decreased from 324,221.8 to 315,913.4 kWh during the same period. In Pasto, the decrease in Scope 2 emissions aligns with diminished demand and a lower grid EF; the substitution of fluorescent tubes with LED alternatives is noted as a verified efficiency measure that aids in reducing demand. In addition, Scope 3 emissions showed significant changes, with an increase in the Bogotá campus (9,2%) and a decrease in the Pasto campus (19.6%). Fig. 2 illustrates a breakdown of the changes in Scope 2 emissions from 2019 to 2022 for the cold-climate campuses, distinguishing the impact of electricity demand (kWh) from the external variation in the national grid EF. For Bogotá, the Scope 2 reduction from 2019 to 2022 is decomposed into a -62.80 tCO_2e contribution from decreased electricity consumption and a -40.21 tCO_2e contribution from the lower grid EF, indicating that demand-side changes account for the larger share of the observed decrease. In contrast, for Pasto the change is dominated by the EF component (-17.06 tCO_2e), while the demand component is comparatively small (-1.38 tCO_2e). These results support a conservative attribution of improvements: while reported campus measures (e.g., lighting retrofits and operational actions) are consistent with reductions in electricity demand, a substantial fraction of the observed Scope 2 change particularly in Pasto reflects external

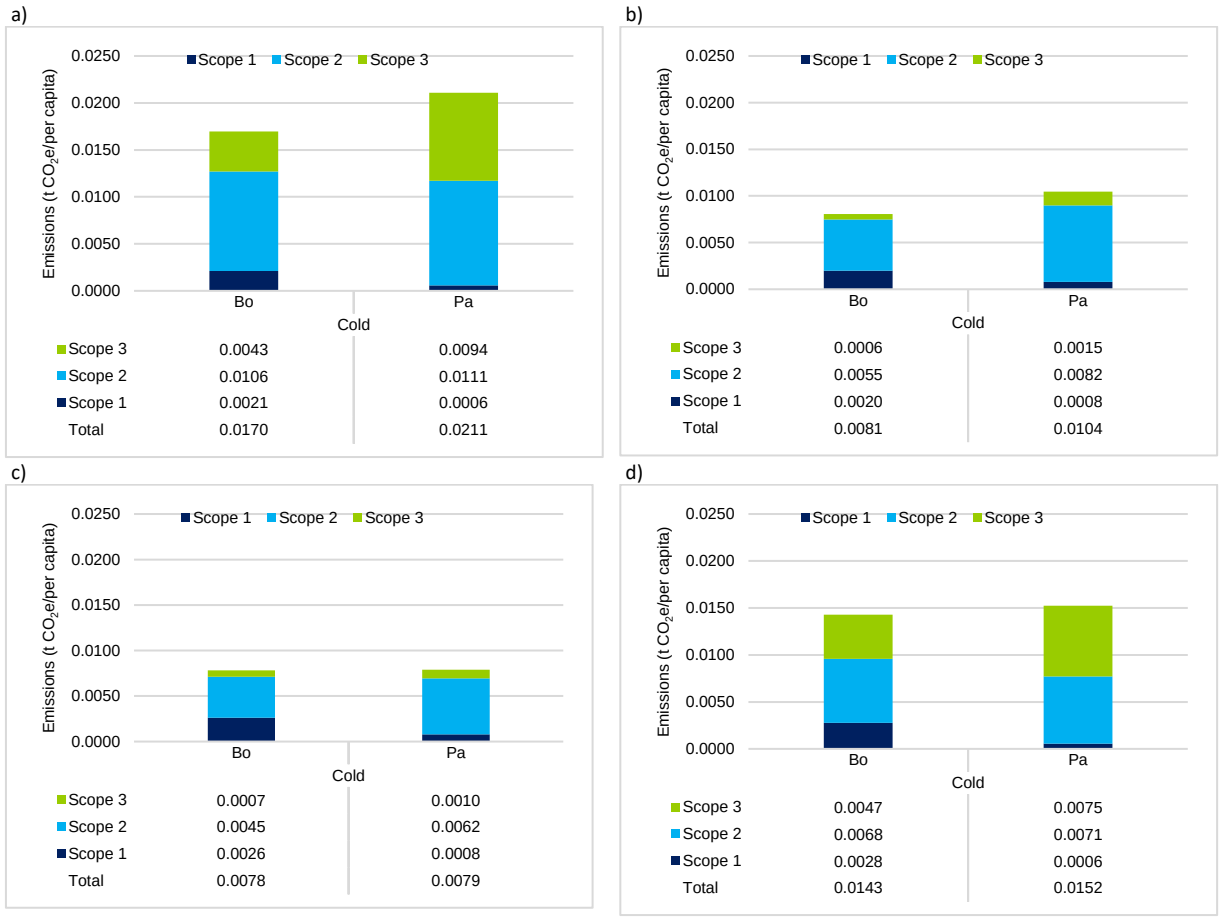

Fig. 1: Summary of greenhouse gas emissions per capita for a) 2019, b) 2020, c) 2021 and d) 2022, categorized by scopes for campuses in cold climates, where Bo: Bogotá and Pa: Pasto

decarbonization of the electricity supply. Thus, future MRV cycles ought to document electricity consumption together the annual grid EF to differentiate operational mitigation impacts from system-wide influences and to prevent misinterpretation of year-on-year variations.

Mild climate campuses

Fig. 3 presents the per capita CF for (a) 2019, (b) 2020, (c) 2021, and (d) 2022, categorized by emission scopes for campuses located in mild climate zones. In 2022, the total and per capita CF values were as follows: Ibagué-Espinal – 147.5 tCO_2eq (0.0163 tCO_2eq/person), Medellín – 200.8 tCO_2eq (0.0270 tCO_2eq/person), National – 258.8 tCO_2eq (0.3839 tCO_2eq/person), Pereira-Cartago – 239.1 tCO_2eq (0.1111 tCO_2eq/person), and Popayán – 67.7 tCO_2eq (0.0375 tCO_2eq/person). Primarily, the National Campus acts as an administrative and coordination entity, featuring an operational profile that is unique compared to teaching-intensive campuses. Its comparatively small annual population denominator (Table 2), combined with a travel-intensive activity profile, amplifies per-capita indicators and explains the higher intensity values observed relative to other campuses. In this context, the per-capita differences between National and Pereira–Cartago were regarded as structural (in relation to functional roles and population dynamics) instead of being a direct reflection of inadequate performance in mitigation strategies.

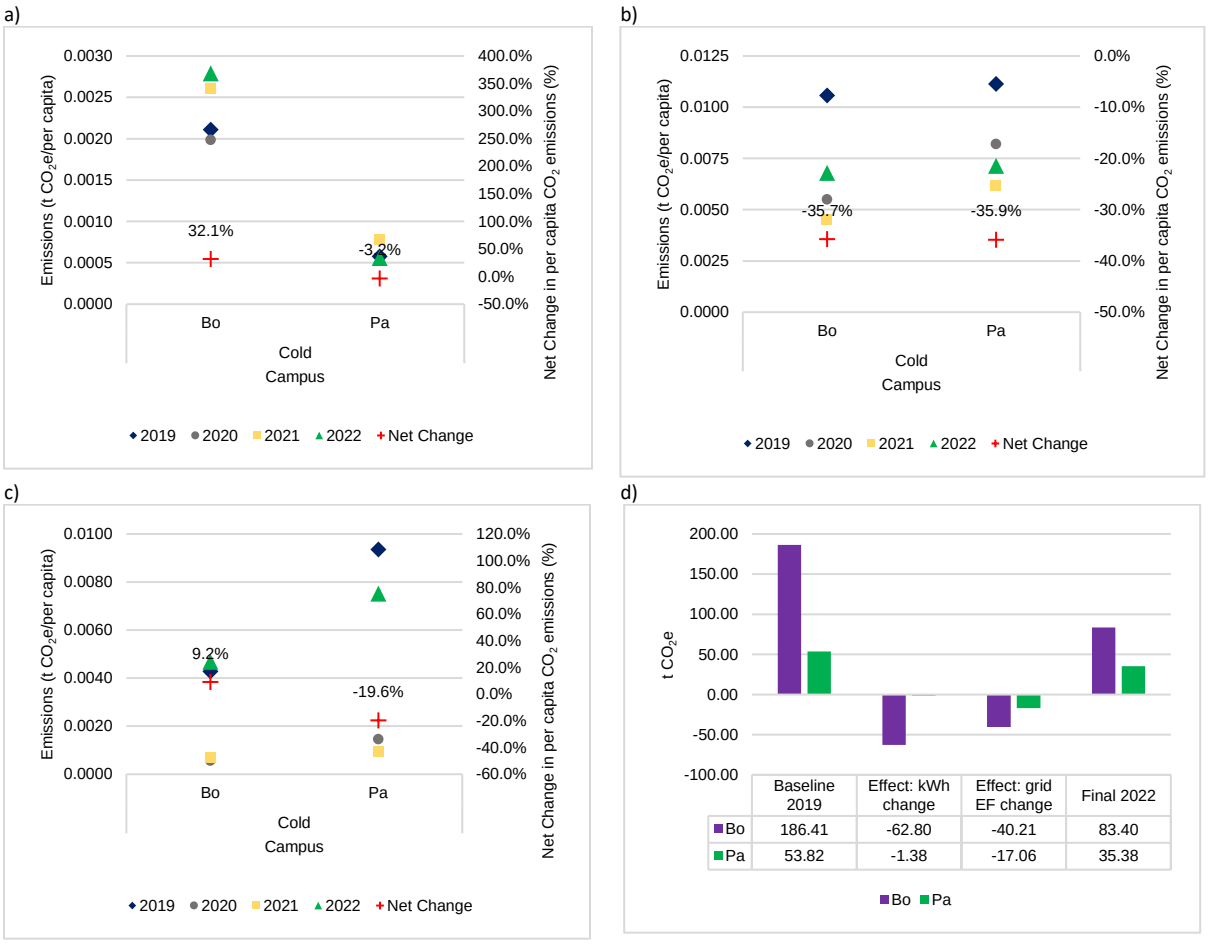

Fig. 2: Net percentage change (%) in per capita CO_2 emissions (2019–2022) by campus for a) Scope 1, b) Scope 2, and c) Scope 3, where Bo: Bogotá and Pa: Pasto, and (d) driver decomposition of the 2019–2022 change in Scope 2 emissions for cold-climate campuses, separating electricity demand (kWh effect) from the national grid emission factor (EF effect)

These Figs. 1-3, represent changes relative to 2019 of +8.78% for Ibagué-Espinal, 33.06% for Medellín, 60.75% for National, +5.18% for Pereira-Cartago, and +37.56% for Popayán. Following the GHG Protocol's recommendation to report biogenic emissions separately, 2022 biogenic CO_2 emissions were as follows: Ibagué-Espinal – 0.1850 $tCO_2(b)$, Medellín – 0.1295 $tCO_2(b)$, National – 2.1143 $tCO_2(b)$, Pereira-Cartago – 0.0076 $tCO_2(b)$, and Popayán – 0.2547 $tCO_2(b)$. Fig. 4 provides a detailed comparison of the percentage change in per capita CO_2 emissions from 2019 to 2022 by campus for (a) Scope 1, (b) Scope 2, and (c) Scope 3, while Table 4 summarizes consumption data across the years 2019–2022 by emission source. At the Ibagué-Espinal campus, there was a 45.3% increase in Scope 1 emissions, primarily influenced by denominator effects linked to a reduced campus population, despite generally stable activity levels. However, Scope 2 emissions decreased by 13.4% because of a reduction in the grid emission factor for electrical energy, rather than to significant structural or infrastructural changes on-site. The Pereira-Cartago campus reported an 11.8% increase in Scope 1 emissions, driven by the increase in R-410A refrigerant use from 45.2 to 54.2 kilograms (kg). Simultaneously, there was a 29.2% reduction in Scope 2 emissions,

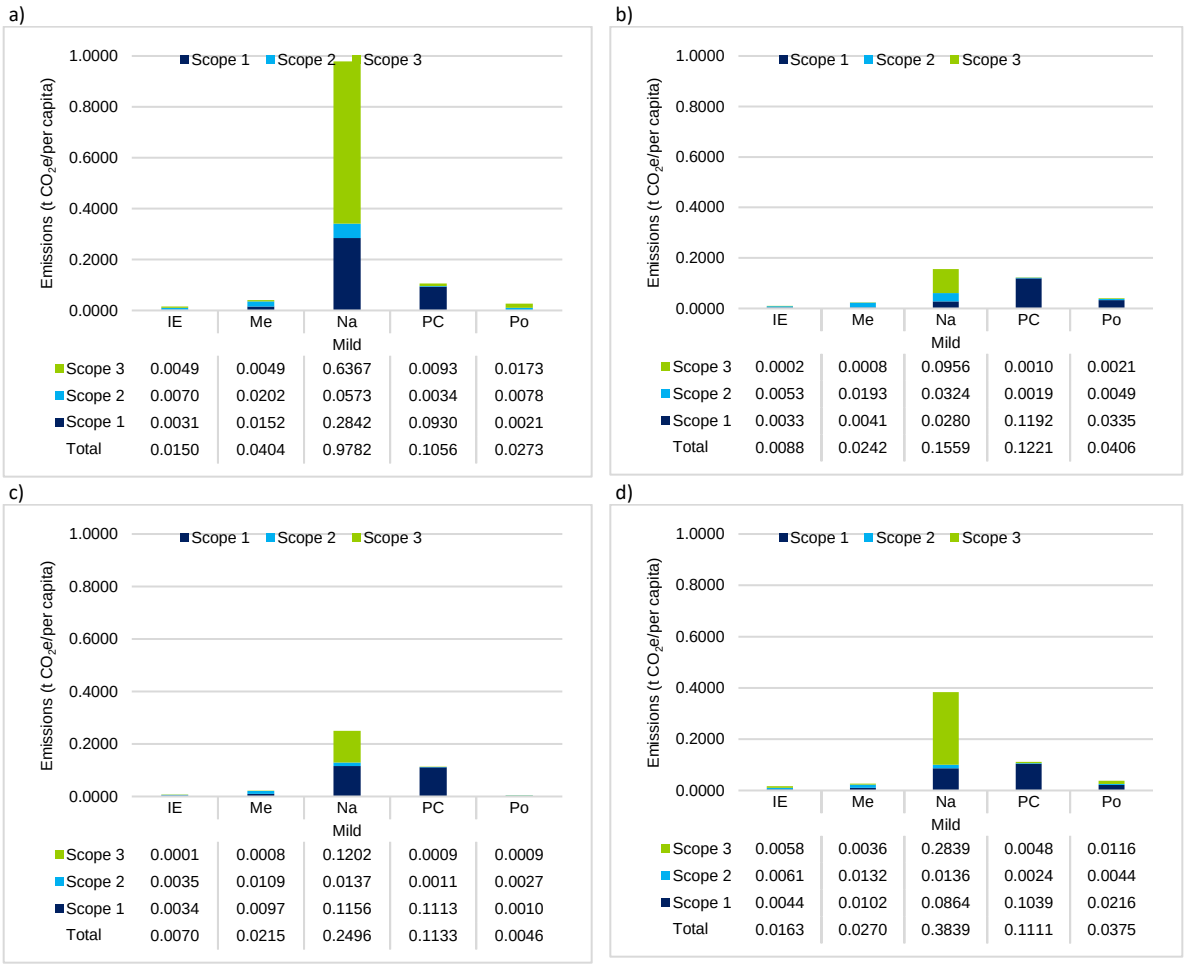

Fig. 3: Summary of greenhouse gas emissions per capita for a) 2019, b) 2020, c) 2021, and d) 2022, categorized by scopes for campuses in mild climates, where IE: Ibagué-Espinal, Me: Medellín, Na: National, PC: Pereira-Cartago, and Po: Popayán

which is also a result of the decreased grid EF for electrical energy. In addition, the Popayán campus reported a 912.2% critical increase in Scope 1 emissions due to the rise in R-410A (from 0 to 11 kg). However, Scope 2 emissions decreased by 43.9% due to a reduction from 103,553.7 to 70,507.4 kWh during the period. This decrease was associated with the execution of energy conservation awareness initiatives aimed at the systematic shutdown of lighting and non-essential electrical devices during times of inactivity. In contrast, the Medellín campus achieved a 32.9% reduction in Scope 1 emissions due to decreases in E10 gasoline fuel (from 1,387.0 to 408.8 for mobile combustion), generic natural gas (from 2,374.5 to 1,391.3 m^3) and R-22 (from 57 to 34.5 kg). Scope 2 emissions also fell by 34.8%, with electricity use dropping from 987,149.8 to 873,520.8 kWh. This decrease was linked to a combination of behavioral strategies (manual shutdown practices) and automation (occupancy sensors) throughout the primary building complexes. National campus reported a 69.6% reduction in Scope 1 emissions, mainly through the decreased

Table 3: Summary of consumption data for 2019, 2020, 2021, and 2022, disaggregated by emission-generating activity for the Bogotá and Pasto campuses

Campus	Scope	Emission source	Description	Unit	2019	2020	2021	2022
Bogotá	Scope 1	Mobile combustion	Fuel Gasoline E10	L	4.614.8	1,944.2	4,492.5	2,955.4
			Fuel–Diesel B10	L	0	0	0	0
		Stationary combustion	Fuel Gasoline E10	L	322.1	322.1	322.1	322.1
			Fuel–Diesel B10	L	965.3	0	477.0	965.3
			Generic natural gas	m^3	0	0	0	0
			Liquefied petroleum gas generic	kg	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	0	0	0	0
			Refrigerant gas–R-410A	kg	0	0	0	0
			CO_2 fire extinguisher	kg	54.4	54.4	54.4	54.4
			BC fire extinguisher	kg	9.1	9.1	9.1	9.1
			Solkaflam fire extinguisher	kg	285.8	285.8	285.8	285.8
	Scope 2	Purchased electricity	Purchased electricity	kWh	1,122,935.0	409,442.0	493,973.0	744,599.7
	Scope 3	Air travel	Domestic	Number	167	26	40	194
			International	of trips	21	3	0	0
Pasto	Scope 1	Stationary combustion	Fuel Gasoline E10	L	0	37.9	0	0
			Fuel–Diesel B10	L	0	416.4	405.0	0
			Generic natural gas	m^3	0	0	0	0
			Liquefied petroleum gas generic	kg	103.1	0	96	96
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	0	0	0	0
			Refrigerant gas–R-410A	kg	0	0	0	0
			CO_2 fire extinguisher	kg	22.7	22.7	22.7	22.7
			BC fire extinguisher	kg	4.5	4.5	4.5	4.5
			Solkaflam fire extinguisher	kg	27.2	27.2	27.2	27.2
	Scope 2	Purchased electricity	Purchased electricity	kWh	324,221.8	185,943.6	235,240.5	315,913.4
	Scope 3	Air travel	Domestic	Number	80	20	14	82
			International	of trips	11	0	0	5

use of R-22 (from 44 to 20 kg). Scope 2 emissions dropped by 76.2%, with electricity use declining from 115,296.4 to 82,126.6 kWh during the same period. The observed decrease in energy consumption was achieved through a strategic alignment with the Medellín campus model, replicating its integrated approach of combining occupant engagement with sensor-based automation to ensure persistent savings. Lastly, Scope 3 emissions showed significant reductions across campuses: Medellín (26.3%), National (55.4%), Pereira-Cartago (48.8%), and Popayán (33.3%), primarily due to reduced domestic travel and an increased reliance on virtual meetings. However, Ibagué-Espinal increased the emissions by +17.7%. Fig. 4(d) presents a driver decomposition of Scope 2 changes (2019–2022) for mild-climate campuses by separating the contribution of electricity demand (kWh effect) from the exogenous change in the national grid emission factor (EF effect). Aggregated across mild-climate campuses, Scope 2 decreased from 279.20 to 175.12 tCO_2e (Δ = -104.08 tCO_2e), with the EF effect accounting for -84.43 tCO_2e and the kWh effect accounting for -19.65 tCO_2e, indicating that system-level decarbonization of electricity supply was the dominant driver of the observed reduction. At the campus level, Medellín exhibited a mixed pattern (−18.86 tCO_2e kWh effect; -47.17 tCO_2e EF effect), consistent with demand-side actions under a declining grid EF, while Popayán and National showed sizable demand contributions alongside EF effects. In contrast, Ibagué–Espinal and Pereira–Cartago displayed positive kWh effects (+9.98 tCO_2e and +0.23 tCO_2e, respectively), partially offsetting EF-driven

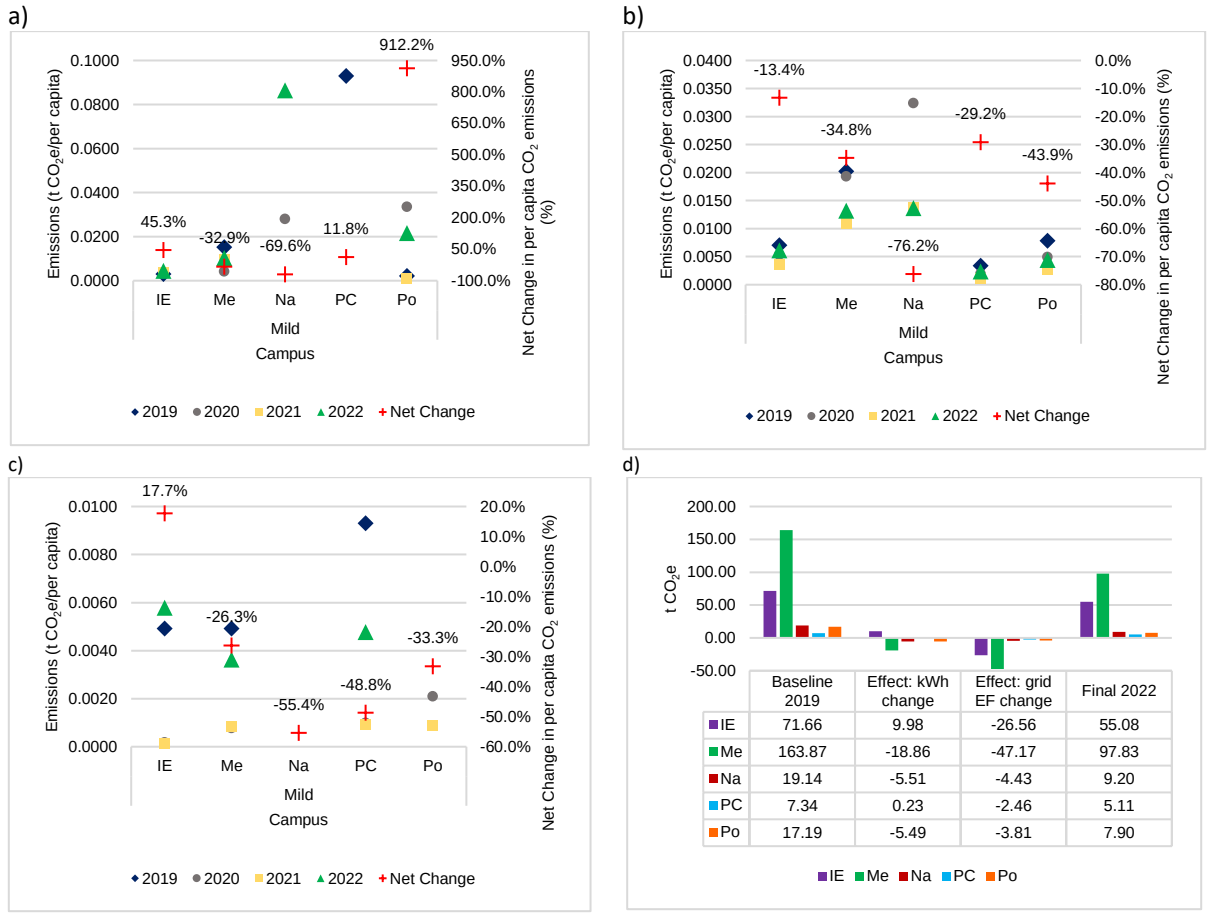

Fig. 4: Net percentage change (%) in per capita CO_2 emissions (2019–2022) by campus for a) Scope 1, b) Scope 2, and c) Scope 3. where IE: Ibagué-Espinal, Me: Medellín, Na: National, PC: Pereira-Cartago, and Po: Popayán, and (d) driver decomposition of the 2019–2022 change in Scope 2 emissions for cold-climate campuses, separating electricity demand (kWh effect) from the national grid emission factor (EF effect).

reductions and reinforcing the need for conservative attribution: improvements in Scope 2 totals should not be interpreted exclusively as mitigation performance unless accompanied by confirmed demand reductions. Consequently, MRV reporting ought to consistently monitor electricity usage and the yearly grid EF to differentiate operational modifications from external influences and to aid in prioritizing demand-reduction strategies when kWh impacts are still unfavorable. While percentage changes compared to 2019 facilitate visualization, it is important to note that when baseline per-capita values are nearly zero (for instance, minimal Scope 1 or Scope 3 activity in 2019), these percentage changes may seem excessively large and should be interpreted with caution. In such cases, extreme percentages primarily indicate the emergence or disappearance of an emission stream rather than a large absolute change. Therefore, the percentage change in Figs 2 and 4 are interpreted alongside the corresponding absolute and per-capita values to avoid overstatement driven by near-zero denominators.

Table 4: Summary of consumption data for 2019, 2020, 2021, and 2022, disaggregated by emission-generating activity for the Ibagué–Espinal, Medellín, National Structure, Pereira–Cartago, and Popayán campuses

Campus	Scope	Emission source	Description	Unit	2019	2020	2021	2022
Ibagué–Espinal	Scope 1	Stationary combustion	Fuel Gasoline E10	L	0	0	0	0
			Fuel–Diesel B10	L	681,4	681,4	681,4	681,4
			Generic natural gas	m^3	0	0	0	0
			Liquefied petroleum gas generic	kg	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	0	0	0	0
			Refrigerant gas–R-410A	kg	0	0	0	4
			CO_2 fire extinguisher	kg	9.1	9.1	9.1	9.1
			BC fire extinguisher	kg	0	0	0	0
			Solkaflam fire extinguisher	kg	326.6	326.6	326.6	326.6
	Scope 2	Purchased electricity	Purchased electricity	kWh	431,674.0	248,073.0	254,307.0	491,780.9
	Scope 3	Air travel	Domestic	Number	111	5	5	93
			International	of trips	16	0	0	21
Medellín	Scope 1	Mobile combustion	Fuel Gasoline E10	L	1,387.0	179.1	222.2	408.8
			Fuel–Diesel B10	L	0	0	0	0
		Stationary combustion	Fuel Gasoline E10	L	0	0	0	0
			Fuel–Diesel B10	L	94.6	94.6	151.4	174.1
			Generic natural gas	m^3	2,374.5	189	74.4	1,391.3
			Liquefied petroleum gas generic	kg	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	57	13.5	35	34.5
			Refrigerant gas–R-410A	kg	0	0	0	0
			CO_2 fire extinguisher	kg	177.2	177.2	177.2	177.2
			BC fire extinguisher	kg	0	0	0	0
			Solkaflam fire extinguisher	kg	48	48	48	48
	Scope 2	Purchased electricity	Purchased electricity	kWh	987,149.8	733,940.2	663,406.5	873,520.8
	Scope 3	Air travel	Domestic	Number	92	14	16	82
			International	of trips	12	2	3	8
National	Scope 1	Mobile combustion	Fuel Gasoline E10	L	4,786.1	3,100.9	9,097.5	10,505.8
			Fuel–Diesel B10	L	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	44	1.5	17	20
			Refrigerant gas–R-410A	kg	0	0	3.5	0
			CO_2 fire extinguisher	kg	2.1	2.1	2.1	4.5
			BC fire extinguisher	kg	0	0	0	0
			Solkaflam fire extinguisher	kg	0	0	0	0
	Scope 2	Purchased electricity	Purchased electricity	kWh	115,296.4	48,811.9	54,404.3	82,126.6
	Scope 3	Air travel	Domestic	Number	563	102	118	547
			International	of trips	41	3	6	31
Pereira–Cartago	Scope 1	Stationary combustion	Fuel gasoline E10	L	37.9	37.9	37.9	37.9
			Fuel–diesel B10	L	0	0	0	0
			Generic natural gas	m^3	0	0	0	0
			Liquefied petroleum gas generic	kg	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	36.7	36.7	36.7	36.7
			Refrigerant gas–R-410A	kg	45.2	68.2	65.2	54.2

Campus	Scope	Emission source	Description	Unit	2019	2020	2021	2022
			CO_2 fire extinguisher	kg	9.1	9.1	9.1	9.1
			BC fire extinguisher	kg	0	0	0	0
			Solkaflam fire extinguisher	kg	326.6	326.6	326.6	326.6
	Scope 2	Purchased electricity	Purchased electricity	kWh	44,212.0	20,227.0	19,787.0	45,610.0
	Scope 3	Air travel	Domestic	Number	68	9	9	30
			International	of trips	4	0	0	2
Popayán	Scope 1	Mobile combustion	Fuel Gasoline E10	L	1,059.4	142.3	75.7	174.9
			Fuel–Diesel B10	L	0	0	0	0
		Stationary combustion	Fuel Gasoline E10	L	132.5	53.0	60.6	79.5
			Fuel–Diesel B10	L	1,010.7	336.9	628.4	749.5
			Generic natural gas	m^3	0	0	0	0
			Liquefied petroleum gas generic	kg	0	0	0	0
		Fugitive emissions	Refrigerant gas–R-123	kg	0	0	0	0
			Refrigerant gas–R-134a	kg	0	0	0	0
			Refrigerant gas–R-22	kg	0	10	0	6
			Refrigerant gas–R-410A	kg	0	20	0	11
			CO_2 fire extinguisher	kg	63.5	63.5	63.5	63.5
			BC fire extinguisher	kg	0	0	0	0
			Solkaflam fire extinguisher	kg	0	0	0	0
	Scope 2	Purchased electricity	Purchased electricity	kWh	103,553.7	47,709.3	39,840.9	70,507.4
	Scope 3	Air travel	Domestic	Number	136	17	9	116
			International	of trips	4	0	0	1

Comparison with different HEIs

Cross-institutional comparisons of campus carbon footprints should be interpreted with caution unless methodological elements are harmonized. The reported values may vary based on boundary definitions (such as the organizational control approach and the buildings/operations included), the temporal coverage, the completeness of the scope (for instance, Scope 1–2 only compared to the inclusion of certain Scope 3 categories), the choices of emission factors (especially regarding electricity), and the normalization denominators (whether considering only students versus the entire campus population, or inclusion/exclusion of part-time staff). Accordingly, the benchmarking discussion below is presented as an indicative contextualization rather than a strict performance ranking, and comparability is considered strongest where studies explicitly align on scopes, boundaries, activity-data definitions, and reporting years under consistent protocols. The CF results acquired in this study were contrasted with data published by HEIs in Colombia and the surrounding region. For example, the Universidad Autónoma Metropolitana (UAM) reported per capita Scope 1 and 2 emissions of 0.2996 tCO_2eq, which are comparable to those reported by the UCC at the National campus 0.3415 tCO_2eq in 2019. The per capita Scope 1 and 2 emissions reported by the UCC Medellin 0.0354 tCO_2eq in 2019 are comparable with those reported by the Universidad Santo Tomás Medellín 0.0359 tCO_2eq in 2018 and the Universidad Pontificia Bolivariana Medellin 0.0237 tCO_2eq in 2020 (Table 5). These comparable findings offer proof that the protocols, methodologies, data quality, and uncertainty management implemented in this study were suitable and strong, resulting in dependable per capita emissions estimates. In contrast, the reported per capita Scope 1 and 2 emissions reported by the UCC Bogota 0.0127 tCO_2eq in 2019 are slightly lower than those reported by the Universidad EAN campus Bogota 0.0201 tCO_2eq with a percentage difference of 37%, respectively (Table 5). These differences in the reported values can be attributed to the dissimilar variables influencing CF outcomes, such

Table 5: CF report for different HEIs in Latin America

University	Campus	Country	Year	Emissions tCO_2eq				Sources
				Scopes 1 and 2		Scope 3		
				Total	Per capita	Total	Per capita	
Autonomous Metropolitan University (UAM)	Cuajimalpa	Mexico	2016	840,0	0,2996	2.160,0	0,7704	Mendoza-Flores *et al.,* (2019)
Saint Thomas University	Medellín	Colombia	2018	1.256,2	0,0359	1.159,6	0,0331	Farfán Parra (2018)
National University of Colombia	Medellín	Colombia	2019	1.213,4	0,0724	6.037,0	0,3601	Cano *et al.,* (2022)
Technological University of Pereira	Pereira	Colombia	2017	297,7	0,0148	8.671,1	0,4321	Varón-Hoyos *et al.,* (2021)
University Pontificia Bolivariana	Medellín	Colombia	2020	508,8	0,0237	188,4	0,0088	Osorio *et al.,* (2022)
	Bucaramanga			315,9	0,0583	24,2	0,0045	
	Montería			182,2	0,0479	22,1	0,0058	
	Palmira			22,3	0,0180	1,3	0,0010	
Universidad Ean	Bogotá	Colombia	2019	205,6	0,0201	-	-	
Universidad Cooperativa de Colombia	Bogotá	Colombia	2019	223,6	0,0127	75,5	0,0043	This study
			2020	113,1	0,0075	8,5	0,0006	
			2021	98,0	0,0071	9,4	0,0007	
			2022	117,6	0,0096	57,3	0,0047	
	Pasto	Colombia	2019	56,6	0,0117	45,2	0,0094	
			2020	41,3	0,0090	6,7	0,0015	
			2021	33,4	0,0069	4,6	0,0010	
			2022	38,2	0,0077	37,3	0,0075	
	Ibagué-Espinal	Colombia	2019	102,9	0,0101	50,0	0,0049	
			2020	81,6	0,0086	1,7	0,0002	
			2021	63,2	0,0069	0,9	0,0001	
			2022	95,3	0,0105	52,2	0,0058	
	Medellín	Colombia	2019	287,5	0,0354	39,9	0,0049	
			2020	180,9	0,0234	6,0	0,0008	
			2021	157,6	0,0206	6,4	0,0008	
			2022	173,9	0,0234	26,9	0,0036	
	National	Colombia	2019	114,1	0,3415	212,7	0,6367	
			2020	18,5	0,0604	29,2	0,0956	
			2021	64,5	0,1294	60,0	0,1202	
			2022	67,4	0,1000	191,3	0,2839	
	Pereira-Cartago	Colombia	2019	210,8	0,0963	20,4	0,0093	
			2020	259,5	0,1211	2,1	0,0010	
			2021	251,1	0,1124	2,1	0,0009	
			2022	228,9	0,1063	10,3	0,0048	
	Popayán	Colombia	2019	21,9	0,0099	38,2	0,0173	
			2020	75,6	0,0385	4,1	0,0021	
			2021	6,9	0,0037	1,7	0,0009	
			2022	46,8	0,0260	20,9	0,0116	

as campus size, student enrollment, academic schedules and local climate conditions. Furthermore, variations in the characteristics of the building stock (such as building age, envelope performance, retrofit history, and the efficiency and controls of HVAC/lighting systems) can significantly affect electricity demand and consequently Scope 2 emissions. While these attributes were not consistently available in a standardized format across campuses for 2019–2022 and were therefore not used for quantitative attribution in Phase I, they represent a key explanatory layer for future MRV cycles, where the collection of a minimum building-asset dataset and, where feasible, energy normalization by conditioned area (kWh/m²) would strengthen interpretation of inter-campus variability. Consequently, direct comparison of the results of this study is intrinsically limited. Despite these circumstantial differences, the internal consistency of the dataset supports the robustness of the applied methodology. Comparisons of Scope 3 emissions on a per capita basis continues to be more difficult because of the increased variability in influencing factors across institutions. For instance, in 2020, the Universidad Pontificia Bolivariana reported per capita Scope 3 emissions of 0,0088 tCO_2eq, meanwhile UCC Medellin reported significantly lower emissions 0,0008 tCO_2eq for the same year. Although both campuses are in similar climatic zones, discrepancies in the campus area, student and staff populations, and data collection approaches likely account for these differences. This instance emphasizes the intricacy involved in assessing Scope 3 emissions and points out the necessity for standardized methods to facilitate more uniform comparisons between institutions. COVID-19 introduced a structural disruption that affected both activity levels and denominators (enrollment/staff), producing a marked deviation from baseline patterns across campuses. As shown in the Results (Figs. 1–4 and Table 2), the 2019–2022 time series reflects a combination of reduced on-site activity during restriction periods and subsequent recovery dynamics, with intensity-based indicators additionally shaped by population changes ("denominator effects"). For this reason, changes are interpreted conservatively as consistent with observed drivers rather than as direct evidence of mitigation impact unless aligned with documented interventions and corroborating activity data. The percentage reduction in per capita emissions between 2019 and 2020 for UCC campuses was as follows: Bogotá 41%, Pasto 23%, Ibagué-Espinal 15%, Medellín 34%, and National 82%. The decrease in CF is ascribed not only to the shift towards remote activities like online classes, which significantly lowered electricity usage, but also to a decline in student enrollment that subsequently resulted in a reduction of both administrative and academic personnel. The decrease in campus personnel during the COVID-19 pandemic was significantly higher in big campuses such as Bogotá, Ibagué-Espinal and Medellín (14%, 7.5% and 4.7%, respectively) than in smaller campuses such as Pereira-Cartago and Popayán (2.1%, respectively). In this case, there is a direct positive correlation between the reduction in the number of students and personnel and the reduction of the CF emissions in the Bogotá, Pasto, Ibagué-Espinal and Medellín campuses (Table 2). In contrast, the Pereira-Cartago campus had a slight increase in the Scope 1 and 2 GHG emissions of 20%, whereas the Popayán campus had an enormous Scope 1 and 2 GHG incremental emissions of 74%.

Key initiatives that contributed to these outcomes include classroom-based projects focused on CF reduction and the integration of environmental topics centered on addressing

climate change into the curriculum. These efforts have played a significant role in enhancing environmental consciousness within the university community, encouraging behavioral modifications that have affected energy demand and resource management. Similarly, the construction of sustainable and innovative spaces has enabled the integration of more efficient technologies into the university infrastructure, reducing energy consumption and improving waste management. The revision of the university's environmental policy has also been a key development, reinforcing the institution's commitment to emission reduction and long-term sustainability. Another prominent initiative has been the establishment of the Reduce Your Footprint manual and the execution of a campaign with the same title, directed towards students, faculty, and staff. This campaign has established a clear foundation for the adoption of concrete actions to support the university's transition toward carbon neutrality. A formal techno-economic evaluation (cost–benefit or payback) of the reported mitigation actions was not conducted within Phase I, as this study concentrated on creating a standardized multi-campus GHG accounting baseline and interpreting trends under documented contextual drivers. Future MRV cycles should integrate economic screening (for instance, simple payback and/or NPV-based evaluation using campus-specific CAPEX/OPEX, tariffs, maintenance costs, and expected lifetimes) to aid in prioritizing portfolios and making scaling decisions without merging emissions diagnostics with investment evaluations. At UCC, carbon management is coordinated through the institutional sustainability function led by the Social Projection office, in collaboration with designated focal points at each campus, and aligned with the National Strategic Plan 2022–2025. Building on these actions, carbon management for this initiative is coordinated through the institutional sustainability function, which is directed by the Social Projection office in partnership with appointed focal points at each campus and aligned with the National Strategic Plan 2022–2025. In practice, this governance arrangement links the GHG inventory to decision-making by establishing a recurring MRV cycle, with results communicated to university leadership to prioritize energy-efficiency investments, refrigerant management, and mobility policies. In this sense, the inventory functions not only have a benchmarking exercise, but also as a governance tool focused on implementation that enhances accountability, enables target-setting, and connects campus actions with broader sustainability and climate-alignment frameworks. To operationalize this MRV approach and ensure comparability across campuses and years, a small and consistent indicator set should be tracked and reported alongside boundary definitions and data-quality notes. At minimum, these include: (i) total emissions by scope (tCO_2e) and intensity (tCO_2e /person) using the annual population denominator reported in Table 2; (ii) electricity consumption (kWh) and electricity intensity (kWh/person and, where available, kWh/m²), reported alongside the annual grid EF to distinguish demand changes from external decarbonization; (iii) fugitive refrigerant losses (kg and tCO_2e) by refrigerant type; and (iv) staff air-travel activity (passenger-km, trips) and resulting emissions (tCO_2e). Milestones for follow-up cycles should include (a) formal assignment of data owners per activity stream and a standardized data template, (b) annual (or semi-annual) reporting with a documented QA/QC step and uncertainty propagation, and (c) progressive expansion of the most material Scope 3 categories as data maturity improves. This MRV framework

enhances comparability over time and aids management decisions by associating observed changes with quantifiable operational levers instead of relying solely on external factors. Within the same implementation logic, to move beyond pilot actions, UCC is framing a portfolio of scalable measures in which demonstrative interventions inform campus-specific feasibility assessments (e.g., roof availability and structural capacity for on-site renewables, load profiles, operational constraints, and procurement/financing conditions). This portfolio method endorses a gradual implementation timeline throughout campuses, focusing on initiatives that possess the highest potential for mitigation and are ready for practical application. Finally, to embed these processes in the university's core functions, integration into institutional practice is envisaged through (i) routine MRV reporting to university leadership using a small set of stable indicators that translate inventory findings into prioritized action plans for electricity demand reduction/decarbonization, refrigerant management, and mobility policies; (ii) curricular deployment via project-based learning in which students use campus-specific inventory data to develop and evaluate mitigation proposals (e.g., energy audits, behavioural programs, and mobility-demand management) under faculty supervision; and (iii) a research pipeline that progressively improves data granularity and Scope 3 completeness, and enables future analytical work such as driver decomposition and ex ante/ex post evaluation of interventions as data maturity and submetering improve.

CONCLUSION

This study reports Phase I results of UCC's multi-campus carbon footprint assessment, evaluating greenhouse gas emissions across seven urban campuses between 2019 and 2022. Using the Corporate Accounting and Reporting Standard Protocol -2005, the research quantified Scope 1, Scope 2, and selected Scope 3 emissions, offering a replicable framework for higher education institutions (HEIs) seeking to standardize carbon accounting in alignment with international protocols. The findings suggest that Scope 2 emissions resulting from electricity usage are the primary factor contributing to the overall carbon footprint across all campuses. Fugitive refrigerant emissions (Scope 1) and staff air travel (Scope 3) were identified as the second and third largest sources, respectively. Notably, campuses located in cold climatic zones (Bogotá and Pasto) achieved substantial reductions in 2022 relative to the 2019 baseline; however, observed changes are interpreted cautiously given the concurrent influence of external drivers (for instance, COVID-19 disruptions, annual grid emission factor changes) and documented operational actions. Conversely, numerous campuses located in temperate climate regions observed a rise in per capita emissions, varying from 5.18% to more than 60%. These disparities underscore the influence of local contextual factors such as campus size, fluctuations in student enrollment, and the effectiveness of air-conditioning system maintenance on institutional sustainability performance. Additionally, the COVID-19 pandemic introduced a pronounced temporal anomaly, with most campuses recording significant emission reductions in 2020 due to the shift to remote activities and the consequent decrease in on-site energy demand. Since Scope 3 was measured solely for employee air travel, which is the only category with adequately consistent activity data and acceptable levels of uncertainty, the inventory ought to be regarded as a conservative (minimum) estimate. The findings

highlight that achieving UCC's 2025 carbon neutrality goal will require a robust, multifaceted strategy focused on the following core principles: 1) energy decarbonization, including expanded on-site renewable energy generation, demand-side management, and strengthened energy-efficiency programs to address the predominance of Scope 2 emissions; 2) refrigerant governance and operational maintenance, implemented through stricter preventive maintenance schedules, enhanced leak detection practices, and a progressive transition toward low–global warming potential refrigerants to mitigate fugitive losses; and 3) sustainable mobility, supported by travel-demand management strategies and the institutionalization of virtual collaboration to reduce avoidable air travel. To guarantee that the noted enhancements can be linked to the mitigation measures put in place, rather than to the effects of enrollment normalization or variations in grid emission factors, future reports should consistently monitor both absolute and intensity-based indicators. This effort should be supported by an annual measurement, reporting, and verification cycle and reinforced through campus-level accountability mechanisms. Ultimately, this study illustrates that standardized carbon accounting serves as a crucial diagnostic instrument for HEIs striving to align their institutional practices with national sustainability goals and global climate action efforts. For transferability beyond UCC, meaningful inter-HEI comparisons require harmonized boundaries, scopes, emission-factor choices (especially grid electricity), and denominator definitions, as well as transparent documentation of campus context (climate, functions, and population dynamics). The approaches and standards outlined in this study lay a vital groundwork for the next stage of the initiative, allowing for the broadening of a standardized accounting method to further UCC campuses, thus bolstering institutional representation and internal consistency. In parallel, future CF assessments should progressively prioritize the inclusion of additional material Scope 3 categories such as commuting, purchased goods and services, waste, water use, and capital goods as data systems mature, thereby improving inventory completeness, decision usefulness, and the effective prioritization of mitigation actions across the university's full emissions profile.

AUTHOR CONTRIBUTIONS

O. Morales has contributed to the field of data collection and tabulation, project administration, resources, supervision. N. Pardo and the corresponding author contributed with conceptualization, formal analysis, investigation, visualization, writing, original draft, writing, review and editing.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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
^{O}C	Degree Celsius
ABC	Ammonium bicarbonate (fire extinguisher classification)
As	Administrative staff
AVIATUR SAS	Colombian travel agency providing institutional air travel records
BC	Bicarbonate (fire extinguisher classification)
B10	Diesel fuel blended with 10% palm biodiesel
CF	Carbon footprint
CH_4	Methane
$CHCl_2CF_3$	2,2-dichloro-1,1,1-trifluoroethane
$CHClF_2$	Chlorodifluoromethane
CH_2F_2	Difluoromethane
CH_2FCF_3	1,1,1,2-Tetrafluoroethane
CHF_2CF_3	Pentafluoroethane
CO_2	Carbon dioxide
$CO_2(b)$	Biogenic carbon dioxide
CO_2e	Carbon dioxide equivalent
COVID-19	Coronavirus 2019
E10	Gasoline blended with 10% ethanol
FECOC	Colombian Emission Factors for Fossil Fuels
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HEI	Higher education institution
IE	Ibagué–Espinal campus
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kg CO_2e/L	kilograms of carbon dioxide equivalent per liter
kg CO_2e/kg	kilograms of carbon dioxide equivalent per kilogram
kg CO_2e/m^3	carbon dioxide equivalent per cubic meter
kg CO_2/kWh	kilograms of carbon dioxide per kilowatt-hour
kWh	Kilowatt-hour
L	Liter
LED	Light-emitting diode
Me	Medellín campus
Minvivienda	Colombian Ministry of Housing, City and Territory
m^3	Cubic meter

MRV	Measurement–reporting–verification
Na	National (Campus National)
N_2O	Nitrous oxide
NCF	Negative carbon footprint
Pa	Pasto campus
PC	Pereira–Cartago campus
Po	Popayán campus
QA	Quality-assurance
QC	Quality-control
R-22	Chlorodifluoromethane refrigerant
R-123	2,2-Dichloro-1,1,1-trifluoroethane refrigerant
R-134a	1,1,1,2-Tetrafluoroethane refrigerant
R-410A	Refrigerant blend of R-32 and R-125
S	Students
SICOM	Fuel distribution chain information system (Colombia)
SIN	National Interconnected System (Colombia)
tCO_2eq	Metric tons of carbon dioxide equivalent
$tCO_2eq/person$	Metric tons of carbon dioxide equivalents/person
UAM	Universidad Autónoma Metropolitana
UCC	Universidad Cooperativa de Colombia
UNFCCC	United Nations Framework Convention on Climate Change
UPME	Mining and Energy Planning Unit (Colombia)
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

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ORIGINAL RESEARCH PAPER

The impact of chronic arsenic exposure on growth impairment and stunting among toddlers living in geothermal areas

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ABSTRACT

BACKGROUND AND OBJECTIVES: Ie Seuum, a hydrothermal system, is in Aceh Besar Regency and is within the outflow zone of Mount Seulawah Agam. The 2004 tsunami resulted in seawater intrusion, resulting in increased salinity and ions and metals, such as arsenic, in the water. The geological activity present in the area contributes to the release of arsenic from rocks into surface waters. The region is utilized for residential, agricultural, animal husbandry, and ecotourism endeavors. This study aimed to assess the levels of arsenic present in the water and to investigate the correlation between arsenic exposure and stunting in toddlers in Mesjid Raya District, Aceh Besar Regency.

METHODS: This investigation adopted an analytical observational cross-sectional methodology to evaluate the relationship between environmental arsenic exposure and stunting in toddlers. Arsenic concentrations were measured in drinking water, domestic water, and toddler hair samples. Anthropometric measurements comprised weight-for-age, height-for-age, and weight-for-height. Arsenic was quantified using graphite furnace atomic absorption spectrophotometry. Pearson and Spearman correlation analyses were performed.

FINDINGS: Arsenic concentrations exceeded the quality standard in 84.31 percent of water samples. Arsenic was detected in 96.08 percent of toddler hair simples. The levels of arsenic found in water demonstrated a moderate correlation with hair arsenic concentrations (Spearman = 0.47, probability < 0.001), indicating the transfer of environmental exposure into biological accumulation. Hair arsenic levels correlated moderately with ordinal height-for-age status (Spearman = 0.59), whereas water arsenic concentrations showed no significant association with height-for-age (Spearman = 0.16, probability = 0.25). The analysis conducted through logistic regression indicated that an increase of one microgram per gram in hair arsenic correlates with a 15.7 percent increase in the odds of stunting (odd ratio = 1.157, 95 percent confidence interval = 1.06–1.26, probability < 0.001). This is further substantiated by the significantly higher levels of hair arsenic found in stunted children relative to non-stunted children (Mann–Whitney U test, Z-statistic = 4.07, probability < 0.001).

CONCLUSION: Arsenic exposure is widespread in the Ie Seuum geothermal area and poses a serious risk to the growth and development of children. A moderate correlation exists between arsenic found in toddler hair and stunting.

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35	5	7

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INTRODUCTION

The Indian Ocean tsunami of 2004 has significantly changed the hydrogeological regime in the Aceh Province due to the intrusion of seawater into the land and groundwater systems, which has increased the salinity level and deteriorated the quality of water in the region, including the Aceh Besar Regency (McLeod *et al*., 2010). The geological characteristics of the Mesjid Raya District are defined by the impact of marine waters and volcanic activity, attributed to its position in the outflow zone of the active stratovolcano Seulawah Agam. Geothermal manifestations, such as the hot springs of Ie Seuum, occur along the fault segments of Aceh and Seulimeuen. This has enabled the ascent of magmatic fluids and the occurrence of significant water-rock interactions, which have elevated the concentration of primary cations including potassium, aluminum, iron, magnesium, and hydrogen ions as well as secondary minerals such as sulfates, pyrite, and carbonates. This has also increased the concentration of toxic trace elements such as arsenic (As), cadmium, mercury, lead, and aluminum. Arsenic is a major environmental and health risk due to its toxic properties and persistence in water. In the *Ie* seuum geothermal area, the concentration levels were reported to be 161 parts per billion (ppb) in 2021, which is beyond the World Health Organization and Indonesian regulations on the allowed concentration levels, which are 50 ppb for clean water and 10 ppb for drinking water (Irnawati *et al*., 2021; Kementerian Kesehatan, 2017). Prior studies have predominantly concentrated on the geochemical analysis of groundwater or the remediation of water contaminated with arsenic (Kapani *et al*., 2024; Nasher, 2022; Rahman *et al*., 2023; Rangasamy and Muniyandi, 2024), while there has been minimal incorporation of environmental and epidemiological methodologies. While drinking water remains the dominant exposure route, recent comprehensive risk assessments have challenged the "drinking-water-only" paradigm (Hu *et al*., 2024). Studies following the 2020 Taal volcanic eruption revealed that dietary intake (via crop irrigation) and dermal absorption (via bathing and sanitation) significantly contribute to total body burden (Luo *et al*., 2025). Recent toxicological reviews have emphasized dermal exposure as a significant yet often neglected route, wherein arsenic present in bathing water can circumvent first-pass metabolism, thereby threatening skin integrity and overall systemic health. This multi-pathway exposure is particularly concerning for toddlers, whose hand-to-mouth behaviors and higher surface-area-to-body-weight ratios amplify their vulnerability to contaminated sanitation water and soil (UNICEF, 2025; Patel *et al*., 2023). The locality functions as a residential and leisure area, where the inhabitants relying on accessible water for consumption, domestic activities, irrigation, and raising animals, which consequently puts them at risk of chronic arsenic poisoning. Biologically, the link between chronic arsenic exposure and growth impairment (stunting) is driven by complex molecular mechanisms. Previous studies from 2024 and 2025 indicate that arsenic induces systemic oxidative stress and mitochondrial dysfunction, which directly inhibit cellular proliferation in growth plates (Tian *et al*., 2025). Epigenetic studies further indicate that higher levels of arsenic exposure are positively correlated with deoxyribonucleic acid (DNA) methylation (Kile *et al*., 2012; Kim, 2024). Recent studies using animal models have provided additional confirmation that exposure to arsenic markedly elevates malondialdehyde levels while reducing the activity of superoxide dismutase in reproductive and developmental tissues (Irnawati *et al*., 2023). Epidemiological evidence reinforces these mechanistic findings. Recent birth cohort studies

in South and Southeast Asia have significant associations of arsenic with epigenetic changes, DNA damage, abnormal birth outcomes, and elevated mortality (Su *et al*., 2025; Hu *et al*., 2024). The prevalence of stunting among the population in the Mesjid Raya District is 25.9 percent (%) compared to the national average (Al Rahmad, 2019). Past studies revealed that the level of geogenic arsenic contamination of water and sediments was severe, up to sixteen times the permissible limit, and the duration of exposure affected the growth of toddlers (probability (p) = 0.046) and development (p = 0.039) of 156 children below five years of age (Fitra *et al*., 2024). Nonetheless, a significant knowledge gap persists concerning the direct connection between environmental exposure pathways and these child health outcomes. Prior studies have not sufficiently measured the relationship between arsenic buildup in biological markers (such as hair) and anthropometric indicators of stunting, nor have they distinguished the effects of water utilized for sanitation compared to that used for consumption. Thus, this study investigates the relationship between arsenic exposure using water for daily use and the prevalence of stunting among children below five years of age. The study was conducted in the Suum, Aceh Besar Regency, Indonesia, in 2023.

MATERIALS AND METHODS

The study area

This study involved toddlers aged 1–5 years (y) from eight villages in Mesjid Raya District, Aceh Besar Regency, surrounding the Ie Seuum geothermal river (Ie Seuum, Meunasah Mon, Meunasah Kulam, Meunasah Keude, Berandeh, Paya Kameng, Ruyung, and Lamreh), selected by cluster random sampling with number (N) = 50; two-proportion hypothesis test). The criteria for inclusion specified that maternal residence should be ≥5 years before childbirth, current residence and the use of well or local water, refrain from using hair dyes or straighteners, no ongoing treatment for chronic diseases, and the necessity of obtaining parental informed consent. Sampling and data collection occurred during community health (*Posyandu*) activities in May–June 2023 with assistance from local health personnel. Arsenic concentrations in water and hair and toddler growth indicators were analyzed at the Research and Analytical Chemistry Laboratories, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Aceh Province, Indonesia.

Water sampling technique

Water samples were collected with a plastic dipper and stored in nitric acid (HNO_3) cleaned polyethylene bottles, pre-rinsed three times with sample water. Samples were taken at 3 different points. The measurements taken in the field included temperature, potential of hydrogen (pH), total dissolved solids (TDS), conductivity, salinity, and sampling coordinates, determined using portable digital thermometers, pH meters, TDS meters, conductometers, and a global positioning system (GPS). Samples for laboratory analysis were preserved with HNO_3 to pH < 2 and stored at 4 ± 2 degree Celsius (°C). Aquadest is used as a blank (Irnawati *et al*., 2021).

Hair sampling and preparation techniques

Hair samples were obtained from five distinct areas of the scalp, cut to a length of 0.5 centimeters (cm) from the root with stainless steel scissors while ensuring dry, non-oily conditions (Vogliardi *et al*., 2015). A 0.2 grams (g) sample was washed with deionized water, shaken for 30 minutes, digested in a 100 milliliters (mL) Erlenmeyer flask with 4 mL sulfuric acid (H_2SO_4) and 3 mL HNO_3 concentrated, then heated with incremental HNO_3 until a brown–black color formed. Addition of 2 mL perchloric acid ($HClO_4$) and reheating produced a clear yellow solution,

which was diluted to 100 mL with deionized water (Irnawati *et al*., 2021).

Arsenic analysis with graphite furnace- atomic absorption spectrometry (GF-AAS)

Arsenic concentration in the sample was determined utilizing an atomic absorption spectrophotometer (AAS), graphite furnace (THGA), autosampler (AS900). The prepared sample was injected as much as 20 microliters (µL) with *Ausampler* into *furnace tube* and atomized. Sample measurements were made at a wavelength of 193.70 nanometer (nm). Each sample was measured 3 times (EPA, 1998). Method validation including calibration curves, Limit of Detection, and Limit of Quantification has been done in previous studies (Irnawati *et al*., 2021).

Measurement of growth and development of children under five

Growth measurement using a calibrated Xiaomi Mi Smart Scale digital weight scale. Height measurement using a microtomies staturameter height measuring instrument. Growth gauges use weight-for-age, height-for-age, and weight-for-height indicators. Development measurement is performed utilizing early stimulation, detection, and intervention in growth and development (SDIGD) kits and forms.

Statistical analysis of arsenic exposure and growth outcomes

Arsenic concentrations in both water and hair were examined as continuous variables. Height-for-age was recorded as an ordinal categorical variable (normal, stunted, severely stunted) and encoded as ordered ranks for analysis. Associations between continuous variables were assessed using both Pearson (r) and Spearman (ρ) correlation coefficients, while associations involving ordinal height-for-age were evaluated using Spearman's rank correlation. Stunting was defined as height-for-age classified as Stunted or Severely Stunted. The correlation between hair arsenic levels and stunting was analyzed through logistic regression, with findings expressed as odds ratios (OR) and 95% confidence intervals (CI). Differences in hair arsenic concentrations between stunted and non-stunted children were assessed using the Mann–Whitney U test. Statistical significance was set at $p < 0.05$. All statistical evaluations were executed utilizing a programming and numeric computing platform (MATLAB); R2021a (version 9.10.0.1602886).

RESULTS AND DISCUSSION

Water Sampling Location and arsenic Levels in each sample

Fig. 1 integrates hydrogeological and arsenic data, revealing a spatial gradient in Mesjid Raya District linked to Ie Seuum geothermal spring proximity. Arsenic concentrations decreased with increasing distance from the Ie Seuum geothermal spring, indicating dilution and attenuation during groundwater flow, but Meunasah Keude Village along the coast showed anomalously high levels. The intrusion of seawater and the presence of sulfide-rich marine sediments probably facilitated the release of arsenic, as reducing conditions promote arsenic mobilization through reductive dissolution of iron oxyhydroxides (Mensah *et al*., 2022). The spatial pattern in Fig. 1 matches the chloride-type hydrothermal system of Ie Seuum, characterized by a reservoir temperature of ~168 °C and high natrium and chloride concentrations that enhance arsenic solubility via ion exchange and complexation (Idroes *et al*., 2019). The reduction of arsenic concentrations away from the spring demonstrates the mixing of deep geothermal fluids and shallow groundwater that is lower in mineral content. Spatial analysis, therefore identifies two dominant geogenic

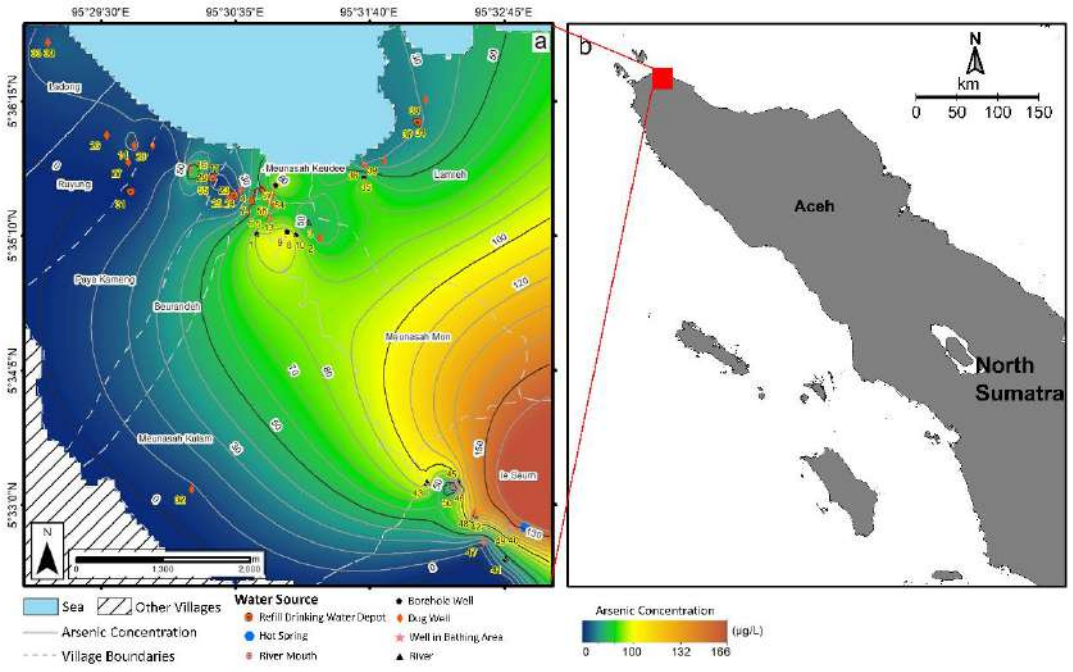

Fig. 1: Geographical location of the study area of arsenic content distribution in Mesjid Raya District, Aceh Besar Regency, Indonesia

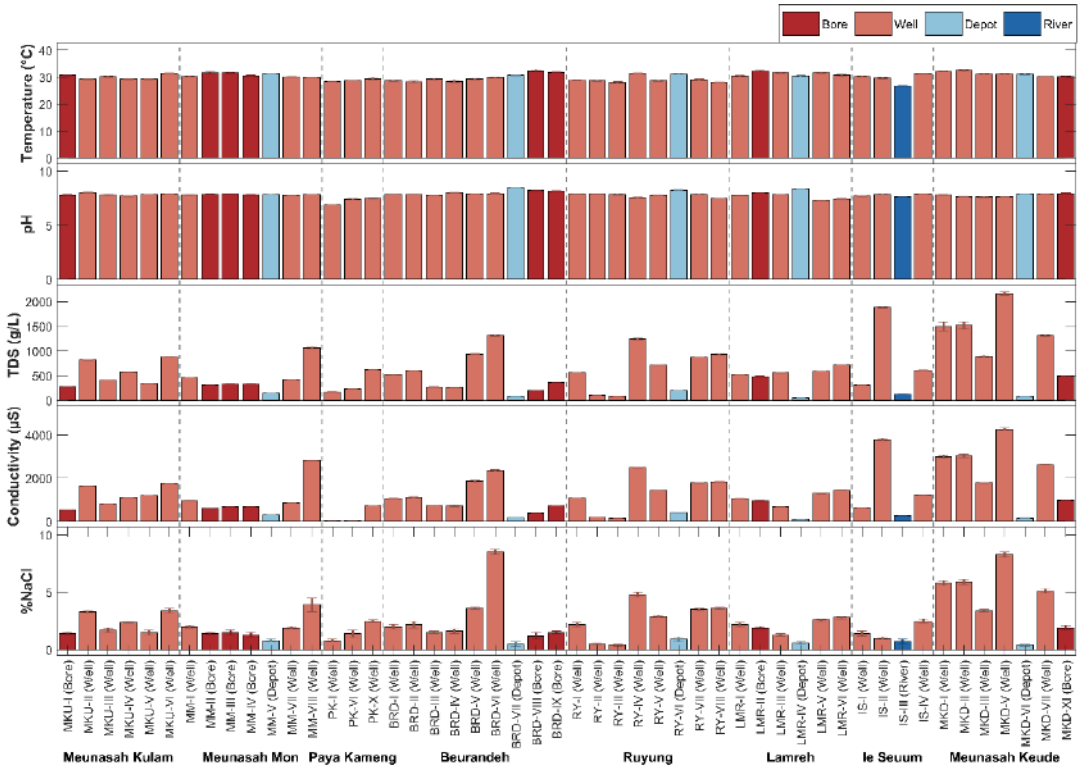

Fig. 2: Distribution of water physicochemical characteristics across eight villages. Each panel shows mean ± SD for temperature, pH, TDS, conductivity, and Sodium Chlorida (NaCl) percentage, illustrating variability among sampling locations and water types

Table 1: In situ data on water samples of dug wells, boreholes and rivers in the District of Mesjid Raya in Aceh Besar Regency in 2023

Village name	Sample code and water type	Characteristics				
		Temperature ± SD (°C)	pH ± SD	TDS ± SD (gram per liter)	Conductivity ± SD (microsecond)	NaCl ± SD (%)
Meunasah Kulam (MKU)	MKU-I (Bore)	30.7 ± 0.2	7.80 ± 0.05	275.7 ± 4.2	543.7 ± 3.2	1.4 ± 0.1
	MKU-II (Well)	29.2 ± 0.1	8.03 ± 0.03	815.7 ± 5.9	1638.7 ± 13.8	3.3 ± 0.1
	MKU-III (Well)	30.2 ± 0.3	7.81 ± 0.07	417.7 ± 2.5	833.0 ± 3.6	1.7 ± 0.2
	MKU-IV (Well)	29.2 ± 0.1	7.68 ± 0.03	571.0 ± 7.7	1128.7 ± 11.5	2.4 ± 0.1
	MKU-V (Well)	29.2 ± 0.1	7.86 ± 0.01	340.0 ± 2.9	1200.0 ± 12.5	1.5 ± 0.2
	MKU-VI (Well)	31.5 ± 0.1	7.92 ± 0.03	878.0 ± 2.6	1754.7 ± 12.9	3.4 ± 0.2
Meunasah Mon (MM)	MM-I (Well)	30.3 ± 0.2	7.81 ± 0.02	463.3 ± 2.5	959.0 ± 1.0	2.0 ± 0.1
	MM-II (Bore)	31.6 ± 0.3	7.87 ± 0.04	309.7 ± 1.5	614.0 ± 1.0	1.4 ± 0.1
	MM-III (Bore)	31.6 ± 0.2	7.89 ± 0.02	335.0 ± 4.4	680.0 ± 2.0	1.5 ± 0.2
	MM-IV (Bore)	30.6 ± 0.2	7.81 ± 0.04	336.7 ± 1.5	662.7 ± 3.6	1.3 ± 0.2
	MM-V (Depot)	31.4 ± 0.1	7.85 ± 0.03	152.3 ± 2.1	306.3 ± 2.1	0.8 ± 0.1
	MM-VII (Well)	30.1 ± 0.1	7.78 ± 0.02	430.0 ± 1.5	860.0 ± 1.8	1.9 ± 0.1
	MM-VIII (Well)	29.9 ± 0.1	7.86 ± 0.02	1071.3 ± 15.7	2826.7 ± 18.6	3.9 ± 0.6
Paya Kameng (PK)	PK-I (Well)	28.4 ± 0.1	6.87 ± 0.02	173.7 ± 1.5	28.6 ± 2.3	0.8 ± 0.1
	PK-VI (Well)	28.8 ± 0.1	7.41 ± 0.04	235.3 ± 1.7	46.9 ± 2.4	1.4 ± 0.3
	PK-X (Well)	29.4 ± 0.4	7.51 ± 0.07	623.0 ± 1.4	703.7 ± 4.9	2.5 ± 0.1
Beurandeh (BRD)	BRD-I (Well)	28.7 ± 0.2	7.87 ± 0.02	522.3 ± 8.7	1062.7 ± 11.5	2.0 ± 0.2
	BRD-II (Well)	28.3 ± 0.3	7.88 ± 0.02	603.7 ± 4.2	1124.0 ± 17.9	2.2 ± 0.3
	BRD-III (Well)	29.3 ± 0.2	7.77 ± 0.02	270.7 ± 9.1	727.7 ± 6.5	1.5 ± 0.1
	BRD-IV (Well)	28.5 ± 0.4	8.03 ± 0.02	259.3 ± 5.5	723.7 ± 41.6	1.6 ± 0.2
	BRD-V (Well)	29.3 ± 0.2	7.92 ± 0.02	938.7 ± 5.4	1863.7 ± 47.4	3.6 ± 0.1
	BRD-VI (Well)	29.9 ± 0.2	7.95 ± 0.04	1310.0 ± 12.6	2350.7 ± 45.3	8.5 ± 0.2
	BRD-VII (Depot)	30.7 ± 0.2	8.53 ± 0.02	87.1 ± 0.1	174.2 ± 2.9	0.5 ± 0.2
	BRD-VIII (Bore)	32.4 ± 0.4	8.21 ± 0.03	196.3 ± 1.5	370.7 ± 3.9	1.2 ± 0.3
	BRD-IX (Bore)	31.8 ± 0.1	8.18 ± 0.02	366.0 ± 1.0	713.3 ± 7.2	1.5 ± 0.1
Ruyung (RY)	RY-I (Well)	28.9 ± 0.2	7.89 ± 0.01	560.3 ± 1.5	1084.3 ± 14.2	2.2 ± 0.2
	RY-II (Well)	28.7 ± 0.2	7.90 ± 0.02	102.6 ± 1.2	203.7 ± 0.4	0.5 ± 0.1
	RY-III (Well)	28.1 ± 0.3	7.84 ± 0.06	77.9 ± 2.8	156.0 ± 0.6	0.4 ± 0.1
	RY-IV (Well)	31.5 ± 0.1	7.56 ± 0.04	1249.3 ± 15.5	2489.7 ± 13.8	4.8 ± 0.2
	RY-V (Well)	28.7 ± 0.2	7.79 ± 0.02	714.3 ± 2.1	1433.0 ± 11.4	2.9 ± 0.1
	RY-VI (Depot)	31.2 ± 0.2	8.24 ± 0.03	194.3 ± 2.1	392.3 ± 2.1	0.9 ± 0.2
	RY-VII (Well)	29.1 ± 0.2	7.85 ± 0.04	870.7 ± 3.8	1783.7 ± 16.8	3.5 ± 0.1
	RY-VIII (Well)	28.2 ± 0.1	7.48 ± 0.03	933.7 ± 8.5	1845.0 ± 11.1	3.6 ± 0.1
Lamreh (LMR)	LMR-I (Well)	30.5 ± 0.2	7.75 ± 0.03	529.7 ± 2.6	1062.0 ± 11.4	2.2 ± 0.2
	LMR-II (Bore)	32.2 ± 0.3	8.00 ± 0.01	485.3 ± 4.5	955.0 ± 4.4	1.9 ± 0.1
	LMR-III (Well)	31.6 ± 0.2	7.84 ± 0.03	552.3 ± 3.1	663.7 ± 3.8	1.3 ± 0.1
	LMR-IV (Depot)	30.6 ± 0.3	8.38 ± 0.02	52.0 ± 1.1	104.4 ± 1.4	0.6 ± 0.1
	LMR-V (Well)	31.6 ± 0.2	7.31 ± 0.03	590.0 ± 2.6	1291.0 ± 15.6	2.6 ± 0.1
	LMR-VI (Well)	30.7 ± 0.5	7.44 ± 0.02	723.3 ± 2.1	1437.3 ± 14.9	2.8 ± 0.1
Ie Seuum (IS)	IS-I (Well)	30.3 ± 0.2	7.68 ± 0.03	313.3 ± 3.1	644.3 ± 3.8	1.4 ± 0.2
	IS-II (Well)	29.6 ± 0.3	7.86 ± 0.04	1887.0 ± 18.4	3781.3 ± 62.7	1.0 ± 0.1
	IS-III (River)	26.8 ± 0.2	7.63 ± 0.02	124.0 ± 2.6	251.7 ± 3.1	0.7 ± 0.2
	IS-IV (Well)	31.3 ± 0.2	7.93 ± 0.02	614.3 ± 2.5	1227.7 ± 16.4	2.5 ± 0.2
Meunasah Keude (MKD)	MKD-I (Well)	32.1 ± 0.2	7.81 ± 0.04	1499.7 ± 89.6	2988.3 ± 82.2	5.8 ± 0.2
	MKD-II (Well)	32.5 ± 0.4	7.65 ± 0.02	1518.3 ± 76.4	3031.7 ± 76.4	5.9 ± 0.2
	MKD-III (Well)	31.2 ± 0.2	7.61 ± 0.05	889.3 ± 22.1	1784.0 ± 17.8	3.4 ± 0.1
	MKD-V (Well)	31.2 ± 0.2	7.63 ± 0.02	2161.7 ± 28.9	4270.0 ± 50.5	8.3 ± 0.2
	MKD-VI (Depot)	31.1 ± 0.3	7.93 ± 0.02	82.7 ± 1.1	166.1 ± 4.4	0.4 ± 0.1
	MKD-VII (Well)	30.3 ± 0.1	7.92 ± 0.03	1312.7 ± 15.3	2630.7 ± 13.8	5.1 ± 0.2
	MKD-XI (Bore)	30.3 ± 0.2	7.95 ± 0.04	492.0 ± 4.6	980.3 ± 5.9	1.9 ± 0.2

factors influencing arsenic distribution: hydrothermal upflow from the Seulawah Agam system and coastal aquifer processes driven by saline intrusion and redox reactions, which elucidate the differing concentrations observed inland and along the coast in the Mesjid Raya District.

Water characteristic data

In conjunction with sampling, data analysis was performed in situ in fields such as pH, TDS, Electrical Conductivity (EC), temperature, and salinity with standard deviations (SD). The findings are illustrated in Fig. 2 and Table 1. All water samples met pH standards (6.5–8.5) (Kementerian Kesehatan, 2010). However, eight locations exceeded World Health Organization (WHO) TDS thresholds (500 and 1000 milligrams per liter (mg/L) (WHO, 2011). Meunasah Keude exhibited the highest TDS, attributed to coastal saline intrusion and enrichment with sodium (Na^+), *chloride* (Cl^-), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) (Adjovu *et al*., 2023). Similarly, Ie Seuum samples surpassed the <0.5% freshwater salinity limit, reflecting hydrothermal influence. Characterized as a chloride-type system (Cl^-) 2656.99 mg/L; Na^+ 2630.03 mg/L) with reservoir and surface temperatures of ~168 °C and 84.2 °C, respectively, and pH 6.61. The origin of this deep reservoir, which experiences minimal meteoric mixing, elucidates the increased geogenic salinity and TDS (Idroes *et al*., 2019).

Relationship between sanitation water source and arsenic level in water

Table 2 illustrates the correlation between public sanitation water sources and arsenic concentrations. The results show that 84.31% of the analyzed water samples exceeded the permissible quality standards for arsenic concentration, while only 15.69% met the standard limits. Of the different water sources examined, well samples demonstrated the highest rate of arsenic contamination, recorded at 60.78%, with borehole water at 19.61% and river water at 3.92%.

Arsenic levels in consumption water

A vast majority of participants (99%) obtain drinking water from commercially obtained refillable treatment drinking water depots. There are 5 refillable drinking water depots serving eight research location villages. Table 3 and Fig. 3 illustrate the outcomes of the arsenic level testing conducted on water samples. Analysis confirmed 100% of treatment depots produced arsenic-free water, as managers source raw water from mountain springs outside the geothermal zone via tanker trucks. While toddlers are provided with safe drinking water, budgetary restrictions limit its utilization to drinking and cooking. Community members utilize arsenic-contaminated groundwater for the purposes of washing food, cleaning utensils, personal hygiene, and agricultural endeavors, thus ensuring continuous exposure to environmental hazards. Additionally, local vegetation such as Chromolaena odorata bioaccumulates geogenic heavy metals, acting as a secondary contamination vector. Consequently, indirect exposure through domestic water usage and local food chains drives chronic arsenic accumulation (Abubakar, 2023).

Analysis of arsenic levels in water and hair, and results of toddler growth measurement

The results of anthropometric measurements and environmental sampling are presented to describe the relationship between arsenic exposure and growth outcomes among toddlers living in the geothermal area. Table 4 offers an in-depth analysis of the frequency distribution of water sources, arsenic concentrations in both

Table 2: The relationship between sanitation water sources and arsenic levels in water

Water sources	Arsenic water content				N	%
	≤ quality standards	%	> quality standards	%		
Well dug	7	13.73	31	60.78	38	100
Borehole	0	0.00	10	19.61	10	
River	1	1.96	2	3.92	3	
Total	8	15.69	43	84.31	51	

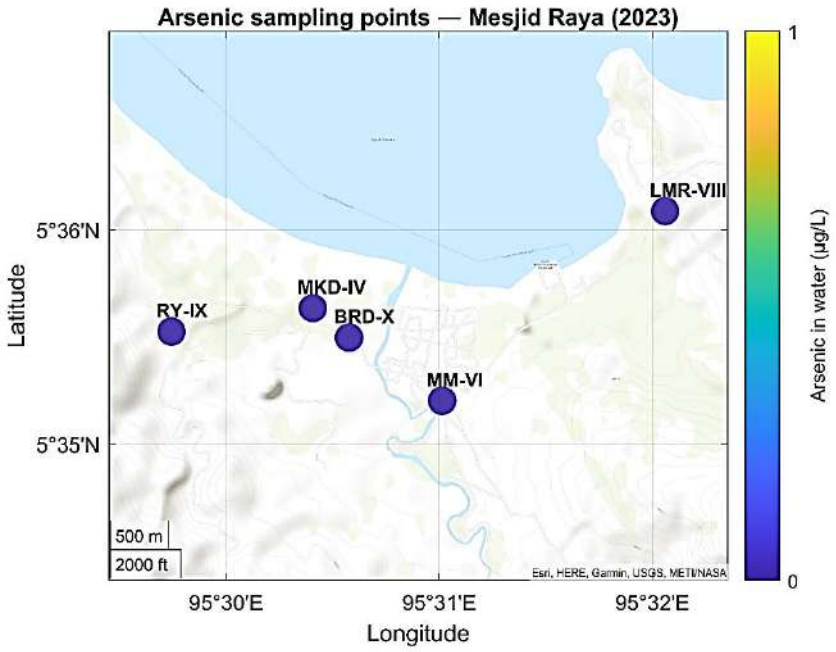

Fig. 3: Spatial distribution of arsenic concentration in drinking water sources across surveyed villages - the colors indicate concentration levels relative to the water quality standard (10 µg/L)

Table 3: Source of drinking water, location, and arsenic levels in the District of Mesjid Raya in Aceh Besar Regency in 2023

No	Sample code	Drinking water sources	Coordinate		Arsenic level in water
			Latitude (°)	Longitude (°)	
1	MM-VI	Treatment drinking water depot	5.593904°	95.506788°	0
2	BRD-X	Treatment drinking water depot	5.591618°	95.50962°	0
3	RY-IX	Treatment drinking water depot	5.592085°	95.49573°	0
4	LMR-VIII	Treatment drinking water depot	5.60146°	95.534324°	0
5	MKD-IV	Treatment drinking water depot	5.593904°	95.506788°	0

water and hair samples, and their correlation with the nutritional status indicators of the children in the study area. Fig. 4 depicts the distribution of nutritional status among children, categorized by the three primary anthropometric indicators, namely height-for-age (stunting), weight-for-height (wasting), and weight-for-age (underweight). Households primarily utilize dug wells (74.51%) for domestic needs, alongside boreholes and river water. Arsenic contamination exceeded the 10 microgram per liter (µg/L) (WHO, 2017) threshold in 84.31% of samples, with mean and maximum concentrations of 44.67 µg/L and 107.81 µg/L, respectively. Biological monitoring detected arsenic in 96.08% of toddler hair samples, indicating widespread chronic exposure

Table 4: Frequency distribution of water sources, arsenic levels in water and hair, weight-for-age, height-for-age and weight-for-height in the District of the Mesjid Raya in Aceh Besar Regency in 2023

No	Variable	N	%
1	Water sources		
	Well	38	74.51
	Bore	10	19.61
	River	3	5.88
	Total	51	100
2	Arsenic level in water		
	≤ Quality standards	8	15.69
	> Quality standards	43	84.31
	Total	51	100
	Std Dev	32.17	
	Median	45.27	
	Minimum	0.84	
	Maximum	107.81	
3	Arsenic levels in hair		
	≤0 µg/g	2	3.92
	>0	49	96.08
	Total	51	100
	Mean	17.90	
	Std Dev	10.70	
	Median	17.17	
	Minimum	0	
	Maximum	39.78	
4	Height-for-age		
	Normal	29	56.86
	Stunted	18	35.29
	Severely Stunted	4	7.84
	Total	51	100
5	Weight-for-height		
	Normal	47	92.16
	Wasted	4	7.84
	Total	51	100.00
6	Weight-for-age		
	Normal	40	78.43
	Underweight	10	19.61
	Severely Underweight	1	1.96
	Total	51	100

Table 5: The effect of arsenic levels in water on arsenic levels in hair

Arsenic levels in water	Arsenic levels in hair				N	%
	≤0 µg/g	%	>0 µg/g	%		
≤ Quality standards (≤10 µg/L)	2	3.92	6	11.76	8	
> Quality standards (>0 µg/L)	0	0	43	84.31	43	100
Total	2	3.92	49	96.08	51	

Hair arsenic concentrations showed a mean of 17.90 µg/g and a maximum of 39.78 µg/g. Anthropometric analysis classified 35.29% of toddlers as stunted and 7.84% as severely stunted based on height-for-age. Furthermore, 19.61% were underweight and 1.96% were severely underweight, while 92.16% maintained normal weight-for-height.

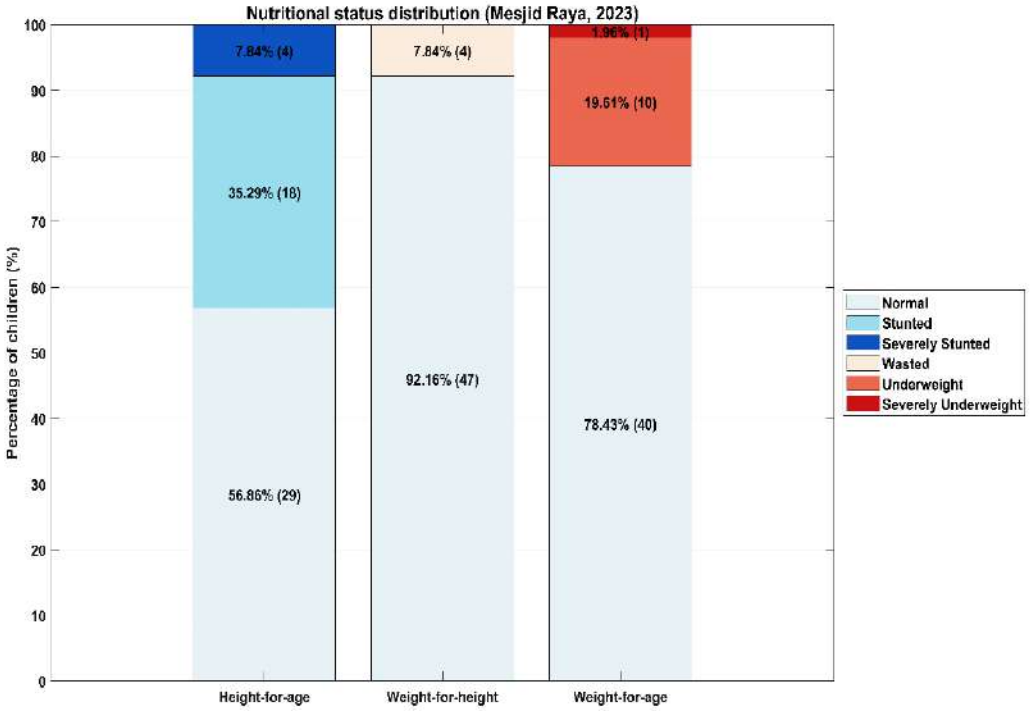

Fig. 4: Nutritional status of children in the study area based on anthropometric indicators. Stacked bar charts represent the percentage and frequency (in parentheses) of each category for height-for-age, weight-for-height, and weight-for-age indices

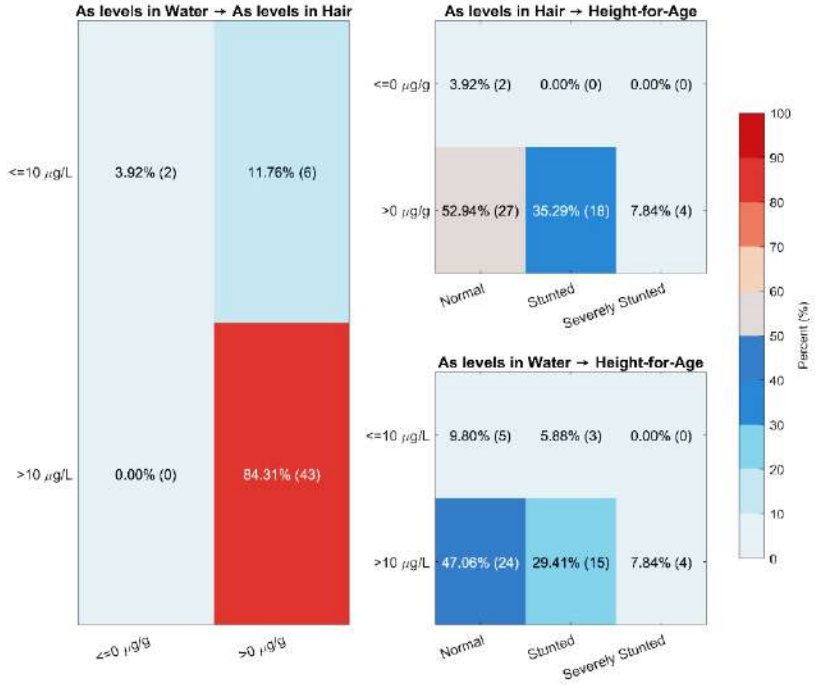

Fig. 5: Relationship between arsenic exposure and nutritional outcomes. Heatmaps summarize associations among arsenic levels in water, arsenic accumulation in hair, and stunting categories (normal, stunted, severely stunted). Cell values denote within-row percentages and frequencies, highlighting stronger nutritional impacts at higher exposure levels

Table 6. The effect of arsenic levels in water and hair on the incidence of stunting

As levels in hair	Height-for-age					%	N	%
	Normal	%	Stunted	%	Severely stunted			
≤ 0 µg/g	2	3.92	0	0	0	0	2	
> 0	27	52.94	18	35.29	4	7.84	49	100
Total	29	56.86	18	35.29	4	7.84	51	
As levels in water								
≤ quality standards (≤ 10 µg/L)	5	9,80	3	5,88	0	0,00	8	
> quality standards (> 0 µg/L)	24	47.06	15	29.41	4	7.84	43	100
Total	29	56.86	18	35.29	4	7.84	51	

Table 7. Summary of correlation, logistic regression, and group comparison analyses assessing associations between arsenic exposure (water and hair) and child growth outcomes (N = 51)

Analysis type	Comparison / Outcome	N	Statistic	Effect Size	*p*-value
Correlation (Pearson)	Water As vs Hair As	51	*r*	0.407	0.003
Correlation (Spearman)	Water As vs Hair As	51	*ρ*	0.469	< 0.001
Correlation (Spearman)	Hair As vs Height-for-age	51	*ρ*	0.594	< 0.001
Correlation (Spearman)	Water As vs Height-for-age	51	*ρ*	0.163	0.252
Logistic regression	Hair As → Stunting	51	OR	1.157	< 0.001

The effect of arsenic contamination in water on arsenic levels in hair

Hair served as a stable, non-invasive biomarker for chronic arsenic accumulation (Ramly *et al*., 2023). Arsenic in hair samples was detected in 84.31% of individuals who used non-compliant water sources, whereas only 11.76% of those utilizing compliant water showed similar results (Fig. 5 and Table 5). This discrepancy highlights secondary environmental pathways, including soil and plants, where high-concentration metal translocation damages organs (Abubakar *et al*., 2023). The safe limit of arsenic levels in hair has not been officially set. However, levels exceeding 0.02 µg/g correlate with systemic oxidative stress (Pan *et al*., 2020), while concentrations <1 µg/g typically indicate no arsenicosis (Ramly *et al*., 2023; Vidosavljevic *et al*., 2022). Normal values fall below 3 milligram per kilogram (mg/kg), contrasting with contaminated populations (<100 mg/kg) and lethal thresholds (210 mg/kg). Hair analysis quantifies 6–12-month exposure durations but poorly predicts specific health outcomes (Mayo Clinic Laboratories, 2020). Fig. 5 and Table 6 demonstrate the correlation between stunting (height-for-age) and arsenic exposure, highlighting that individuals who are unexposed typically have levels <1 µg/g. The analysis revealed a significant association between hair arsenic levels and stunting incidence, with 35.29% of toddlers exhibiting stunting and 7.84% severe stunting, where this figure is higher than in the 2019 study (Al Rahmad, 2019). During keratinization, arsenic is incorporated into the hair's protein structure, effectively sealing the metalloid within the shaft, where it can remain for decades (Katz, 2019). Chronic high-dose exposure damages cells, induces inflammation, and depletes tissue antioxidants (Irnawati *et al*., 2023). This type of toxicity hinders growth by obstructing the absorption of micronutrients such as Fe and Zn, causing harm to organs including the liver, kidneys, and bones, and disrupting vital growth hormones like insulin (Moody *et al*., 2020). Additionally, arsenic-induced immunotoxicity increases susceptibility to infections, further inhibiting growth. Interviews revealed that a few residents are consuming groundwater, probably

unaware of the dangers posed by geothermal heavy metal. Arsenic toxicity remains insidious; dermal symptoms require 1200 µg/L concentrations over 6 months to 3 years, while weight impact manifests after 4 months in 1800 µg/L (Fatoki and Badmus, 2022). Although daily intake remains below the lethal dose of 2 milligrams per kilogram per day (mg/kg/day) (UNL-EHS, 2007), the lack of immediate symptoms necessitates preventive measures.

Integrated Analysis of Correlation and Stunting Outcomes

Based on Table 7, Water arsenic concentration was moderately correlated with hair arsenic levels (Pearson $r = 0.41$, $p = 0.003$; Spearman $\rho = 0.47$, $p < 0.001$), indicating that arsenic exposure from water was reflected in biological accumulation. Hair arsenic showed a strong positive association with ordinal height-for-age status (Spearman $\rho = 0.59$, $p < 0.001$), whereas water arsenic concentration was not significantly associated with height-for-age ($\rho = 0.16$, $p = 0.25$). Consistent with these correlations, logistic regression analysis demonstrated that higher hair arsenic concentration was significantly associated with increased odds of stunting (OR = 1.157, 95%, CI: 1.06–1.26, $p < 0.001$), corresponding to a 15.7% increase in the odds of stunting for each 1 µg/g increase in hair arsenic. The identified relationship between arsenic levels in hair and stunting is categorized as a moderate correlation, based on widely accepted interpretation standards for correlation coefficients (Schober *et al*., 2018). Non-parametric group comparison further showed that hair arsenic levels were significantly higher in stunted children compared with non-stunted children (Mann–Whitney U test, *Z-statistic* = 4.07, $p < 0.001$).

CONCLUSION

This study identifies the Mesjid Raya District, particularly the Ie Seuum hydrothermal area, as a high-risk zone for geogenic arsenic contamination. Hydrogeochemical evidence confirms the area as an outflow zone of the Seulawah Agam volcanic system characterized by chloride-type hydrothermal fluids. Interaction between volcanic processes and post-tsunami seawater intrusion generated a complex groundwater regime, with 84.31% of water sources exceeding the national safety threshold of 10 µg/L and concentrations reaching 107.81 µg/L. Dug wells, which serve 74.51% of households with water, demonstrated the most significant contamination, allowing arsenic to migrate from deep magmatic reservoirs into shallow aquifers used for daily domestic activities. A notable inconsistency was observed regarding the safety of drinking water in relation to biological arsenic buildup. Although all commercial refill drinking-water depots were arsenic-free, 96.08% of toddlers exhibited detectable hair arsenic with a mean concentration of 17.90 µg/g, indicating persistent chronic exposure from non-drinking pathways. Water arsenic concentrations correlated moderately with hair arsenic levels (Pearson r = 0.41, p = 0.003; Spearman ρ = 0.47, p < 0.001), demonstrating that household water contamination translated into biological accumulation. Exposure to the skin while bathing, the use of polluted water for food preparation, and indirect dietary intake probably constitute the main exposure pathways that have not been adequately addressed. Bioaccumulated arsenic showed a clear association with impaired linear growth. Hair arsenic concentrations correlated strongly with ordinal height-for-age status (Spearman ρ = 0.59, p < 0.001), while water

arsenic levels did not demonstrate a significant relationship with height-for-age (ρ = 0.16, p = 0.25). Logistic regression analysis further demonstrated that each 1 µg/g increase in hair arsenic increased the odds of stunting by 15.7% (OR = 1.157; 95% CI: 1.06–1.26; p < 0.001). Non-parametric comparison confirmed significantly higher hair arsenic levels among stunted children than non-stunted children (Mann–Whitney U test, Z = 4.07, p < 0.001). Overall, stunting affected 35.29% of toddlers, including 7.84% classified as severely stunted. These observations demonstrate that hair arsenic is a more trustworthy biomarker of chronic exposure and a superior predictor of stunting compared to arsenic levels found in household water alone. Mitigation strategies focused exclusively on drinking-water quality therefore underestimate health risks in geothermal settings. To achieve effective intervention in Aceh Besar Regency, it is essential to implement a holistic treatment of water for all domestic applications, restore contaminated dug wells, and provide specific public education that focuses on dermal and indirect oral exposure to geogenic contaminants. This study provides a reference framework for communities living in the volcanic Ring of Fire, where geogenic contamination may discreetly jeopardize child development despite access to safe drinking water. Interpretation of these results must consider the limited sample size and single-season sampling. Subsequent studies ought to incorporate larger cohorts, sampling over multiple seasons, evaluations of multimedia exposure, and longitudinal frameworks to strengthen reliability and investigate the persistence or reversibility of growth impairment due to arsenic exposure.

AUTHOR CONTRIBUTIONS

I. Irnawati, as the corresponding author, contributed to the conceptualization, formal analysis, funding acquisition, methodology development, project administration, resource management, supervision, and preparation of the original draft. I. Seriana was responsible for data curation, methodology, resource provision, software development, and validation. G. Gustiana contributed to resources, validation, and methodological support. U. Zulfiani contributed to writing, reviewing, and editing, as well as data visualization. M.N. Hidayat contributed to writing, review, editing, and visualization.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest and affirm compliance with ethical standards, including plagiarism, informed consent, misconduct, data fabrication, double submission, and redundancy. The Health Research Ethics Committee of the Aceh Polytechnic of Health, Ministry of Health, approved the study protocol [No. LB.02.03/025/2023; May 17, 2023]. Guardians provided written informed consent for the use of clinical information and images, understanding that names and initials remain unpublished to ensure anonymity.

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☑ **Negative AI Statement**

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

ABBREVIATIONS

%	Percent
^{o}C	Degree Celsius
µL	Microliters
µg/L	Microgram per liter
µg/g	Microgram per gram
As	Arsenic
ρ	Spearman coefficient correlation
BRD	Beurandeh
Cl^-	Chloride
CI	Confidence intervals
cm	Centimeters
DNA	Deoxyribonucleic acid
EC	Electrical conductivity
g	Grams
GPS	Global positioning system
GF-AAS	Graphite furnace- atomic absorption spectrometry
H_2SO_4	Sulfuric acid
$HClO_4$	Perchloric acid
HNO_3	Nitric acid
IS	Ie Seuum
LMR	Lamreh
MATLAB	A programming and numeric computing platform
mg/kg	Milligram per kilogram
mg/kg/day	Milligrams per kilogram per day
mg/L	Milligrams per liter
Mg^{2+}	Magnesium
MKD	Meunasah Keude
MKU	Meunasah Kulam
mL	Milliliters
MM	Meunasah Mon
N	Number
Na^+	Sodium
NaCl	Sodium Chloride
nm	Nanometer
OR	Odd ratio
p	Probability
pH	Potential of hydrogen
PK	Paya Kameng
ppb	Parts per billion
r	Pearson coefficient correlation
RY	Ruyung
SD	Standard deviations
SDIGD	Stimulation, detection, and intervention in growth and development
SO_4^{2-}	Sulfate
TDS	Total dissolved solids
WHO	World Health Organization

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ORIGINAL RESEARCH PAPER

Wastewater uses for agricultural production from weak and strong sustainability perspectives

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ABSTRACT

BACKGROUND AND OBJECTIVES: Investigations into the utilization of wastewater as a substitute for agricultural purposes have become increasingly significant in nations experiencing or anticipated to experience water scarcity. Mexico stands out as one of the countries with the highest use of untreated wastewater in agricultural production. The Mezquital Valley, located in Hidalgo, Mexico, has been studied for this reason for more than 25 years, as it has received untreated wastewater for over 100 years. The advancement of social and economic conditions in this region is associated with the water that moves through the drainage system of Mexico City, which, considering the city's extent of industrialization, introduces escalating risks to its application. The objectives of this study were to analyze the Mezquital Valley from the perspectives of weak and strong sustainability to identify the limitations and opportunities for wastewater reuse in agriculture.

METHODS: A comprehensive bibliometric analysis was conducted using the Scopus database and VOSviewer software to visualize the results. Consequently, a thorough literature review was undertaken to pinpoint the key themes explored and to evaluate whether sustainability methods had been applied. This study is enhanced by statistical data pertaining to the region.

FINDINGS: The bibliometric review covering the years 1991 to 2024 indicates that research primarily concentrates on pollution related to water, soil, and health, with a notable emphasis on environmental sciences. In contrast, investigations into sustainable development are limited, comprising only 6 out of 79 studies. On the other hand, it is found that the average volume of wastewater over the last 25 years was 1,405,811 thousand m^3, distributed across irrigation districts 003 Tula, 100 Alfajayucan, and 112 Ajacuba to more than 56,000 users across 77,415 hectares, mainly for corn and alfalfa.

CONCLUSION: The region faces growing environmental and social degradation, serious risks to public health, and a population in which more than 70 percent lack social security, resulting in increased healthcare spending. Consequently, moving towards strong sustainability necessitates the establishment of solid regulatory frameworks, ongoing financial support, and inclusive strategies that engage indigenous and rural communities in decision-making processes, incorporating technical, social, and ecological aspects.

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INTRODUCTION

All economic activities require water, still, approximately 24 percent (%) of the world's land surface suffers from severe shortages, and 35% of the global population lives in areas affected by this issue (Borsato *et al.,* 2020). Overall, economic development is achieved at the expense of excessive use of water resources. For over five decades, it has been acknowledged that humanity faces risks stemming from the management of nature, especially water. To date, managing global water resources sustainably has proven to be a significant challenge. In the last century, water extraction rates have increased almost sixfold (De Castro *et al.,* 2023). The problem is mostly with irrigated agriculture, as irrigated areas represent only 18% of the world's cropland, a relatively small portion of the total cropland. Still, they use, on average, 70% of each country's water. While irrigated agriculture yields higher profits compared to rainfed agriculture, contributing around 40% to global food production (Borsato et al., 2020), sustaining this level of water usage is not feasible in the long run. Furthermore, the growing population and climate change exacerbate the agricultural challenges faced by countries with limited water resources, as they experience both water scarcity and thermal stress (Mainardis *et al.,* 2022). As demand for freshwater rises, conflicts among water users and even between countries become more evident, underscoring the need for alternative water sources for agriculture (Ricart *et al.,* 2019). Treated or reclaimed wastewater is progressively being recommended as an alternative across in various economic sectors, particularly agriculture (Penserini *et al.,* 2024; Mainardis *et al.,* 2022; Khan *et al.,* 2022; Rossi *et al.,* 2021; Chojnacka *et al.,* 2020; Ricart *et al.,* 2019). In addition, agrochemical-based agriculture imposes intense pressure on planetary boundaries, including biosphere integrity, earth system changes, freshwater use, and nitrogen fluxes (Gerten *et al.,* 2020). Fertigation (the use of nutrients from wastewater for agricultural irrigation) can assist in alleviating these pressures (Penserini *et al.,* 2024). However, 400 cubic kilometres (km^3)/year of sewage is generated worldwide, yet less than 20% is treated, and only 2% to 15% is reused for irrigation (Christou *et al.,* 2024). This would correspond to approximately 20 million hectares of land being irrigated using non-conventional water resources (Trotta *et al.,* 2024). In Mexico, irrigation with wastewater is practiced in various regions mainly through irrigation districts, as is the case in the states of Chihuahua, State of Mexico, Puebla, Morelos, Michoacán, Tamaulipas Aguascalientes and Durango, but it is the Mezquital Valley region in Hidalgo, the most extensive area and with the longest tradition in this practice (Cisneros and Saucedo, 2016; IWMI, 2017). On a national scale, it is estimated that approximately 350,000 hectares (ha) are irrigated using wastewater, predominantly in semi-arid regions; however, the extent of wastewater treatment and its application for irrigation can differ markedly across various areas, influenced by factors such as the accessibility of alternative water sources, local regulations, and the current state of treatment infrastructure (Gilabert *et al.,* 2018; Rosas and García, 2024). In the Mezquital Valley region, wastewater for irrigation is intrinsically linked to economic and social development. Since colonial times, farmers in the valley have used wastewater from Mexico City, locally known as "black waters", to irrigate approximately 563 square kilometres (km^2) of grain crops (Hernández *et al.,* 2021; García, 2019). The primary source of this wastewater is the drainage of the Metropolitan Area of the Valley of Mexico (MAVM), which discharges without conventional treatment. A significant recipient of this wastewater is the Tula River, which crosses the Mezquital Valley, ultimately directing its flow to the Irrigation District 003 Tula, located in the municipalities of Tula and Mixquiahuala (Siebe and Cifuentes, 1995). In this region, mainly alfalfa, corn, and bean crops are irrigated due to Mexican

regulations that restrict the use of untreated wastewater for the irrigation of crops consumed raw and with low stem (CIMMYT, 2012; Garcia, 2019). The emergence of wastewater in this area, historically occupied by the Otomí people, was originally perceived as an issue. Over time, however, it transformed the valley into one of the most productive agricultural areas of Hidalgo. It is now known as the breadbasket of Hidalgo, home to 79% of the state's total irrigated area. In the region, this water is known as the "black gold" that helped lift people out of the poverty they lived in (Inegi, 2022; García, 2019). The persistent supply of nutrient-rich water from the MAVM's sewage system facilitated farmers to achieve higher yields than in rain-fed agriculture, with a primary focus on cultivating alfalfa and corn. The volume of wastewater from the MAVM to the Mezquital Valley became so significant that it exceeded the flow of many of the country's major rivers, making the valley one of the largest wastewater agriculture systems in the world, after China (Bonhevi and Denizen, 2024; CIMMYT, 2012; Jiménez and Asano, 2008). The enhancement of agricultural output results in adverse effects on the environment and social dynamics. High levels of total coliforms in surface and groundwater where wastewater irrigation is practiced in the Mezquital Valley pose a continuous risk of gastrointestinal diseases (Downs *et al*., 2000). Since the 1990s, a notable rise in the occurrence of diarrheal diseases and parasitic infections has been recorded in adults, especially in children (Cifuentes *et al.,* 1991; 1994; 2000; Contreras *et al*., 2017; Domínguez-Narváez *et al.,* 2023). In addition, the soil is contaminated with lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), chromium (Cr), copper (Cu), and arsenic (As), as well as pathogenic microorganisms such as Escherichia coli. Emerging contaminants have also been detected in wastewater, such as antibiotics such as sulfonamides, ciprofloxacin, trimethoprim, and unmetabolized drugs that contribute to the emergence of drug-resistant bacteria (Cajuste *et al*., 1991; Durán-Álvarez *et al*., 2023; Ortíz-Olguín., 2023). By law, crops grown with wastewater in Mexico should be used only for animal feed; however, various crops such as beans, corn, squash, and some vegetables are marketed and consumed by humans (Contreras *et al.,* 2020). According to the available literature, the predominant grains in the regions utilizing wastewater for irrigation alfalfa, corn, and wheat, which tend to accumulate mainly Cd, Pb, Cu, and Zn (Salazar-Ledezma *et al*., 2018; Lara-Viveros *et al*., 2015). Furthermore, the topic of sustainability in the region has received scant attention, despite the existing social and environmental consequences. It has mainly been addressed within the Sustainable Development Goals. However, the weak and strong sustainability approaches have a theoretical basis that enables the generation of alternatives to this type of environmental problem and the analysis of the scope of strategies to mitigate or prevent environmental damage. That is why the aims of this study were to analyse the Mezquital Valley case using the weak and strong sustainability approaches to identify the limitations and opportunities of wastewater reuse in agriculture. The methodology applied is documentary, relying on the examination of recent statistical data and a comprehensive bibliometric review of specialized literature. This document presents a theoretical overview of weak and strong sustainability, including their association with wastewater in agriculture, to enhance the analysis. This study has been conducted using the database Scopus, covering the years 1991 to 2024. For statistical analysis, data were obtained from the Institute of Statistics and Geography, the Agrifood and Fisheries Information Service, the National Water Commission, and the National Council for the Evaluation of Social Development, covering 2020 and 2023. The study aims to address the question: Is it possible to achieve strong sustainability in a region that presents social and environmental impacts of the magnitude of those in the

Mezquital Valley? This study has been contacted in Mexico in 2025.

Weak and strong sustainability in agriculture with wastewater

The theoretical frameworks of environmental and ecological economics support the weak and strong sustainability approaches. Environmental economics is based on neoclassical economics, which advocates for the free market and the privatization of natural resources as mechanisms for conservation while adopting an anthropocentric perspective. Its link to the definition of sustainable development is direct, as it focuses on the satisfaction of present and future human needs. Therefore, the weak sustainability perspective accepts both trade-offs and collaborations in the Sustainable Development Goals (De Castro *et al.,* 2023; Borsato *et al.,* 2020). Conversely, ecological economics asserts that economic goals are often at odds with environmental aims. This is exemplified by the fact that the economic growth target of the Sustainable Development Goals hinders the attainment of other objectives, as its robust sustainability framework only permits synergies among goals that align with the notion of planetary boundaries (Hirai, 2022). The concept of weak or strong sustainability concerning irrigation can be examined through the lens that water is a renewable resource if specific conditions are satisfied. Consequently, from the standpoint of Borsato *et al*. (2020), its application could be interpreted as strong sustainability, but this would only be valid if the following conditions adhered to: the preservation of water reserves such as aquifers, lakes and rivers is guaranteed, which meaning that their utilization should facilitate natural replenishment; the exploitation of water sources does not generate losses of aquatic habitat or biodiversity and irrigation should not inflict other forms of environmental damage such as soil loss and contamination. In addition to the environmental aspect, economic viability is also considered within the perspective of strong sustainability, meaning that the cost of irrigation should be lower than the value of the marginal productivity compared to rainfed production. Furthermore, when considering Sustainable Development Goal 6.4, it is essential that water-use indicators take into account the variability in water availability. They should also be spatially explicit to account for the spatial variability in water scarcity driven by climatic, topographic, and land-use conditions (Vanham *et al.,* 2018). Moreover, natural water resources must be differentiated from surface water, groundwater, and non-conventional water such as reclaimed or wastewater. In contemporary times, it is essential to recognize alternative or non-conventional sources of high-quality water for agricultural production, including reclaimed water, which refers to treated municipal wastewater that complies with state-specific water quality standards and is intended for reuse (Gerdes *et al.,* 2020). The reuse of treated wastewater for agricultural purposes is classified into two categories: direct and indirect reuse. The former occurs when irrigation water is supplied directly from the wastewater treatment plant (WWTP). The latter situation arises when wastewater is directed downstream and has the potential to become contaminated with sewage. However, in the case of indirect wastewater reuse, controlling irrigation water quality is challenging because it depends on several factors, including the quality of the treated wastewater effluent and the hydrological conditions of the stream into which the effluent is discharged (Jeong *et al.,* 2016). One of the main risks associated with water flows from wastewater treatment plants (WWTPs) and onsite wastewater treatment facilities is the release of micropollutants into receiving water bodies. In any case, the construction of WWTPs is costly and falls under the logic of weak sustainability, given the high costs of energy and construction materials (Gago *et al.,* 2017). Additionally, various treatment techniques are under development to

deliver water of suitable quality for designated reuse purposes, complementing the role of WWTPs. Selective approaches have been proposed, with the "fit-for-purpose" concept gaining significant attention because it can reduce energy use and the complexity of WWTPs, thereby avoiding unnecessary treatment steps (Cecconet *et al.,* 2017). However, treated effluents may still contain antibiotics, antibiotic-resistant bacteria and genes, as well as several emerging contaminants that conventional treatments have not removed, including pharmaceuticals and toxic organic compounds (Mainardis *et al.,* 2022). Domestic wastewater is made up of three key elements: black water from toilets, which is often mixed with yellow water (urine), and gray water from showers, dishwashers, and washing machines. Non-segregated wastewater typically exhibits variable quality parameters that depend on local conditions and the level of industrialization in the locality or city. In contrast, drip fertigation is appropriate for customizing the supply of water and nitrogen to align with crop requirements, thus enhancing product yield, water use efficiency, and nitrogen use efficiency, while decreasing evapotranspiration compared to flood irrigation (Li *et al.,* 2021). Drip irrigation offers many advantages, but it also has a few disadvantages, the latter of which are related to specific crop characteristics or clogging problems. Clogging is predominantly limited to the inlet and vortex areas, and it can be substantially alleviated through appropriate hydrodynamic design and management (Lequette *et al.,* 2020). Subsurface drip fertigation is particularly efficient at reducing water use in rice (48-53%) and wheat (42-53%) cultivation in South Asia, yielding results comparable to those of flood irrigation while requiring lower nitrogen fertiliser demand (-20%) (Mainardis *et al.,* 2022). Anaerobic biological processes constitute another treatment mechanism, offering a sustainable alternative to energy-intensive aerobic processes (Capodaglio and Olsson, 2019). Drip irrigation with wastewater aligns with the principles of Strong Sustainability because it uses less water without compromising crop yields. However, the treatment applied to the water must be low in energy consumption. From the standpoint of weak sustainability, the application of treated or untreated wastewater in agricultural practices, based on traditional economic views, serves as an efficient strategy to maximize limited water resources. This method enables a partial substitution of natural capital (clean water) for manufactured capital (treatment infrastructure) or even direct utilization of untreated wastewater when circumstances are favorable (Jiménez and Asano, 2008). Therefore, this practice is sustainable because it maintains or increases the total capital stock while generating economic and social benefits: I) it reduces pressure on freshwater sources, II) it guarantees supply for productive activities in areas of scarcity, and III) it provides nutrients that partially substitute fertilizers, reducing costs (Drechsel *et al.,* 2010). In this framework, a limited decline in water quality is deemed acceptable if it is balanced by growth in economic or human capital, for instance, through elevated agricultural earnings or betterment in infrastructure and productive capacities. However, this reasoning has critical limitations when wastewater is used without adequate treatment, as is often the case in large agricultural regions of Mexico, India, or North African countries, because the negative impacts on human health, soil degradation, and aquifer contamination often outweigh the short-term economic benefits (Qadir *et al.,* 2010). Furthermore, the logic of weak sustainability implies that future investments in health, infrastructure, or decontamination technologies may counterbalance these effects; however, various studies demonstrate that reversing such damages is frequently problematic, especially in rural communities that are vulnerable and have low institutional capacity along with restricted public investment (Jiménez, 2006; Drechsel *et al.,* 2015). From the Strong Sustainability perspective,

the use of wastewater without adequate treatment is a classic case of false substitution, i.e., degraded natural capital (soil, public health, groundwater quality) cannot be entirely replaced by economic or manufactured capital because ecosystem services and the health of rural populations are essential and irreplaceable components of wellbeing (Martinez-Alier, 2021; Daly, 1996). Conversely, the intended and controlled application of treated wastewater could be in harmony with the tenets of weak sustainability, contingent upon investments in infrastructure and capacity that preserve total capital stock and prevent irreversible degradation of natural capital. However, this requires robust regulatory frameworks, sufficient financing, and monitoring systems that are often absent in contexts where reuse of untreated wastewater is most common (Jiménez and Asano, 2008). Thus, the case of the agricultural use of wastewater highlights both the possibilities and limitations of weak sustainability: while it helps identify pragmatic solutions to water scarcity, it risks legitimizing practices that, far from being sustainable, compromise ecological resilience and social equity over the long term, contrary to what Strong Sustainability postulates.

MATERIALS AND METHODS

The study begins with a bibliometric analysis and then proceeds to a statistical and documentary review of the Mezquital Valley region, located in Hidalgo, Mexico (Fig. 1). This region practices both rainfed and irrigated agriculture; the latter is distinguished by the heavy reliance on wastewater, which is applied with little to no treatment and forms the productive core of the region in a context of water scarcity. Wastewater comes mainly from the irrigation districts (003 Tula, 100 Alfajayuca, and 112 Ajacuba). This agricultural system operates mainly through gravity irrigation via an extensive network of open canals, which allows for continuous cultivation and intensive production, especially of alfalfa and forage corn. The reason for employing these two methods is that the literature review obtained from the bibliometric analysis provides information concerning the environmental consequences of using agricultural wastewater, but it fails to provide direct data on agricultural production in the region. Bibliometric analysis provides an overview of the literature on the topic, helping identify knowledge gaps and position contributions that broaden research on the phenomenon under study (Donthu *et al.,* 2021). Here, bibliometric analysis is used to examine the literature on agriculture with wastewater in the Mezquital Valley; however, because only one document was found containing the terms “agriculture and wastewater and mezquital and valley,” the literature on the terms “wastewater and mezquital and valley” was reviewed in the Scopus database, using 1991 to 2024. It should be noted that the term “sustainability,” as used in the revised terms, did not yield any data, so it was decided to use only the words mentioned. The VOSviewer software, which visualizes scientific landscapes, was utilized to generate maps depicting word co-occurrence, enabling the examination of the conceptual structure within a research field, as well as co-authorship, and co-citation (Aria and Cucurullo, 2017). After the data were extracted, the records were carefully reviewed to select papers on agriculture and wastewater use in this region and to remove duplicates and irrelevant entries before importing them into VOSviewer. This software was utilized develop and assess network maps that recognized the most impactful publications, authors, and emerging research topics in the field (Judijanto *et al.,* 2025). Quantitative bibliometric metrics, including publication counts and citation frequencies, were calculated to elucidate research development and discipline. Table 1 identifies the thematic axes of the theoretical references on weak and strong sustainability for the analysis of the literature.

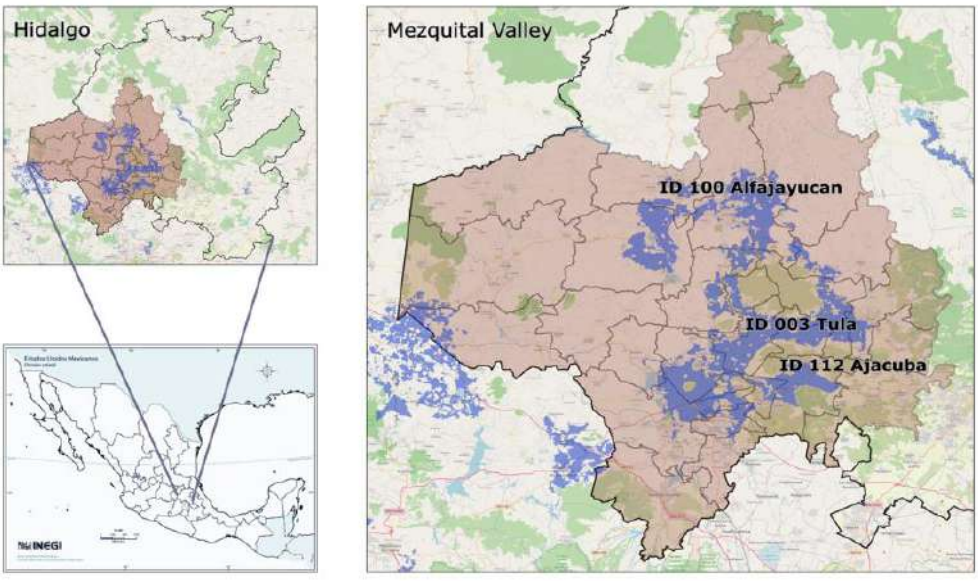

Fig. 1: Geographic location of the study area in Mezquital Valley, Hidalgo, Mexico

Table 1: Irrigation from sustainability perspectives

Weak sustainability	Strong sustainability
Wastewater Treatment Plant: Direct and Indirect Reuse	Conservation of water reserves such as aquifers, lakes, and rivers
Partial degradation of water quality is acceptable if offset by increases in capital	No loss of aquatic habitat or biodiversity
The impacts of wastewater use, or pollution are offset by future investments	No soil loss or pollution
Requires infrastructure and decontamination technologies	Economic viability
Energy-intensive	Regenerated water
Allows for biodiversity loss	Drip fertigation

Strong sustainability to prevent damage and weak sustainability to regulate impacts require robust regulatory frameworks, sufficient financing, and monitoring systems.

The statistical review discussed in the preceding section relied on the following databases to present a summary of wastewater application in agriculture in the designated study region: (a) Agricultural Census-2022 of the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía, Inegi); (b) Agrifood and Fisheries Information Service (Servicio de Información Agroalimentaria y Pesquera, SIAP) of the Ministry of Agriculture and Rural Development, with data from 2023; (c) Agricultural Statistics of the Irrigation Districts of the National Water Commission (Comisión Nacional del Agua, Conagua) and the Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales, Semarnat), with data from the 2022-2023 agricultural year; and (d) Poverty measurement at the municipal level in 2020, from the National Council for the Evaluation of Social Development Policy (Consejo Nacional de Evaluación de la Política de Desarrollo Social, Coneval).

RESULTS AND DISCUSSION

Irrigated agriculture in the Mezquital Valley, Hidalgo, from the perspective of sustainability

The Mezquital Valley region, which includes 28 of the 84 municipalities that make up the state of Hidalgo, is semi-arid, with low rainfall and xerophytic vegetation that limits agriculture; however, agriculture and livestock are its main economic activities. Its altitude ranges from 1,500

to 2,200 meters (m) above sea level, with average annual temperatures between 16 and 20 degrees Celsius (°C) and yearly rainfall of up to 500 millimeters (mm), concentrated during the rainy season from June to September (Moreno *et al.,* 2006). With a population of 1,019,865 in 2020, 43% live in poverty (90% moderate and 10% extreme), and 17% are indigenous (Coneval, 2022). It is inhabited in primarily by *ñähñú* (Otomí) indigenous communities, concentrated in the municipalities of Ixmiquilpan, Cardonal, Santiago de Anaya and San Salvador. These communities maintain their cultural traditions and organizational structures, despite confronting systemic issues of poverty, marginalization, and inequality. Nevertheless, they exhibit a notable ability to adapt and demonstrate resilience when faced with environmental and economic challenges (Granados *et al.,* 2004; García, 2019).

Bibliometric analysis of the literature on wastewater and the Mezquital Valley and weak and strong sustainability

The review was conducted using the Scopus database and the search query "Mezquital Valley" and "wastewater," which yielded 79 documents, including 70 articles, four book chapters, four conference papers, and a review. Environmental sciences are the disciplines with the greatest quantity of documents (50), agriculture and biological sciences (22), medicine (14), engineering (eight), and earth sciences (seven). The investigation covers the period from 1991, the year the initial published article was discovered, to 2024. First, the mapping identifies an analysis of citations in which Siebe with various co-authors (Siebe and Cifuentes, 1995; Friedel *et al*., 2000; Vázquez-Alarcón *et al*., 2001; Ortega-Larrocea *et al*., 2001; Ortega-Larrocea *et al*., 2007; Siemens *et al*., 2008; Dalkmann *et al*., 2012; Müller *et al*., 2012; Dalkmann *et al*., 2014a; Dalkmann *et al*., 2014b; Broszat *et al*., 2014; Guédron *et al*., 2014; Jechalke *et al*., 2015; Zamora-Martínez *et al*., 2016; González-Méndez *et al*., 2017; Contreras *et al*., 2017; Lüneberg *et al*., 2018; Salazar-Ledesma *et al*., 2018; Lüneberg *et al*., 2019; González-Méndez *et al*., 2020; Contreras *et al*., 2020; Heyde *et al*., 2021; Aguilar-Santos *et al*., 2024; Espiral *et al*., 2024) has 25 documents with 952 citations. This constitutes the most substantial number of citations pertaining to the theme of wastewater and agriculture in the Mezquital Valley; Broszat follows this with 269 citations and four documents (Broszat *et al*., 2014; Dalkmann *et al*., 2012; Jechalke *et al*., 2015; Broszat and Grohmann, 2017), then Jan Siemens with six documents (Siemens, *et al*., 2008; Dalkmann *et al*., 2012; Dalkmann *et al*., 2014a; Dalkmann *et al*., 2014b; Heyde *et al*., 2021; Carrillo *et al*., 2016b) and 254 citations, and Amelung with four papers (Dalkmann *et al.,* 2012; Dalkmann *et al.,* 2014a; Dalkmann *et al.,* 2014b; Carrillo *et al*., 2016a) and 230 citations as well as Philipp Dalkmann (Dalkmann *et al.,* 2012; Dalkmann *et al.,* 2014a; Dalkmann *et al.,* 2014b; Carrillo *et al*., 2016b) with four documents and 230 citations. The issues addressed in Table 2 highlight the environmental and health risks associated with the use of untreated wastewater for agriculture in the Mezquital Valley. Since Christina Siebe is based in Mexico, 1848 citations are in this country, 671 in Germany, 204 in the United States, and 156 in the United Kingdom, indicating that this has been a relatively relevant topic for researchers based in Mexico. Regarding the institutions where the researchers who have carried out work on the use of wastewater and agriculture in the Mezquital Valley are located, find that they are mainly in the Geolo gy Institutes of the National Autonomous University of Mexico (Universidad Nacional Autónoma de México, UNAM), as is the case of Christina Siebe, in Fig. 2 she is located in a green node with a size that stands out about other centers. In the case of Melanie Broszat, she is located at the University Medical Centre Freiburg, Division of Infectious Diseases, Freiburg, Germany, and in the case of Jan Siemens, she works at the Department of Soil Science, Berlin University of Technology. It should be noted that this author has worked with Christina Siebe.

Table 2: Topics Addressed in the Mezquital Valley by the most cited authors

Authors	Main research topics	Environmental relevance
Siebe and Cifuentes, 1995	Impact of untreated wastewater irrigation on soils and agriculture; accumulation of toxic contaminants; soil microbiology.	Evaluation of long-term soil quality changes and environmental risks derived from wastewater irrigation practices.
Broszat *et al.*, 2014	Effects of wastewater on soil bacterial communities; presence of potentially pathogenic bacteria; dissemination of antibiotic resistance genes and mobile genetic elements.	Assessment of microbial health risks and spread of antibiotic resistance in agricultural systems.
Siemens *et al.*, 2008	Behavior of pharmaceutical and emerging contaminants in irrigated soils; accumulation of microorganisms and resistance genes.	Analysis of mobility, persistence, and ecological risks of emerging contaminants in agroecosystems.
Carrillo *et al.*, 2016a	Accumulation and persistence of emerging contaminants (pharmaceuticals and resistance genes); interaction between soil organic matter, microflora, and persistent pollutants.	Understanding how soil properties regulate contaminant retention and long-term environmental impact.
Dalkmann *et al.*, 2012	Accumulation and transport of antibiotics and pharmaceuticals in wastewater-irrigated soils; dissipation and retention processes.	Investigation of contaminant fate, transport mechanisms, and implications for soil and environmental sustainability.

Note: Co-citation mapping in VOSviewer measures how often two authors are cited together, not their total citation counts. Therefore, an author ranked fifth may still be highly influential if frequently co-cited with leading scholars in the field.

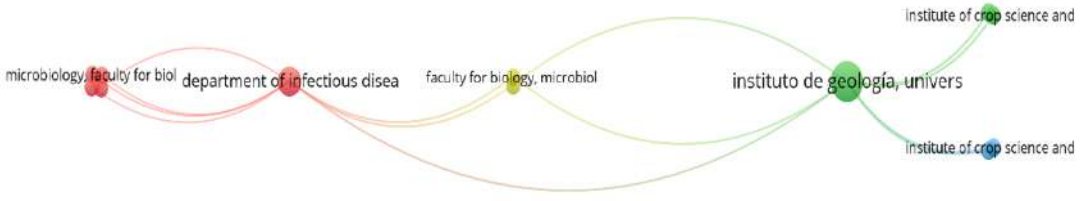

Fig. 2: Institutes where the researchers on the subject are located

Finally, co-occurrence analysis is a technique that examines the actual content of the publications, derived from the keywords provided by the authors. Moreover, it remains possible to depict words that are highlighted in titles, abstracts, and entire texts for analytical purposes. Regarding Fig. 3, the key words can be recognized as "Mexico," stemming from the fact that the Mezquital Valley is situated in this country, as well as, "wastewater", and "Mezquital Valley". This image shows four clusters: the olive-green cluster links wastewater with the Mezquital Valley and irrigation, contaminated soil, concentration, and composition, and grains such as alfalfa and corn. The green cluster links groundwater issues, water quality, drinking water, water supply, and groundwater contamination. In the red cluster, find wastewater management, agriculture, environment, controlled studies, untreated wastewater, and wastewater reuse, among others. Finally, in the blue cluster, topics such as soil contamination, untreated wastewater, soil moisture, and wastewater effluent can be found. The clusters indicate a lack of research on social issues in the region. The red cluster associated with the term "children" is the most similar to these, having been pertinent in research concerning gastrointestinal diseases, although it originates from the 1990s. Additionally, the term "sustainability" is not present. To enhance comprehension of the data presented by the co-occurrence analysis, Table 3 outlines seven themes central to the research, all of which are associated with wastewater and agriculture in the Mezquital Valley. The seven topics identified are: Wastewater and its impact on groundwater;

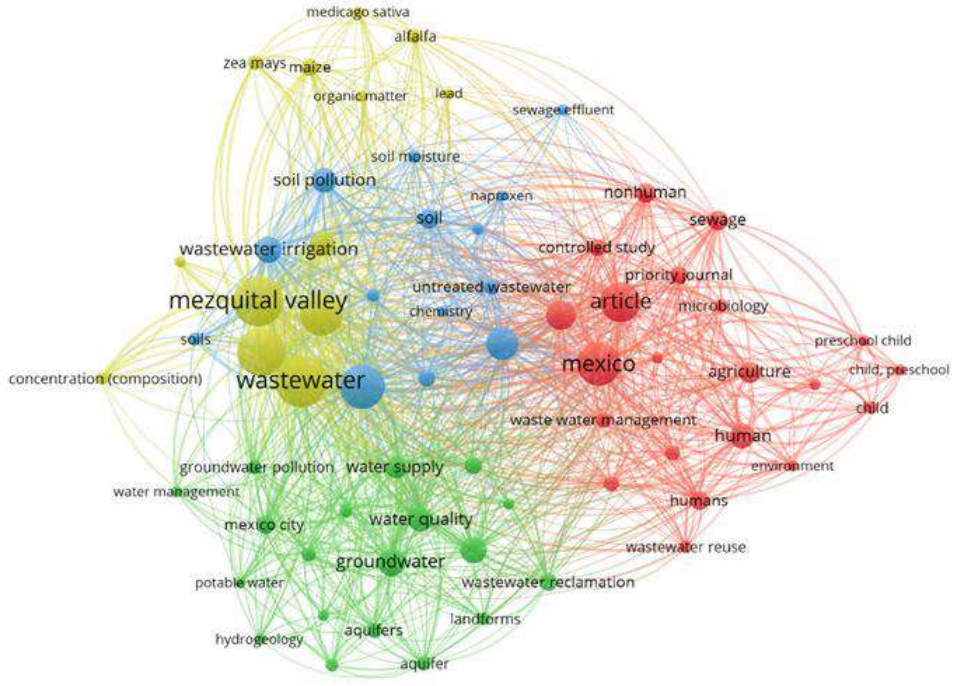

Fig. 3: Analysis of co-occurrences in the literature on wastewater and the Mezquital Valley. Source: Own elaboration based on Scopus data and Vosviewer software

Table 3: Identification of issues related to wastewater in agriculture in the Mezquital Valley

General subject matter	Topic related to agriculture	Number of documents
Wastewater and its impact on groundwater	Evaluation of the existence and severity of bacterial and pathogenic infiltration in the local aquifer. Occurrence of fecal coliforms, fecal enterococci, and Escherichia coli, Calculation of volumes. Groundwater quality. Wastewater volumes are exported to the Mezquital Valley.	15
Wastewater for crop irrigation and its pollutants	Analysis of the existence of trihalomethanes (THM). Sodium, ammonium, potassium, calcium, and magnesium content. Pharmaceutically active compounds (FAAC). Existence of micropollutants. Mercury, arsenic, and lead. Presence of SARS-CoV-2 in wastewater. Physicochemical characterization of water.	23
Contamination of agricultural products by wastewater use	Bioaccumulation of heavy metals in cucumber. Analysis for corn, sunflower, and alfalfa.	5
Impacts on soil due to wastewater use	Agricultural soil conditions resulting from wastewater use. Soil redox potential analysis. Salinity and sodicity. Temporary accumulation of quaternary alkylammonium (QAAC) in soils. Change of land use. Measurement of zinc, lead, copper, and cadmium.	15
Health and wastewater	Characterization of the spatial dynamics of wastewater. Health risks. Diarrheal diseases.	9
Wastewater and climate change	Nitrous oxide (N_2O) emissions and wastewater in agriculture. GHG emissions	4
Agriculture, wastewater, and sustainable development	Reduction of heavy metal concentration in different plant structures. Producers, wastewater use, and sustainable development. Safe use of wastewater.	6

Wastewater for crop irrigation and its pollutants; Contamination of agricultural products by wastewater use; Impacts on the soil by wastewater use; Health and wastewater; Wastewater and climate change; and Agriculture, wastewater, and sustainable development. Only six articles were found on this topic out of the 79 documents reviewed; however, the term does not appear in the title of the publications. It is worth noting that two papers were discarded because they did not fit any of the identified general topics. The exclusion criterion was that the study site was not in the Mezquital Valley. The topic that has generated the most significant concern among researchers has been the physicochemical study of wastewater pollutants, which encompasses 23 research articles. This is followed by apprehension regarding groundwater pollution, as the irrigation method in this region is flooding. Lastly, there is the evaluation of different soil pollutants resulting from wastewater usage, including the presence of heavy metals and conditions of salinity and sodicity. A less relevant topic, yet one that has raised concerns, is the connection between wastewater and health, with nine studies investigating diseases associated with exposure to this type of water. The analysis of existing literature regarding the application of wastewater in agriculture and its diverse effects indicates the necessity to evaluate both the strong and weak sustainability of irrigation methods in the area. Despite six documents discussing sustainable development, these two perspectives remain unutilized. In general, the research focuses on the relevance of using treated wastewater, the resistance of producers to changing their irrigation systems and water use, and a proposal to reduce heavy metal concentrations through spatial reorganisation. Regarding producers' resistance to the use of treated water, Rosas and García (2023) mention that agricultural producers perceive that there are negative effects on the soil due to the use of wastewater, but on the one hand, agriculture is an activity they inherited from their parents, as is the method of irrigation, so they consider it normal to irrigate with sewage water. Conversely, the matter of the activity's profitability arises, as the extensive application of agrochemicals results in soil productivity being one of the highest in the country. The literature also provides information on the creation of the Atotonilco WWTP (Table 4). To analyze the only sustainability strategy implemented, the proposed theoretical lines of analysis are revisited. In the case of strong sustainability, the results show that wastewater use has a naturally positive effect on aquifer recharge, although the extent of this effect is unknown. Regarding the need for regulation in both cases, Mexico has the following standards: “NOM-CCA/032-ECOL/1993, which establishes the maximum permissible limits of contaminants in urban or municipal wastewater for disposal through agricultural irrigation” (DOF, 1993a: 1); NOM-CCA-033-ECOL/1993 “which establishes the bacteriological conditions for the use of urban or municipal wastewater or a mixture of this with water bodies in the irrigation of vegetables and horticultural products” (DOF, 1993b: 1) and NOM-001-ECOL-1996 “which establishes the maximum permissible limits of contaminants in wastewater discharges into national waters and property” (DOF, 1997: 1). However, there is no compliance due to lack of monitoring and lack of infrastructure. Among the strategies that have gained interest in recent years for economical wastewater treatment is constructed wetlands, which are categorized as conventional and intensified. For the Mezquital Valley, an enhanced system is essential owing to the significant contaminants found in the water. Aeration increases the rate of contaminant removal, and plants capable of absorbing contaminants are integrated into its operation. However, further research is still needed to remove specific compounds, such as nitrogen, and emerging pollutants (Zurita and Sandoval, 2024). Drip irrigation is a type of irrigation that fits within the logic of strong sustainability. Each plant is addressed separately, employing minimal but regular and precise volumes of water via emitters,

Table 4: Application of sustainability perspectives

Weak sustainability	Strong sustainability
▪ The geographical location of Atotonilco WWTP implies indirect water reuse. According to Espira *et al.* (2024), there is evidence of recontamination of wastewater treated by local communities downstream of the plant. ▪ Atotonilco WWTP, due to its location, allows for partial degradation of water quality. However, there is no compensation or remediation of any kind. ▪ The construction of the Atotonilco WWTP required infrastructure and decontamination technologies and is energy intensive.	▪ Conservation of water reserves such as, lakes, and rivers. ▪ The use of untreated wastewater has led to artificial recharge of the aquifer. As a result, the water table has risen, and in recent decades, several springs with flows of 100-600 liters per second have appeared (Jiménez and Chavez, 2004). However, cases such as the Mezquital Valley show additional aquifer recharge, but the results are uncertain, as this could affect the balance of groundwater systems. But it may also induce lasting hydrochemical changes in aquifers and ecosystems, the effects of which are unknown (Hernandez-Espriú *et al.,* 2016). ▪ Drip irrigation would be required, unlike the practices currently used by agricultural producers of surface water (Burgos and González, 2014).

referred to as drippers (Table 4) (Burgos and González., 2014). However, this cannot be applied efficiently in the Mezquital Valley because its main difficulty is that the water contains suspended particles (Rosas and García, 2023).

Contexto actual de la producción agrícola del Valle del Mezquital

Consequently, the subsequent analysis pertains to irrigated agriculture in the Mezquital Valley, derived from a review of multiple information sources that offer a comprehensive overview of the present circumstances. Fragile soil and limited natural water availability in the region have led to intensive use of wastewater from the MCMA for agricultural activities, enabling irrigated agriculture in a naturally dry region. Nonetheless, considerable environmental effects have been recognized, such as soil and groundwater pollution and risks to public health, as indicated in the bibliometric analysis (Rosas and García, 2024; Lara and García, 2019). However, evidence has also been presented that, due to the soil conditions in the irrigated area, this acts as a slow filtration system. The main reservoir and canals serve as waste stabilisers. Downs (2000) found that levels of basic/neutral/acidic semi-volatile organic compounds in surface water after reservoir retention were much lower than before, while levels in groundwater were significantly lower than in surface water. All nitrate levels in groundwater exceeded drinking water standards and were higher than those in surface water. Concentrations of metals in groundwater were found to be beneath the acceptable standards for drinking water; conversely, in surface water, they were above these standards for a limited number of metals. Pesticides were detected at low to moderate levels. However, it should be noted that a more up-to-date study would be needed to review these results 25 years after that study. It should be noted that water in this region is distributed mainly through the irrigation districts 003 Tula, 100 Alfajayucan, and 112 Ajacuba (Fig. 1). It is through modules that water is administered and distributed (an average of 1,405,811.25 thousand cubic meters (m^3) over 25 years) to agricultural users (56,284 on average) on an average planted area of 77,415 ha (Fig. 4). The main crops grown in the irrigation districts are alfalfa (445,170 tons) and grain corn (3,739,027 tons) being 003 Tula is the one that concentrates 64% and 69% of the production of both crops in the region, in addition to the fact that this district is the one that primarily uses untreated wastewater in the region (Table 5). The utilization of these substantial volumes of wastewater accounts for the significant apprehension surrounding the issues highlighted in the 23 articles concerning pollutants. Hernandez *et al.* (2025) mention that the farmers in the region possess a significant availability of this type of water. Its treatment is perceived as a threat, hence their opposition to the Atotonilco WWTP. Treated water is more expensive than wastewater. In addition to alfalfa and grain corn, forage oats, zucchini, green chilli, and green tomatoes are also grown (Table 6).

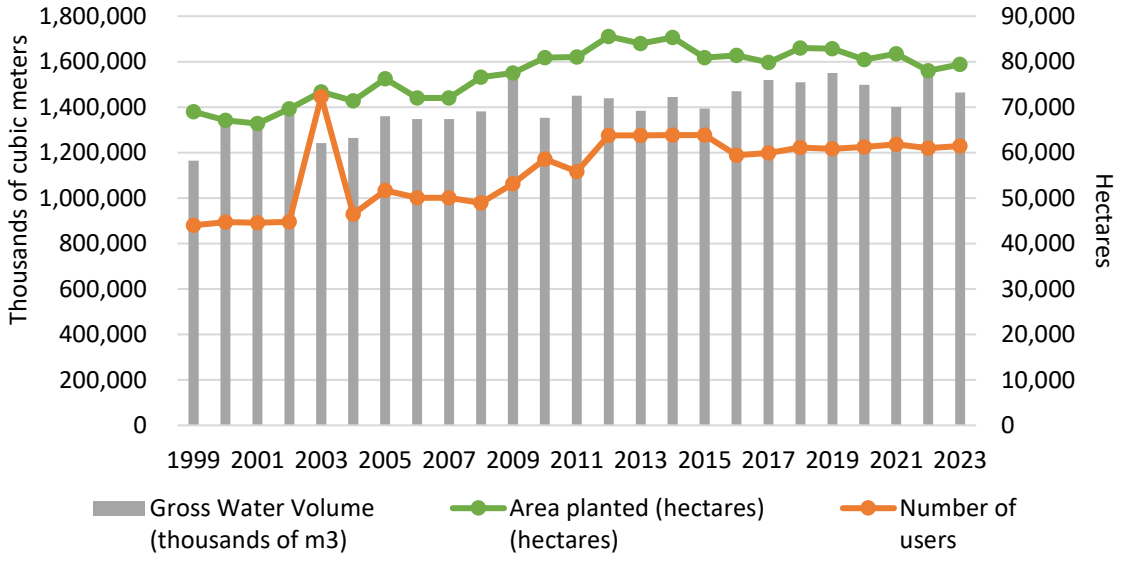

Fig. 4: Irrigation Districts in the Mezquital Valley, agricultural year 2022–2023. Note: Irrigation districts 003 Tula, 100 Alfajayucan, and 112 are included (Semarnat and Conagua, 2023)

Table 5: Characteristics of the irrigation districts of the Mezquital Valley, agricultural year 2022-2023

Irrigation District	Area planted (ha)	Number of users		Gross Water (thousands of m^3)
		Ejidal	Small property	
003 Tula	44,414	21,472	15,794	916,388
100 Alfajayucan	29,473	9,472	11,630	492,718
112 Ajacuba	5,498	2,588	516	54,622
Total	79,385	33,533	27,940	1,463,728

The municipalities of Ixmiquilpan, Mixquiahuala de Juárez, Tezontepec de Aldama, Alfajayucan, and San Salvador account for 43% of agricultural production in the Mezquital Valley and make the most use of wastewater; however, between 48 and 55% of their populations are poor. Wastewater irrigation does not benefit all producers equally due to inequalities in access, distribution, and geographic location, which create differences in water quantity and quality. These limitations, combined with restricted investment capabilities, hinder productive growth. As a result, economic benefits are inconsistent, and rural poverty along with social vulnerability continues to persist and exist (García, 2019; Rosas and García, 2023). Although the Mezquital Valley region accounts for 84% of the total value of agricultural production in Hidalgo derived from wastewater use, the impact on the health of the population and the environment is also increasing. Tula is recognized as an area facing an environmental crisis and is among the most polluted locations globally, primarily due to the agricultural and industrial operations that define this region. Notably, 28% of its population lacks access to health services, 73% lack access to social security, and 27% lack access to food (Coneval, 2022). One solution to counteract the social and environmental impacts is the Atotonilco WWTP, located in the Valley region and considered one of the largest sanitation infrastructures in the world today. With a capacity to treat up to 35,000 litres per second, it processes approximately 60% of the total wastewater generated in MAVM before discharging into the Mezquital Valley (García, 2018). This facility spans approximately 160 ha

Table 6: Main irrigated crops in the Mezquital Valley, 2023

Cultivation	Area planted (ha)	Production (t)	Performance (t/ha)
Alfalfa	42,575.50	4,375,416.90	102.8
Grain corn	41,112.95	398,073.22	9.9
Bean	3,909.39	7,065.87	1.8
Green fodder oats	2,264.42	90,678.29	40.0
Zucchini	1,617.77	29,663.30	18.6
Green chili	1,220.00	14,482.41	11.9
Green tomato	1,027.51	14,790.69	14.4
Other Crops	2,864.67	82,647.74	28.9
Total	96,592.21		

Note: *Includes: avocado (1%), garlic (3%), broccoli (1%), barley grain (2%), onion (4%), cauliflower (20%), peach (3%), asparagus (0.1%), guava (2%), lettuce (5%), feed corn (12%), apple (1%), *nopalitos* (1%), walnut (6%), cucumber (3%), red tomato (25%) and wheat grain (11%). Source. Based on SIAP (2023) data.

and was established to alleviate the adverse effects of previous sewage application in agricultural practices within the region. The treatment process at the Atotonilco WWTP includes physical pretreatment, biological treatment using activated sludge, filtration, disinfection, and additional physicochemical treatment during the rainy season. The sludge generated is stabilized via anaerobic digestion, enabling the generation of biogas that contributes partially to the plant's energy needs (Semarnat and Conagua, 2012). The plant aims to deliver treated water with valuable nutrients for crops (such as nitrogen and phosphorus) to farmers, free of organic and microbiological contaminants, thereby benefiting more than 700,000 people in this area (García, 2018). Its implementation responded to the socio-environmental problems that have characterised the Mezquital Valley for over 100 years. Nonetheless, contemporary studies examining the ecological consequences of wastewater application reveal that wastewater remains in use (Landero *et al.,* 2024; Espira *et al.,* 2024; García *et al.,* 2024). In the context of the Mezquital Valley, the utilization of wastewater for irrigation cannot be classified under the framework of strong sustainability. This is primarily since the introduction of wastewater into this region has led to the contamination of the Tula River and the Endhó dam, which predominantly receives rainwater from Mexico City. According to Borsato *et al*. (2020), the principles of strong sustainability necessitate the preservation of water reserves, including aquifers, lakes, and rivers. This requirement is not being met, as evidenced by the designation of the area as one of environmental emergency, and efforts to restore it have been ongoing since 2020. The type of remediation that has been carried out falls predominantly under the logic of weak sustainability, supported by environmental economics and by authors such as Pearce and Turner (1990) and Jiménez and Asano (2008), which justifies the continued use of untreated wastewater as a strategy of economic efficiency in the face of water scarcity, this is supported by the growth of agricultural production in the Mezquital Valley, which is representative of the state of Hidalgo. This, along with the understanding that within the discussions of the agricultural industry, these waters, referred to as "black gold", have enabled the local population to rise above poverty, nonetheless, this advantage has primarily favored those with closer access, leaving those further away at a disadvantage, as exemplified by the municipality of Nicolás Flores, where a significant portion of the population lives in poverty (68%). Its irrigated agriculture is one of the smallest (153 ha). The government's response, through the construction of the Atotonilco WWTP, falls within the weak sustainability perspective, characterized by high levels of infrastructure investment and intense energy use. Conversely, due to its upstream location, the water that

agricultural producers receive is indirect, leading to downstream contamination, as noted by Espiral *et al.* (2024). Additionally, it can be said that what producers perceive as real, the treatment removes nutrients from the water, reducing its productivity and imposing a cost on them, as mentioned by García and Fuente (2021). This view is consistent with Drechsel *et al.* (2010) and Borsato *et al.* (2020), who argue that wastewater reuse can be sustainable if a functional balance is maintained between economic efficiency and environmental management. From a robust sustainability viewpoint, the conditions that need to be ensured include: the preservation of water reserves like aquifers, lakes, and rivers, which is currently occurring, albeit with uncertainties regarding the effects of artificial recharge using wastewater; whether the utilization of water for irrigation results in the degradation of aquatic habitats or biodiversity, and whether irrigation contributes to other forms of environmental harm such as soil erosion and pollution (Borsato *et al.*, 2020). From this point of view, soil contamination, the infiltration of pollutants into aquifers, and impacts on human health in the Mezquital Valley cannot be considered "acceptable externalities" but rather evidence of a false substitution that compromises ecological resilience and the population's well-being. The application of untreated wastewater is at odds with the principles of the strong approach, as it breaches ecological limits and fundamental rights, such as the right to access clean water and a healthy environment. The contrast between the two approaches is reinforced by the findings of the bibliometric analysis, which show that most studies focus on the environmental and health risks of wastewater use without incorporating a normative assessment of the model's sustainability. Authors such as Mainardis *et al.* (2022) and Cecconet *et al.* (2017) have shown that, even with advanced technologies, untreated emerging pollutants persist, prompting us to reconsider whether current technical solutions are sufficient or whether structural changes are required in the productive logic and the management of water resources. Ultimately, the practice of wastewater irrigation frequently enhances short-term economic results by boosting crop yields, guaranteeing consistent water supply throughout the year, and lowering fertilizer expenses owing to its rich nutrient composition. In a scenario characterized by weak sustainability, these benefits lead to increased earnings and improved production stability for certain farmers as a result of water accessibility. However, from a strong sustainability perspective, the gains are uneven and often offset by long-term risk soil degradation, health costs, environmental pollution, and persistent social inequalities—that limit household resilience. In contrast to traditional or treated water sources, wastewater may enhance immediate productivity; however, it can jeopardize long-term socioeconomic and ecological sustainability.

CONCLUSION

The bibliometric analysis shows the type of research carried out on a topic that is currently of great importance for maintaining and even increasing agricultural production in regions experiencing water stress. The Mezquital Valley serves as a prominent illustration of how rural communities have embraced wastewater in their primary economic endeavor, which is agriculture. Wastewater has been part of the life of these communities for over a hundred years; however, it has been accompanied by environmental impacts that, to date, have been documented in research focused on analyzing soils, grains, surface water, and groundwater. These studies reveal considerable health and environmental dangers associated with irrigation techniques and the pollution of wastewater from a heavily populated and industrialized zone. Nevertheless, the bibliometric review also highlights the need for health studies that systematically monitor the evolution of diseases across the region, particularly in the most contaminated area, the Endhó dam. Studies on biodiversity loss in the

area. Another missing research topic is the analysis of governance and public policies to guide government actions to address the problem, which could be bottom-up rather than top-down, as was the case with the decision to build the Atotonilco WWTP, which ultimately did not provide the expected response either socially or environmentally. To assist in governmental decision-making, it is crucial for public institutions to create systems for monitoring and gathering data regarding environmental impacts. Furthermore, it is important to note that statistical analysis shows that the use of wastewater has enabled the expansion of irrigated agriculture in the Mezquital Valley, benefiting more than 56,000 users across approximately 77,000 ha and with large annual water volumes. Nonetheless, these advantages are not uniformly distributed owing to variations in access, geographical location, water quality, and the restricted investment capacity of small-scale producers. Although the region generates 84% of the state's agricultural production value, between 48% and 55% of the population in municipalities with the highest wastewater use lives in poverty. In addition, in areas such as Tula, 73% of the population lacks social security and 28% has no access to health services. Overall, the existing production model supports agricultural activities; however, it has not alleviated structural inequalities, poverty, and social vulnerability. Strong sustainability is far from being achieved in this area, as it would require agreements involving the treatment of wastewater from the ZMVM prior to discharge, monitoring of compliance with environmental regulations for industries in this region that discharge heavily contaminated water. This obligation should also encompass the industrial sector of the Mezquital Valley and its municipalities, since Mexican law stipulates that all municipalities must treat their wastewater, a requirement that is not being fulfilled. Agriculture ought to be regarded as a strategic sector rather than merely another economic sector. Until the necessary changes are made, the region will continue to accumulate environmental impacts that may become irreversible; the weak sustainability perspective, as we have seen, is not sufficient to solve the problem.

AUTHOR CONTRIBUTIONS

M. Rosas Baños conceptualization, funding acquisition, investigation, methodology, project administration, writing, original draft. E.M. García Salazar, the corresponding author, investigation, data curation, application of statistical analyzes, visualization, supervision, writing, review and editing.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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
Conagua	Comisión Nacional del Agua
Coneval	Consejo Nacional de Evaluación de la Política de Desarrollo Social
km^2	Square kilometer
km^3	Cubic kilometer
m^3	Cubic meter
ha	Hectare
Inegi	Instituto Nacional de Estadística y Geografía
m	Meter
MAVM	Metropolitan Area of the Valley of Mexico
mm	Millimetre
Mt	Million ton
Semarnat	Secretaría de Medio Ambiente y Recursos Naturales
SIAP	Servicio de Información Agroalimentaria y Pesquera
t	Ton
UNAM	Universidad Nacional Autónoma de México
WWTPS	Wastewater treatment plants

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ORIGINAL RESEARCH PAPER

The combined effects of lead contamination and seasonal variations on growth performance of agar yield quality

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ABSTRACT

BACKGROUND AND OBJECTIVES: Seasonal variability represents a critical environmental driver influencing seaweed growth and heavy metal accumulation in coastal aquaculture systems. Variations in rainfall intensity, salinity regimes, and water circulation patterns may alter environmental stability and pollutant dynamics, consequently influencing both production efficiency and product safety. Notwithstanding its significance, detailed information concerning the synergistic impacts of seasonal conditions on biomass growth and lead contamination in cultivated Gracilaria verrucosa is still scarce, especially in tropical pond ecosystems. The objectives of the study were to investigate the impact of dry and wet seasons on growth characteristics, production yield, and lead accumulation in pond cultivated G. verrucosa in the coastal area of Ujungpangkah, Gresik, Indonesia.

METHODS: Field observations and sample collection were conducted during the dry season from April to September 2024 and the wet season from October 2024 to March 2025. Sixty samples were obtained in each season. The indicators of growth performance, comprising absolute biomass, growth rate, and production yield, were established using standardized methods for evaluating cultivation. Lead concentrations in seaweed tissues were quantified through laboratory based chemical analyses. Independent statistical tests were employed to assess seasonal differences and identify significant variations across sampling periods.

FINDINGS: The results demonstrated clear seasonal contrasts in biomass production and lead accumulation, both of which were markedly higher during the dry season. In the dry period, the mean absolute biomass was 128.33 ± 60.41 grams, more than twice that of the wet season's 55.83 ± 20.54 grams ($P = 0.021$). Likewise, lead concentrations were significantly elevated under dry conditions (4.57 ± 0.79 milligrams per kilogram) compared with the wet season (2.99 ± 0.58 milligrams per kilogram; $P = 0.006$). Conversely, neither the specific growth rate nor the agar yield exhibited significant variations between seasons ($P > 0.05$), implying that the essential physiological efficiency remained relatively consistent throughout the annual cycle.

CONCLUSION: The findings confirm that seasonal variation plays a decisive role in regulating biomass production and lead accumulation in Gracilaria verrucosa culture systems. While the dry season enhances productivity, it concurrently increases the risk of contamination. Consequently, the implementation of seasonally adaptive management practices, continuous environmental monitoring, and strengthened pollution control measures is essential to ensure sustainable production and food safety in coastal seaweed aquaculture.

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INTRODUCTION

Seaweed aquaculture is one of the fastest-growing sectors in global aquaculture, driven by its role in coastal food security, ecosystem services, and industrial raw materials (Chopin *et al*., 2012; Buschmann *et al*., 2017). Among cultivated macroalgae, *Gracilaria verrucosa* stands out as a significant species for agar production, extensively utilized in the food, pharmaceutical, and biotechnology industries (McHugh, 2003; Azhar and Hanif, 2022). Its broad environmental tolerance and adaptability to pond-based systems make it particularly suitable for tropical and subtropical aquaculture. Seaweed productivity and biochemical composition are strongly influenced by water chemistry and anthropogenic pollutants (Li *et al*., 2023; Oros, 2025). The operations within the industrial sector, particularly those related to oil and gas, may lead to heightened Pb (lead) concentrations in coastal waters, which can disturb physiological processes and introduce risks associated with trophic transfer (Ali *et al*., 2019). Due to their high surface area-to-volume ratio and ion-binding cell walls, seaweeds act as effective bioaccumulators, meaning Pb uptake can directly affect growth performance and product safety (Ramasamy, 2025). Seasonal variation further modifies salinity, nutrient availability, and redox conditions, influencing metal speciation, bioavailability, and metabolic responses (Jamaluddin, 2019). Periods conducive to swift biomass production may concurrently elevate Pb accumulation, resulting in a production–safety trade-off where enhanced yield aligns with an increased contamination risk. However, field-based studies assessing the combined effects of seasonal shifts and Pb contamination in pond-cultivated *G. verrucosa* remain limited. In Indonesia, *G. verrucosa* is extensively cultivated in coastal ponds, including those in Pangkahkulon Village, Ujungpangkah District, Gresik Regency, East Java. This area is influenced by industrial development, aquaculture, and coastal infrastructure, all of which may contribute to Pb inputs. Additional sources such as agricultural runoff, domestic wastewater, and atmospheric deposition are possible, although no formal source apportionment analysis has been performed. Consequently, the origins of Pb are understood to be associative rather than causative. Such contamination may reduce growth and agar yield while increasing food safety risks (Rahim, 2018). Lead exposure can interfere with photosynthetic pigments, compromise antioxidant defenses, and hinder polysaccharide biosynthesis in red algae (Trentin *et al*., 2024). In agar-producing species such as *G. verrucosa*, this may suppress biomass accumulation and alter agar yield and structural properties, including gel strength (Lee *et al*., 2016). Metal-induced stress may impair carbon fixation and enzyme-mediated biosynthesis, affecting both agar quantity and structural integrity. Assessing the relationship between seasonal changes and Pb contamination is crucial to ascertain if improved growth correlates with diminished agar quality or increased Pb levels that surpass food safety limits. Elevated biomass levels do not inherently assure higher product quality, especially when faced with contamination challenges (Banach *et al*., 2024). Year-round pond systems offer a realistic framework for assessing cumulative exposure compared with short-term laboratory experiments, capturing prolonged contamination and seasonal dynamics (Tresnati *et al*., 2021; Marinho-Soriano and Bourret, 2003). Prolonged observation is required to separate consistent Pb accumulation from seasonal fluctuations and to recognize strains that are tolerant or have low accumulation, making them suitable for environments influenced by industrial operations. This study investigates how seasonal environmental variation and industrial Pb contamination jointly influence growth performance, agar yield, and Pb accumulation in year-round cultivated *G. verrucosa*. Conducted in brackishwater ponds in Pangkahkulon Village, Ujungpangkah District, Gresik Regency, East Java,

Indonesia, during 2024 and 2025, the study integrates growth, agar yield, sediment contamination, and food safety considerations. Furthermore, the observational nature of the study leads to the interpretation of the identified relationships as associative rather than strictly causal, thus offeringfield-based insight into seasonal trade-offs between productivity and contamination risk.

MATERIALS AND METHODS

Study cultivation period

The study was conducted in a 2,000 square meter (m^2) pond. To improve representativeness and decrease site-specific bias, the area was partitioned into three comparable plots within the same pond complex, with each plot acting as an independent field replicate under consistent management. However, as the experiment was confined to a single pond system without spatial replication across independent sites, the observed seasonal patterns in growth performance, agar yield, and Pb accumulation primarily reflect local environmental and contamination conditions. Therefore, caution is required when extrapolating these findings to other coastal pond systems with different hydrological or management characteristics. The ponds are in a coastal area affected by industrial operations, aquaculture, and coastal development, all of which could lead to the introduction of environmental metal inputs. Nevertheless, no source apportionment, tracer-based, or comparative watershed analysis was conducted. Potential non-industrial inputs, including agricultural runoff, domestic effluents, and atmospheric deposition, were not quantified. Consequently, Pb inputs are understood to be associative instead of causative. Furthermore, these systems serve as essential platforms for studying the enduring effects of environmental contamination on seaweed yield within practical agricultural contexts. The cultivation trial lasted 12 consecutive months, covering the dry season (April–September 2024) and the wet season (October 2024–March 2025). Seasonal classification was based on regional meteorological data from the local climatological authority. The dry season was defined by precipitation of <100 millimeters per month (mm/month), higher evaporation, and elevated salinity, whereas the wet season was characterized by rainfall >150 mm/month, increased freshwater input, and lower salinity. Subsequent references to millimetres per month are expressed as mm/month. This design, applicable throughout the year, aimed to encapsulate the variability of seasons and its interplay with Pb contamination in operational pond settings. Due to the absence of controlled laboratory or mesocosm experiments, it was not possible to separate Pb effects from seasonal environmental fluctuations. The study was deliberately conducted under natural field conditions to ensure ecological relevance and to represent realistic aquaculture practices.

Seaweed material and cultivation technique

Gracilaria verrucosa thalli were obtained from local farmers and acclimatized prior to stocking. The species was identified for its economic relevance as a major agar-producing seaweed and its established resilience to changing environmental conditions in pond-based aquaculture. Previous studies indicate that *G. verrucosa* adapts well to variations in salinity, nutrient availability, and moderate environmental stress, supporting year-round cultivation. Cultivation was performed in a broad pond-based system adhering to conventional local methods. The initial fresh weight was measured at the beginning of each planting season (Fig. 1). Thalli were evenly distributed on the pond bottom using the broadcast method, commonly applied in Indonesian brackishwater ponds. The implementation of routine management, which included water exchange and sediment disturbance control, was carried out uniformly throughout the study to mitigate non-seasonal variability.

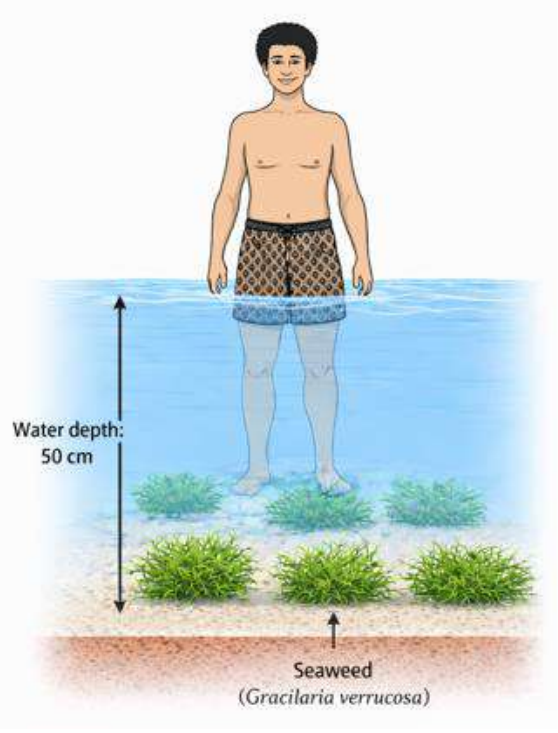

Fig. 1: Cultivation and sampling of *Gracilaria verrucosa* in pond systems. The figure shows harvested biomass, while the diagram illustrates the cultivation layout at 50 centimeters (cm) water depth with an initial weight of 50 gram (g) per unit

Growth performance analysis

Growth performance of *Gracilaria verrucosa* was assessed using absolute weight and specific growth rate (SGR), widely recognized indicators of seaweed productivity under field conditions. All parameters were computed utilizing a standardized initial biomass of 50 grams (g) per unit along with a uniform cultivation timeframe to maintain seasonal comparability. Absolute weight gain (AWg) was determined according to Eq.1 (Wiyanto, 2014):

$$AW = Wt - W0 \quad (1)$$

Where:
Wt is the final fresh weight (g) and
W0 is the initial fresh weight (g).

Also, Yong *et al*. (2013), proposed the SGR, percent per day (%/d) which was calculated using Eq. 2:

$$SGR = [(\ln Wt - \ln W0) / t] \times 100 \quad (2)$$

Where:
Wt is the final fresh weight (g),
W0 is the initial fresh weight (g),
and t is the cultivation period (days).

Agar yield analysis

Agar yield was evaluated based on agar yield, which represents the proportion of extractable agar relative to seaweed dry biomass. Agar yield is a key quality parameter in agarophyte research, as it reflects both physiological condition and polysaccharide biosynthesis efficiency. Fresh seaweed samples underwent a thorough washing to remove any debris and epiphytes, dried until a constant weight was achieved, and processed in accordance with standard agar extraction procedures commonly reported in agar research. Agar yield (%) was calculated using Eq. 3 (Rocha *et al*., 2019). All agar extractions were conducted

using identical drying procedures, extraction time, temperature, and solvent conditions to minimize methodological variability among samples:

Yield (%) = (Weight of extracted agar/Dry weight of seaweed) × 100 (3)

Quality of Agar parameters

In this study, the quality characteristics of agar, which encompass gel strength, viscosity, and sulphate content, were not analyzed. Agar assessment was limited to yield percentage due to technical and instrumental constraints; therefore, the potential effects of Pb contamination on agar physicochemical properties could not be directly evaluated. Physiological responses of *Gracilaria verrucosa* to Pb exposure and seasonal variation were assessed indirectly through growth performance, agar yield, and water quality parameters. Specific biochemical stress indicators, including chlorophyll content, activities of antioxidant enzymes, and levels of malondialdehyde (MDA), were not assessed as the experimental design focused on field-based productivity and environmental monitoring. Consequently, Pb-related stress was inferred from integrated responses in biomass production, agar yield, and metal accumulation rather than from direct biochemical analyses.

Pb *content analysis*

Pb concentrations in seaweed, water, and sediment were assessed to analyze bioaccumulation and environmental contamination during cultivation process. All compartments were sampled concurrently to allow for direct comparison and evaluation of Pb transfer pathways. The seaweed samples underwent oven drying, grinding, and homogenization. Sediment samples were air-dried, sieved to <63 micrometres (µm), and homogenized to assess the role of benthic metal reservoirs in seasonal bioavailability and uptake dynamics. Water samples were filtered through 0.45 µm membrane filters and acidified with ultrapure nitric acid to potential of hydrogen (pH) < 2 for preservation. Seaweed and sediment were digested using concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) at regulated temperatures until clear solutions were achieved, while water samples underwent digestion with HNO_3 prior to analysis. Pb concentrations were quantified by atomic absorption spectrophotometry (AAS) under optimized conditions. Although Pb was measured concurrently in all compartments, bioaccumulation factors were not calculated, as the study emphasized direct concentration measurements rather than ratio-based indices. Sampling was performed monthly to record temporal variations occurring within each season. All analyses were conducted in accordance with standardized protocols, encompassing calibration with certified reference standards, blank analyses, and triplicate measurements to ensure both analytical accuracy and precision. Calibration curves were prepared using certified Pb standards ranging from 0.01–5.00 milligrams per liter (mg/L) with correlation coefficients (R^2) > 0.995. The method detection limit was 0.003 milligram per kilogram (mg/kg), and the limit of quantification was 0.010 mg/kg. Method reliability was confirmed using certified reference materials and spike recovery tests, yielding recoveries ranging from 92.4–105.6% with relative standard deviations <5%. Quality assurance encompassed regular examination of blanks, duplicates, and calibration standards. Pb concentrations in seaweed and sediment are expressed on a dry weight basis (mg/kg), whereas water concentrations are reported in mg/L. All procedures complied with the established protocols for conducting heavy metal analysis in marine and environmental samples (Paz *et al.*, 2019).

Water quality assessment

Water quality parameters, including salinity, temperature, potential of hydrogen (pH), and dissolved oxygen (DO), were monitored weekly from April 2024 to March 2025 at fixed pond

locations using calibrated portable instruments. The evaluation of salinity and temperature was conducted as they are primary factors affecting hydrological variation and metal speciation, while pH and DO were investigated for their role in the solubility and bioavailability of Pb. Pb concentrations were additionally assessed in pond water and surface sediments to determine environmental exposure and benthic contributions to bioaccumulation. Collectively, these variables provided an environmental framework for interpreting seasonal patterns in growth performance, agar yield, and metal uptake. Temperature measurements were taken with a digital thermometer, pH levels were evaluated using a digital pH meter, salinity was gauged with a refractometer and DO was quantified with a DO meter. All measurements were conducted in situ during morning hours (08:00–10:00), with three replicate readings per sampling point. Instruments were calibrated prior to use. The monthly values were derived from weekly observations and are expressed as mean ± standard deviation (Zuhaer *et al*., 2026). Weekly measurements were aggregated monthly to capture intra-seasonal variability in water quality and Pb exposure throughout the cultivation period.

Statistical analysis

All statistical analyses were performed using Minitab version 22 and Microsoft Excel 365. Seasonal differences in growth performance, agar yield, and Pb accumulation were evaluated using independent samples *t*-tests and comparative trend analyses across sampling periods. Despite the absence of formal two-way interaction models, temporal and seasonal patterns were analyzed to evaluate the cumulative effect of seasonality and Pb exposure. Pb concentrations were measured simultaneously in water, sediment, and seaweed tissues; however, bioaccumulation factors (BAF) were not calculated. The analysis emphasized direct concentration measurements and seasonal relationships among environmental and biological compartments. Growth parameters, including absolute weight, SGR, and agar yield, together with Pb concentrations in seaweed, water, and sediment, were analysed for the dry season (April–September 2024) and the wet season (October 2024–March 2025). Ten samples were collected monthly for each variable, resulting in 60 observations per season (n = 60). The assessment of data normality was conducted preliminarily using histograms created in Microsoft Excel 365. Descriptive statistics are presented as mean and standard deviation (SD) (Tomy *et al*., 2021). Seasonal differences were tested using independent samples *t*-tests in Minitab (Agbangba *et al*., 2024), with statistical significance set at a 95% confidence level ($P < 0.05$). All results are reported as mean ± SD. BAF values relating Pb concentrations in water and sediment to seaweed tissues were not determined, as the study focused on direct concentration assessments. Physiological and biochemical stress indicators were also excluded from statistical analysis because they were not measured during the experimental period. The interpretation of statistical results was conducted to guide practical suggestions on the ideal periods for harvesting, the management of pond water, and approaches to mitigate Pb exposure risks in seaweed products, reflecting the observed seasonal trends. As the dataset was derived from a single pond complex, the results represent localized patterns rather than regional-scale dynamics. Future studies incorporating multi-site sampling and broader spatial replication are recommended to improve robustness, comparability, and general applicability of seasonal assessments.

RESULTS AND DISCUSSION

Absolute weight (g)

There were notable seasonal differences in the absolute weight of seaweed between the dry and wet seasons (Fig. 2). During the dry season, absolute weight increased from April to August, reaching a peak in August (190 g), followed by a

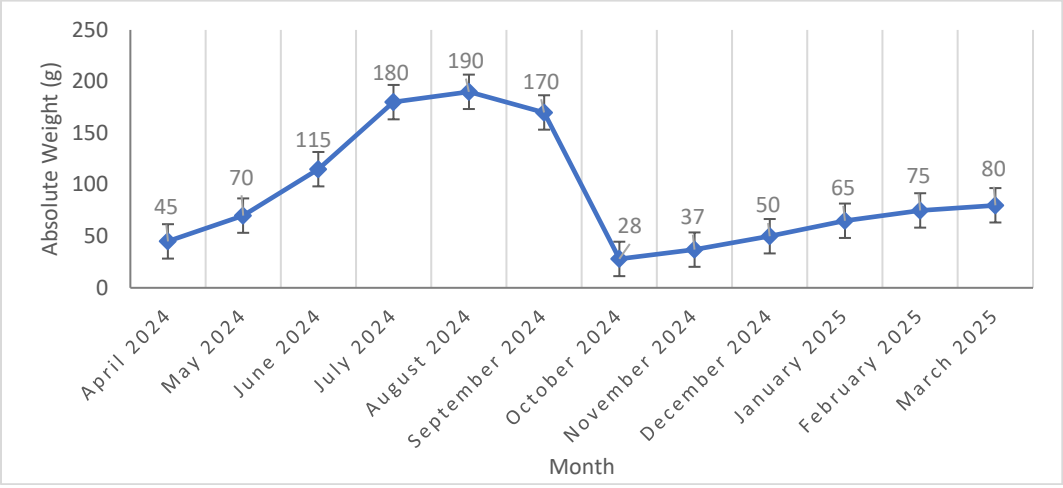

Fig. 2: Absolute weight gain of seaweed during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

slight decline in September. In contrast, absolute weight during the wet season increased gradually from October to March, with substantially lower values compared to the dry season. In general, seaweed demonstrated greater biomass accumulation in the dry season compared to the wet season. The significantly higher absolute weight observed during the dry season compared with the wet season indicates that seasonal conditions strongly regulate biomass accumulation of *Gracilaria verrucosa* in pond-based systems. During the dry season, which is characterized by consistent salinity and improved light availability, photosynthetic efficiency and carbon fixation are enhanced, leading to increased thallus development and overall biomass production (Buschmann *et al*., 2017; Kim *et al*., 2017). Conversely, a reduced absolute weight in the wet season indicates that heightened rainfall and the influx of freshwater restrict growth. Reduced salinity and water transparency may constrain light penetration and disrupt physiological processes related to photosynthesis and nutrient assimilation in shallow pond environments (Fethi and Ghedifa, 2019; Lee *et al*., 2016). Even though growth was not completely hindered, these restrictions curtailed biomass accumulation rates, leading in persistently lower values during the wet season. Nevertheless, the progressive increase in absolute weight across both seasons demonstrates that *G. verrucosa* maintains year-round growth. Seasonal variation influences growth intensity rather than direction, with the dry season contributing more substantially to annual biomass yield, while the wet season remains comparatively less favorable yet still productive. This pattern underscores the primary role that dry-season conditions play in driving biomass production within pond-based cultivation systems (Buschmann *et al*., 2017; Kim *et al*., 2017).

Specific growth rate (SGR) (%/day)

SGR of *Gracilaria verrucosa* varied markedly between seasons (Fig. 3). During the dry season, SGR reached its maximum value in April (2.14%/day) and subsequently declined toward September, with the lowest rate observed at the end of the season (0.77%/day). In the wet season, SGR values were generally lower and decreased progressively from October (1.48%/day) to March (0.78%/day). Overall, greater SGR values were consistently documented throughout the dry season when compared to the wet season, demonstrating more conducive growth conditions during the dry period.

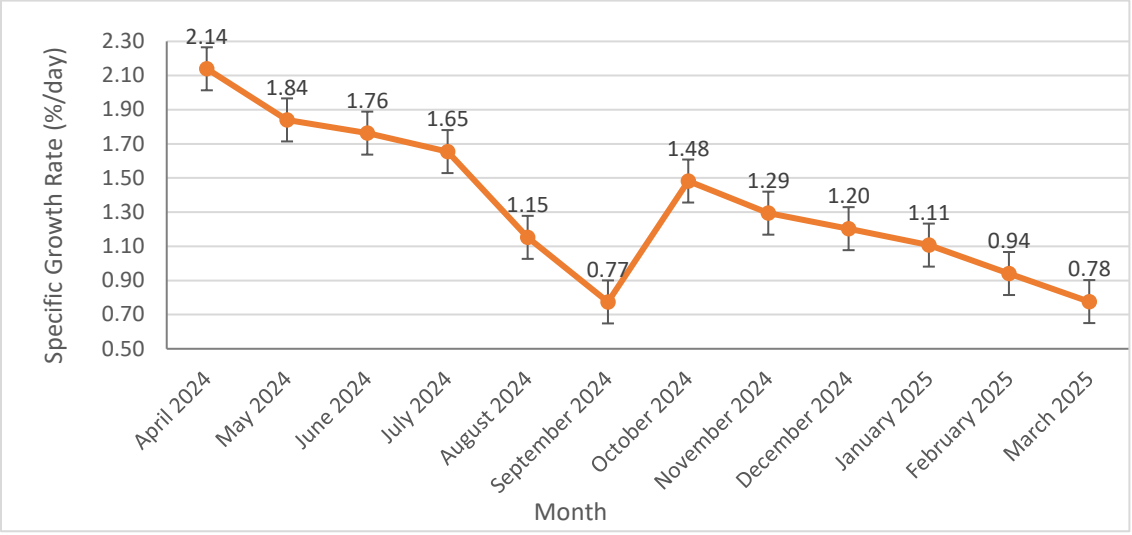

Fig. 3: Daily specific growth rate (SGR) of *Gracilaria verrucosa* during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

Although mean SGR values were slightly higher in the dry season than in the wet season, the differences were not statistically significant ($P > 0.05$), indicating limited seasonal influence on growth efficiency under the present conditions. Minor monthly variations are probably indicative of temporary environmental changes rather than stable seasonal regulation. Overall, *G. verrucosa* maintained relatively stable physiological performance, demonstrating strong adaptability to changing pond environments. The peak of the SGR in April indicates that the conditions during the early dry season were particularly advantageous, while the gradual decrease observed towards September and throughout the wet season reflects the rise in environmental limitations. Higher SGR during the dry season is likely related to improved light penetration, lower turbidity, and more stable salinity, which enhance photosynthesis and nutrient utilization (Ruslaini, 2017; Noor *et al*., 2021). In contrast, greater freshwater input, suspended particles, and unstable conditions during the wet season may impose cumulative stress that suppresses growth. Variations in seasonal growth also influence metal dynamics: swift growth can lead to the dilution of Pb in biomass, while a slower growth rate may heighten vulnerability to metal accumulation (Luo *et al*., 2020; Luo *et al.,* 2021). These findings underscore growth performance as a key link between environmental variability, biomass production, and ecosystem resilience, highlighting the need for seasonally adaptive management in sustainable *G. verrucosa* cultivation. Despite seasonal variation in Pb accumulation, the relatively stable SGR across both seasons indicates that Pb concentrations observed in this study did not directly impair fundamental physiological processes such as photosynthesis, nutrient assimilation, or cellular metabolism. The lack of a notable reduction in SGR implies a considerable tolerance capacity in *G. verrucosa*, indicating that the decrease in biomass during the wet season was mainly influenced by environmental factors such as decreased salinity, heightened turbidity, and restricted light availability, rather than direct Pb toxicity.

Agar yield (%)

The agar yield of *Gracilaria verrucosa* varied noticeably between seasons (Fig. 4). In the dry season, agar yield peaked in April (19.16%) and declined steadily to its minimum in July (10.11%), before showing a slight recovery toward the end

of the season. By contrast, agar yield during the wet season remained relatively stable, fluctuating from 10.17% in January to a maximum of 14.39% in March. In general, higher agar yields were observed at the early stage of the dry season, while the wet season was characterized by more moderate and consistent yield levels. Agar yield of *G. verrucosa* showed clear seasonal variation, with maximum values at the onset of the dry season and relatively stable but lower levels during the wet season. The peak observed in April indicates that the conditions during the early dry season created an ideal physiological setting for agar biosynthesis. This is likely attributed to the beneficial interactions among light intensity, temperature, and salinity that enhanced carbon fixation and polysaccharide accumulation. This timeframe thus signifies a critical opportunity for optimizing yield. The subsequent decline toward mid-dry season may reflect increasing physiological constraints and shifts in nutrient allocation. During the wet season, agar yield remained moderate and consistent despite reduced growth and fluctuating water conditions, indicating maintained biosynthetic capacity. Similar trends have been observed in agarophytes, where stable environmental conditions encourage the accumulation of polysaccharides, while variations in hydrographic conditions restrict metabolic efficiency (Marinho-Soriano and Bourre, 2003; Afonso *et al*., 2021; Mendes *et al*., 2022). The absence of significant seasonal differences further suggests that Pb accumulation did not markedly disrupt carbohydrate synthesis or metabolic allocation to agar production within the concentration range detected. Thus, Pb exposure was insufficient to impair major biosynthetic pathways related to agar formation. Overall, environmental stability appears to be a primary regulator of agar productivity in *G. verrucosa*. The high yields observed in the early dry season demonstrate efficient use of resources, whereas the conditions during the wet season impose moderate physiological restrictions. However, because gel strength, viscosity, and sulphate content were not measured, the influence of Pb on detailed quality attributes could not be assessed; the findings therefore represent yield responses only. Although qualitative parameters such as gel strength, viscosity, clarity, sulphate content, and polysaccharide composition were not quantified, seasonal conditions likely influence these properties indirectly. Stable salinity, enhanced light availability, and moderate temperatures in the dry season may facilitate the biosynthesis of polysaccharides and their structural arrangement, whereas fluctuating salinity, turbidity, and nutrient variability in the wet season may alter carbon allocation and sulphate esterification, potentially affecting molecular structure and functionality. Future studies integrating physicochemical and molecular analyses are needed to clarify the relationships among seasonal dynamics, Pb exposure, and detailed agar quality attributes.

Seaweed Pb Content (mg/kg)

The Pb content in *Gracilaria verrucosa* exhibited distinct seasonal differences between the dry and wet seasons (Fig. 5). During the dry season, Pb concentrations increased from April and reached the highest level in July (5.49 mg/kg), followed by a slight decline in August and a subsequent increase toward September. In contrast, Pb content during the wet season remained at lower levels, ranging from 2.15 mg/kg in November to a maximum of 3.95 mg/kg in February. Overall, Pb concentrations measured during the dry season were consistently higher than those recorded during the wet season. Pb concentrations in *G. verrucosa* displayed significant seasonal fluctuations, consistently showing elevated levels in the dry season compared to the wet season. Although Pb accumulation in seaweed tissues was confirmed, its incorporation into extracted agar and persistence after processing were not evaluated. The extraction procedure—comprising repeated washing, heating, and filtration steps—has the potential to diminish metal residues; nevertheless, without direct analysis of the

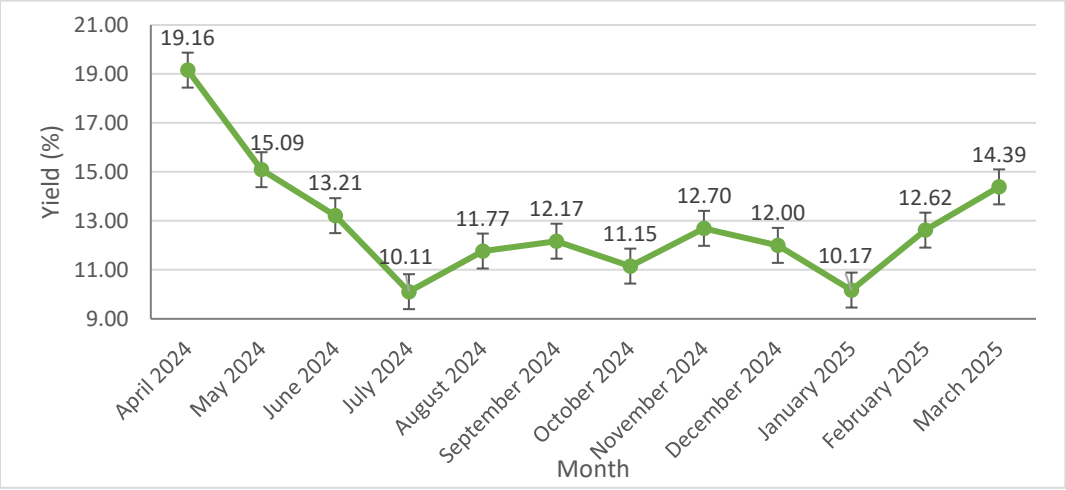

Fig. 4: Agar yield (%) of *Gracilaria verrucosa* during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

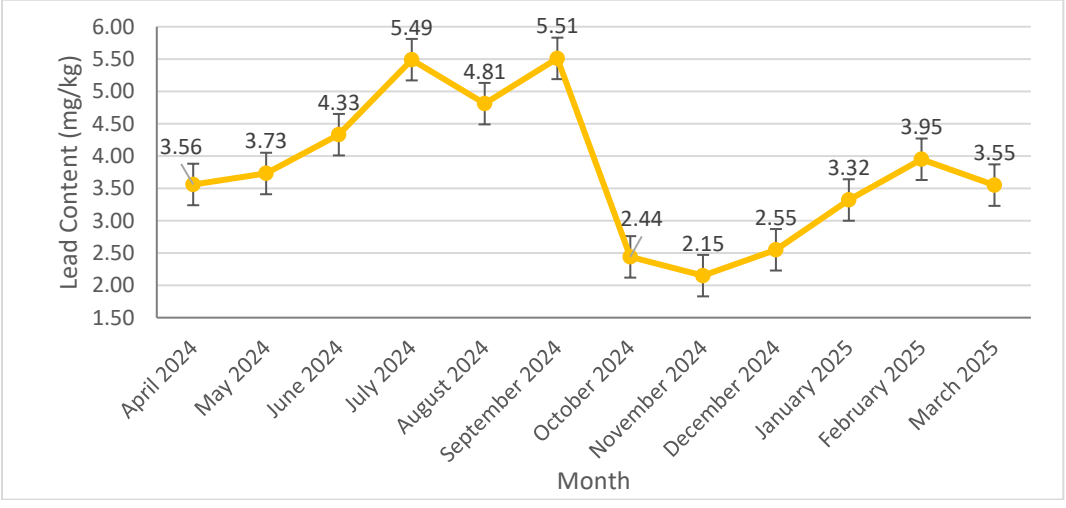

Fig. 5: Pb content in *Gracilaria verrucosa* during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

processed agar, the extent of Pb removal remains uncertain. Prior studies have demonstrated that heavy metals may associate with polysaccharide matrices or persist with cell wall components, hinting at potential retention in agar products. Thus, despite stable growth and agar yield, Pb transfer into agar cannot be excluded. Direct quantification of metals in extracted agar is therefore required to assess processing efficiency and food safety risks. Seasonal Pb bioavailability was strongly influenced by rainfall, salinity, temperature, and water exchange. During the dry season, the combination of low precipitation, heightened salinity, and increased temperatures resulted in diminished dilution and an extended water residence time, thereby elevating dissolved Pb concentrations and encouraging desorption from sediments. Limited freshwater input and restricted circulation enhanced metal retention within the pond system, facilitating uptake by *G. verrucosa*. Sediments functioned as seasonal sinks, accumulating Pb under low hydrodynamic

conditions and releasing it during periods of elevated salinity and temperature. Conversely, heavy rainfall and regular water turnover during the wet season led to a reduction in salinity and temperature, improved mixing, and increased dilution and flushing, which in turn diminished the residence time and bioavailability of Pb. Concentrations increased in April, peaked in July, and remained elevated through September, whereas wet-season values were lower and more stable. This pattern corresponds with the established affinity of macroalgal cell walls for dissolved metal ions (Lindenmayer *et al*., 2023). Greater dry-season accumulation may also reflect prolonged exposure and slower biomass turnover, limiting biological dilution. Nonetheless, since this study was observational, these mechanisms remain hypothetical; direct measurements of metal speciation and hydrodynamics were not performed. Similar seasonal trends have been reported in other coastal aquaculture systems (Lao *et al*., 2022). These findings collectively indicate that the accumulation of Pb in *G. verrucosa* is significantly influenced by seasonal environmental changes, highlighting the necessity for ongoing monitoring and adaptive management (Huang *et al*., 2025). Regarding food safety, the World Health Organization and the Food and Agriculture Organization, through the Codex Alimentarius framework, recommend maximum Pb limits in food commodities of approximately 0.1–0.3 mg/kg (FAO and WHO, 2021). The European Commission sets a maximum level of about 3.0 mg/kg (dry weight) for dried algae and seaweed products (European Commission, 2023). In this study, Pb concentrations ranged from 2.15 to 5.51 mg/kg, with peak values during the dry season. All measurements surpassed the recommendations set by Codex, and numerous samples gathered from July to September 2024 exceeded the limits established by the European Union limits. Comparable exceedances have been documented in anthropogenically influenced aquaculture systems (Lao *et al*., 2022; Lindenmayer *et al*., 2023). Even though accelerated growth may lower tissue metal concentrations through biological dilution, this mechanism could be insufficient in environments that are contaminated (Chen *et al*., 2023; Lee *et al*., 2023). Chronic Pb exposure is associated with neurological, renal, and metabolic disorders (Tchounwou *et al*., 2012; Sharma *et al*., 2020). Thus, despite favorable growth performance, a substantial proportion of samples—particularly from the dry season—may not comply with established safety standards. A quantitative human health risk assessment, including estimated daily intake (EDI), target hazard quotient (THQ), and hazard index (HI), was not conducted, limiting comprehensive evaluation of long-term exposure risks. Consequently, the implications of food safety are determined by comparisons to regulatory thresholds instead of relying on probabilistic risk modeling. The absence of watershed-scale monitoring, source apportionment, bioaccumulation factor calculations, and direct Pb analysis in agar further constrains interpretation (Izydorczyk *et al*., 2021; Dharini *et al*., 2023). Future studies should integrate EDI, THQ, and HI assessments; evaluate Pb residues in processed agar; and incorporate source-tracking approaches to clarify contamination pathways. Improved environmental management, careful site selection, and persistent monitoring are vital to decrease Pb accumulation, protect consumer health, and guarantee the sustainable future of seaweed aquaculture systems.

Seasonal variation of water quality

Fig. 6 illustrates the monthly dynamics of salinity, temperature, pH, and DO in extensive ponds cultivated with *Gracilaria verrucosa* across the dry and wet seasons. During the dry season (April–September 2024), salinity increased from 31.8 g/L in April to a peak of 33.8 g/L in August, followed by a slight decline in September, reflecting intensified evaporation and reduced freshwater input. In contrast, the wet season (October 2024–March 2025) demonstrated lower

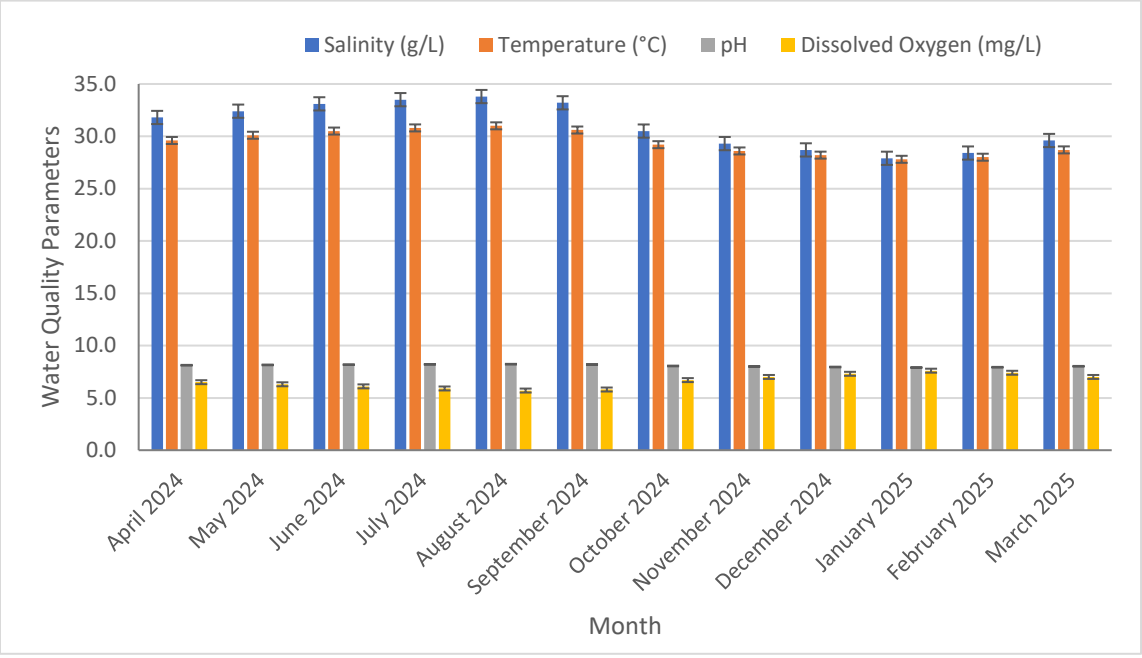

Fig. 6: Monthly variation of salinity, temperature, pH, and DO in extensive pond cultivation of *Gracilaria verrucosa* during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

and more fluctuating salinity levels (27.9–30.5 g/L), which were linked to heightened rainfall and runoff. Water temperature exhibited a comparable seasonal trend, with elevated values during the dry season (29.6–31.0 °C) and reduced values in the wet season (27.8–29.2 °C), reflecting changes in solar radiation and precipitation. pH remained relatively stable throughout the study, ranging from 8.12 to 8.22 in the dry season and from 7.90 to 8.05 in the wet season, indicating well-buffered pond conditions. DO concentrations gradually declined during the dry season from 6.5 to 5.7 mg/L, likely due to reduced oxygen solubility at higher temperatures, whereas higher values were recorded in the wet season (6.7–7.6 mg/L), particularly in January, possibly driven by lower temperatures and enhanced mixing. In summary, the findings indicate that seasonal climatic variability has a significant impact on water quality in large *G. verrucosa* ponds, which may affect growth performance and cultivation efficiency. The observed ranges of salinity, temperature, pH, and DO fall within levels generally considered optimal for the growth of *G. verrucosa* (Ruslaini, 2017; Tanaka *et al*., 2020; Panasani *et al*., 2024). These conditions imply a largely beneficial aquatic setting for physiological performance, photosynthesis, and biomass generation, which aids in efficient nutrient absorption and carbon assimilation (Hurd *et al*., 2014). Seasonal fluctuations were consistent with patterns typical of tropical coastal aquaculture systems, characterized by higher temperature and salinity during the dry season and lower values during the wet season due to rainfall and terrestrial runoff (Hurtado *et al*., 2014). Consistent pH levels indicate a well-buffered pond ecosystem, while the decrease in DO during the dry season is probably linked to higher temperatures and diminished oxygen solubility, which is a typical characteristic of shallow aquaculture settings (Ross *et al*., 2013; Boyd, 2020). Ecologically, dry-season conditions may stimulate metabolic activity and growth but can also increase physiological stress when accompanied by lower DO (Wernberg *et al*., 2016). Conversely, cooler

and more oxygen-rich wet-season conditions promote metabolic stability, although salinity fluctuations may induce osmotic stress and affect cellular homeostasis (Souza *et al.,* 2019). Overall, water quality at the study site remains suitable for year-round cultivation of G. verrucosa. However, adaptive management—particularly during the dry season—such as improving water circulation and optimizing stocking density, is necessary to mitigate environmental stress (Mendes *et al.,* 2024). Ongoing monitoring and proactive management are crucial for maintaining productivity, ensuring ecosystem stability, and fostering long-term resilience in seaweed farming amidst rising climatic variability (Duarte *et al.,* 2020).

Seasonal variation of Pb in water and sediment

Fig. 7 presents the temporal dynamics of Pb concentrations in water and sediment across the dry and wet seasons in extensive Gracilaria verrucosa ponds. During the dry season (April–September 2024), Pb in water increased from 0.010 mg/L in April to 0.014 mg/L in August, followed by a slight decline in September. Sediment exhibited a similar pattern, rising from 19.8 mg/kg in April to 25.9 mg/kg in September, indicating progressive accumulation under reduced freshwater input and intensified evaporation. In the wet season (October 2024–March 2025), water Pb concentrations continued to rise, peaking at 0.022 mg/L in January before moderately declining toward March. Sediment Pb also showed a continuous increase, reaching 32.8 mg/kg in March. Increased concentrations during the wet season are likely indicative of heightened surface runoff and augmented terrestrial contributions, which aid in the transport of metals into the pond system. Overall, the levels of Pb in sediment consistently surpassed those found in water, highlighting its function as the main metal reservoir. These results demonstrate that seasonal hydrological processes strongly regulate Pb distribution and accumulation in extensive seaweed cultivation systems. Pb contamination in coastal aquaculture ponds can arise from various human activities, such as offshore oil and gas operations, industrial processes, maritime transport, and urban runoff. Potential inputs arise from produced water discharge, infrastructure corrosion, fuel combustion residues, and chemical additives. Nevertheless, in the absence of site-specific source apportionment, this study cannot definitively ascertain the relative contribution of each source. Seasonal hydrology further modulates Pb loading. In the wet season, increased rainfall leads to heightened terrestrial runoff and river discharge, which facilitates the movement of industrial and urban pollutants into pond systems. In contrast, reduced freshwater input during the dry season limits dilution and favors Pb accumulation. Tidal currents and hydrodynamic circulation subsequently transport contaminated seawater into ponds through water exchange channels, constituting a major pathway for long-term Pb enrichment (Zhang *et al*., 2023; Al-Kahtany *et al*., 2024). In aquatic ecosystems, Pb exhibits a significant attraction to suspended particles and dissolved organic matter, which aids in its movement from the water column to the sediment at the bottom. Petroleum-derived residues and industrial organic compounds may further enhance adsorption in energy-affected coastal areas. Consequently, sediments serve as the main long-term sink for Pb, indicating ongoing anthropogenic contributions. Nevertheless, variations in pH, redox potential, microbial activity, and management practices (e.g., pond drying and harvesting) can disturb sediments and promote remobilization, leading to secondary Pb release into overlying waters (Wang *et al*., 2024). The persistent exchange of sediment and water contributes to ongoing contamination in semi-enclosed ponds, which in turn diminishes the efficiency of conventional water management strategies. Elevated Pb concentrations pose ecological risks through bioaccumulation and physiological stress in cultured organisms, potentially reducing productivity and compromising food safety.

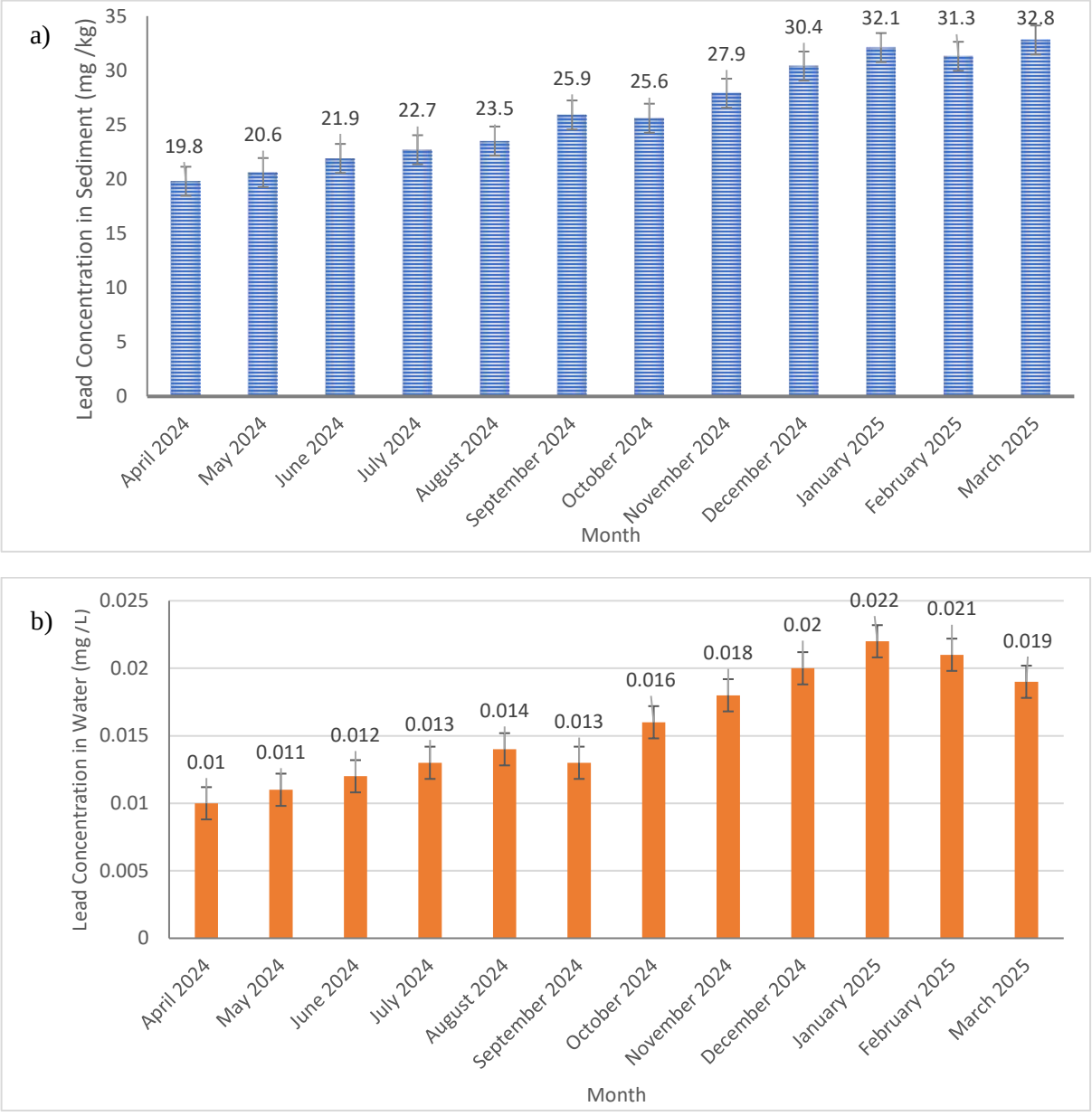

Fig. 7: Monthly variation of Pb concentrations in (a) sediment (mg/kg) and (b) water (mg/L) in extensive *Gracilaria verrucosa* ponds during the dry season (April–September 2024) and the wet season (October 2024–March 2025). Data points represent mean values ± SD

Limited water renewal in coastal ponds, such as those in Ujungpangkah, further intensifies pollutant retention and exposure. Thus, extensive monitoring of industrial effluents, coastal waters, and pond sediments—augmented by stricter regulatory enforcement and improved waste treatment technologies—is imperative for the sustainable advancement of aquaculture (Hossain *et al*., 2023).

Seasonal comparison of growth performance, yield, and Pb accumulation

Table 1 summarizes the independent samples *t*-test assessing seasonal differences in growth

performance, agar yield, and Pb accumulation in *Gracilaria verrucosa*. Absolute weight was significantly higher in the dry season than in the wet season ($P = 0.021$), indicating a measurable seasonal effect on biomass accumulation. The concentration of Pb varied considerably across different seasons ($P = 0.006$), showing elevated levels during the dry season, which indicates increased absorption due to lower freshwater availability. In contrast, SGR and agar yield did not differ significantly between seasons ($P = 0.097$ and $P = 0.346$, respectively; $P \geq 0.05$), indicating stable physiological growth efficiency and production yield. Accordingly, no statistically supported claims of seasonal variation in SGR or agar yield can be made. The discussion is therefore confined to statistically significant outcomes ($P < 0.05$), demonstrating that seasonal effects were limited to absolute biomass and Pb accumulation, whereas SGR and agar yield remained statistically stable throughout the cultivation period. Numerical variations in parameters deemed non-significant are approached with caution and are not regarded as proof of seasonal impact unless additional supporting analyses are provided. Although seasonal patterns in Pb accumulation and growth were evident, this study did not apply correlation, regression, or multivariate analyses to quantify relationships between Pb and growth parameters (absolute weight, SGR, and agar yield). The results thus indicate seasonal correlations instead of confirmed causal relationships. Formal normality and homogeneity tests were also not conducted, warranting cautious interpretation of statistical significance. Future studies should incorporate correlation analysis, multivariate modeling, mixed-effects approaches, and interaction-based frameworks (e.g., two-way ANOVA) to better resolve the combined effects of environmental variables and Pb exposure. The comparative analysis with prior studies (Table 2) reveals that seasonal environmental factors influenced biomass and productivity more profoundly than Pb stress. Seasonal differences were assessed using independent *t*-tests, which identified significant effects on absolute weight and Pb accumulation but not on SGR or agar yield. The minimal seasonal variation observed in SGR and yield, despite high Pb concentrations in the dry season, implies that the effects are mainly additive instead of synergistic or antagonistic effects. Environmental drivers—light availability, salinity stability, temperature, and hydrological dynamics—remained the principal regulators of growth and agar production, whereas Pb functioned as a secondary stressor within the detected concentration range. Increased biomass observed during the dry season is likely indicative of favorable conditions, such as improved light penetration, consistent salinity levels, and reduced turbidity, all of which facilitate photosynthesis and carbon assimilation (Luo *et al*., 2021). Conversely, the stable SGR and yield across seasons indicate strong metabolic flexibility and adaptive capacity in *G. verrucosa* (Luo *et al*., 2020; Hidayatullah *et al*., 2023). Furthermore, the elevated Pb levels observed in the dry season correlated with a decrease in freshwater inflow, limited dilution, increased salinity, and a longer water residence time, collectively resulting in greater metal bioavailability and its adsorption to algal tissues (Huang *et al*., 2025). Enhanced metabolic activity may further facilitate uptake through passive and active pathways, with Pb accumulating in cell walls and intracellular compartments (Almahera *et al*., 2024). From a public health perspective, chronic Pb exposure is linked to neurological, renal, and cardiovascular disorders (WHO, 2023). Moreover, the consistent performance of SGR and agar yield implies that Pb concentrations were maintained below levels that could cause notable disruption to photosynthesis, nutrient uptake, or cellular integrity in real-world settings. Seasonal biomass reduction during the wet period is therefore more plausibly attributed to hydrological instability, freshwater dilution, and reduced photosynthetic efficiency than to metal toxicity. Strategic harvest timing and improved pond management can enhance agar safety without compromising productivity. Gathering in

Table 1: Independent t-test analysis of growth performance, yield, and Pb content of *G. verrucosa* during dry and wet seasons

Parameter	Dry Season (Apr–Sep 2024) Mean ± SD	Wet Season (Oct 2024–Mar 2025) Mean ± SD	t-value	P-value
Absolute weight (g)	128.33 ± 60.41	55.83 ± 20.54	2.83	0.021*
Specific growth rate (% /day)	1.55 ± 0.47	1.13 ± 0.26	1.79	0.097^{NS}
Yield (%)	13.59 ± 3.37	12.17 ± 1.54	1.01	0.346^{NS}
Pb content (mg/kg)	4.57 ± 0.79	2.99 ± 0.58	3.42	0.006*

Values are presented as mean ± SD (n = 60 per season). Differences between seasons were analyzed using independent samples t-test. Asterisks (*) indicate significant differences at ($P < 0.05$). NS = non-significant ($P \geq 0.05$)

Table 2: Comparison of growth performance, agar yield, and Pb accumulation of *Gracilaria sp.* with previous studies

Findings	Location	Season	Absolute Weight (g)	SGR (%/day)	Agar Yield (%)	Pb Content (mg/kg)	Sources
Growth and agar yield controlled by temperature and light	Coastal lagoon, Portugal	Seasonal	–	0.9–1.8	12.5–18.7	<2.0	Afonso *et al.*, 2021
Growth dilution reduced metal accumulation	Coastal farms, China	Annual	–	1.1–2.3	11.0–17.5	1.5–4.2	Luo *et al.*, 2020
Stable agar yield under moderate stress	Offshore culture, Brazil	Dry–Wet season	–	1.0–1.9	13.2–20.1	<3.0	Mendes *et al.*, 2022
High Pb accumulation near industrial areas	Polluted coast, Asia	Annual	–	–	–	3.8–6.5	Lindenmayer *et al.*, 2023
Higher biomass and Pb in dry season; stable SGR and yield	Pond, Indonesia	Dry–Wet season	55.83–128.33	0.77–2.14	10.11–19.16	2.15–5.51	Present study (2024–2025)

the early part of the dry season—when agar yield is elevated and Pb accumulation is somewhat moderate—strikes a practical balance between quality and safety. Regular water exchange, sediment removal, and inlet-water filtration may further reduce Pb residence time and bioavailability. Integrating seasonally adjusted harvesting with proactive management and continuous monitoring, alongside stricter control of industrial effluents, is essential to optimize productivity, protect consumer health, and ensure sustainable aquaculture development (Pratiwi *et al.*, 2019). The comparative analysis indicates that the biomass, SGR, and agar yield observed in this study align with the values documented for tropical and subtropical systems (Afonso *et al.*, 2021; Luo *et al.*, 2020; Mendes *et al.*, 2022). Peak SGR and agar yield during the early dry season confirm that stable salinity and high light availability are primary drivers of growth and polysaccharide production in *G. verrucosa*. Pb concentrations (2.15–5.51 mg/kg) were higher than those reported in less impacted areas and approached levels typical of industrially influenced environments (Lindenmayer *et al.*, 2023). Nonetheless, the yields of SGR and agar were found to be like those reported in earlier studies, indicating a significant physiological tolerance to moderate metal stress, which is probably facilitated by mechanisms of growth dilution and cellular sequestration (Luo *et al.*, 2020). Overall, seasonal environmental conditions predominantly regulated biomass and agar production, whereas local anthropogenic pressures determined Pb accumulation and related food safety risks. The main contribution of this study lies in its integrated evaluation of seasonal growth, agar productivity, sediment–water Pb dynamics, and food safety within a long-term, pond-based cultivation system. In contrast to the majority of studies carried out in open coastal environments, this research emphasizes the trade-offs between productivity and contamination in semi-enclosed aquaculture systems affected by anthropogenic inputs. The year-round monitoring approach and combined assessment of productivity and safety provide empirical evidence to support sustainable aquaculture management in industrialized coastal regions.

Linking productivity and food safety

To elucidate the connection between productivity and food safety, a comprehensive seasonal evaluation of biomass, agar yield, and Pb accumulation was performed (Table 3). A clear trade-off emerged: the dry season (April–September 2024) showed superior productivity, with higher biomass (45–190 g), elevated (SGR; 0.77–2.14%/day), and greater agar yield (10.11–19.16%). However, this period also coincided with increased Pb accumulation in sediments (19.8–25.9 mg/kg) and seaweed tissues (3.56–5.51 mg/kg), indicating heightened food safety risk. Conversely, the wet season (October 2024–March 2025) exhibited moderate productivity—lower biomass (28–80 g), reduced SGR (0.78–1.48%/day), and relatively stable agar yield (10.17–14.39%)—while tissue Pb concentrations were comparatively lower (2.15–3.95 mg/kg) despite higher sediment levels (25.6–32.8 mg/kg), likely due to enhanced dilution and water exchange. The consistent performance of SGR and agar yield throughout the seasons suggests that moderate exposure to Pb did not significantly hinder physiological functioning, likely due to growth dilution and intracellular sequestration. Nonetheless, the concurrence of peak productivity and elevated Pb accumulation during the dry season highlights a critical trade-off between production efficiency and food safety in pond-based seaweed cultivation systems. An evident seasonal balance between productivity and food safety was detected in the cultivation practices of *Gracilaria verrucosa*. The dry season supported higher biomass, growth rate, and agar yield but coincided with elevated tissue Pb concentrations exceeding safety thresholds established by the World Health Organization, the Food and Agriculture Organization, and the Codex Alimentarius Commission. Similar patterns have been reported in tropical aquaculture systems, where favorable environmental conditions enhance both productivity and metal uptake (Luo *et al*., 2020; Afonso *et al*., 2021; Mendes *et al*., 2022). Conversely, the wet season demonstrated moderate productivity along with diminished Pb accumulation, likely attributable to greater dilution and water exchange. In light of these trends, various management strategies are proposed. Harvesting should be prioritized during the early dry season (April–May), when growth and agar yield are high while Pb concentrations remain relatively moderate. During the peak dry season (June–August), regular water exchange, sediment removal, inlet-water filtration, and improved circulation are necessary to reduce metal residence time and bioavailability. Regular monthly assessments of Pb levels in water, sediment, and seaweed tissues—backed by early warning thresholds that conform to international standards—ought to inform harvest choices and avert the introduction of contaminated products into the market. Although consistent seasonal trends were observed, formal interaction analyses were not conducted; thus, the relationships should be interpreted as associative rather than mechanistic. Future studies employing factorial designs, multivariate modeling, or controlled experiments are needed to quantify interaction effects between seasonal drivers and metal stress. Integrating adaptive harvest scheduling, proactive pond management, and continuous monitoring is therefore essential to optimize productivity while safeguarding food safety in *G. verrucosa* cultivation.

CONCLUSION

This study provides robust evidence that seasonal variability plays a crucial role in regulating growth performance and Pb accumulation in pond cultivated *Gracilaria verrucosa* in the coastal region of Ujungpangkah, Gresik. The results suggest that both absolute biomass and Pb concentration are notably affected by seasonal variations, exhibiting elevated levels during the dry season, while SGR and yield tend to stay fairly stable across the year. These findings suggest that seasonal environmental dynamics primarily affect total biomass production and contaminant uptake, while fundamental physiological growth processes are maintained through effective metabolic adaptation. The augmented biomass recorded throughout the dry season can be linked to more

Table 3: Seasonal linkages between productivity, sediment pb, and food safety risk of *Gracilaria verrucosa*

Season	Sediment Pb (mg/kg)	Tissue Pb (mg/kg)	Absolute weight (g)	SGR (%/day)	Agar yield (%)	Productivity Level	Food safety risk
Dry season	19.8–25.9	3.56–5.51	45–190	0.77–2.14	10.11–19.16	High	High
Wet season	25.6–32.8	2.15–3.95	28–80	0.78–1.48	10.17–14.39	Moderate	Moderate-High

Food safety risk categories were defined based on international guidelines (WHO/FAO/Codex): Low risk ≤ 2.0 mg/kg; Moderate risk 2.1–3.5 mg/kg; High risk > 3.5 mg/kg.

advantageous and stable environmental factors, which encompass enhanced light availability, steady salinity, and diminished turbidity. Such conditions enhance photosynthetic performance and carbon assimilation, thereby supporting greater tissue development and structural growth. However, these same environmental characteristics also promote higher Pb bioavailability because of reduced freshwater dilution, extended water residence time, and intensified interactions between seawater and contaminated sediments. Furthermore, periods of increased productivity are directly correlated with a heightened risk of contamination, demonstrating a fundamental trade-off between production efficiency and environmental safety in coastal aquaculture systems. The lack of significant seasonal variation in SGR and yield further indicates that *G. verrucosa* exhibits strong physiological flexibility and resilience to moderate environmental fluctuations. This flexibility empowers the species to uphold consistent metabolic functions and optimize nutrient utilization amid fluctuating seasonal circumstances, consequently securing steady production outcomes. While such stability represents a favorable attribute for long term aquaculture development and economic security, it should not be interpreted as evidence of low pollution risk. The present findings demonstrate that stable growth efficiency does not necessarily correspond to reduced heavy metal accumulation, emphasizing the importance of evaluating productivity and product safety simultaneously. From the perspectives of environmental and public health, the increased levels of Pb found during the dry season pose significant concerns about food safety and long-term human exposure. Long term consumption of contaminated seaweed may increase the risk of neurological impairment, renal dysfunction, and cardiovascular disorders. In addition, excessive metal accumulation can reduce market acceptance and export competitiveness, potentially undermining the livelihoods of coastal farming communities. Consequently, the efficient management of heavy metal pollution is crucial not only for the protection of ecosystems but also for the preservation of public health, as well as for ensuring ongoing socioeconomic advantages. In response to these challenges, the adoption of seasonally adaptive management strategies is strongly recommended. Routine monitoring of Pb levels in water, sediments, and biomass should be intensified, particularly during periods of elevated risk. Improvements in water exchange systems, sediment management practices, and harvesting schedules may contribute to reducing pollutant accumulation and exposure. Moreover, it is essential to implement stricter regulations on industrial discharges and to improve wastewater treatment infrastructure in order to reduce the external influx of heavy metals into coastal ecosystems. Integrating aquaculture management with broader coastal pollution control policies will be fundamental to achieving long term environmental sustainability. Although growth and agar yield were measured using standardized procedures, this study did not include physicochemical analyses of agar yield such as gel strength, viscosity, and sulphate content. C Therefore, the consequences of Pb contamination on the functional characteristics of agar have yet to be clarified. Pb quantification was conducted

using rigorous quality control procedures, the lack of bioaccumulation assessment and agar residue analysis restricts a comprehensive evaluation of metal transfer and potential food safety risks. Future studies should prioritize long term investigations of seasonal and interannual variability in heavy metal dynamics, as well as experimental studies on the physiological mechanisms underlying metal uptake, transport, and detoxification in *G. verrucosa*. Further exploration of bioremediation strategies, selective breeding for metal-tolerant varieties, and eco-friendly cultivation methods is likewise advocated. These approaches may strengthen the resilience of seaweed farming systems against environmental stressors and contamination.

AUTHOR CONTRIBUTIONS

A. Rahmad Rahim conceptualized the study design, field and laboratory investigation, data collection and management, formal data analysis, original draft preparation, critical revision, supervision, and project administration**.** D.R. Utami performed the methodology development, experimental implementation, data validation, statistical analysis, manuscript drafting, editing, and technical support. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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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
%/day	Percent per day
±	Plus–minus (Mean ± SD)
°C	Degree Celsius
AAS	Atomic absorption spectrophotometry
ANOVA	Analysis of variance
AW	Absolute weight
cm	Centimeter
DO	Dissolved oxygen
EDI	Estimated daily intake
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
g	Gram
G. verrucosa	*Gracilaria verrucosa*
$HClO_4$	Perchloric acid
HNO_3	Nitric acid
kg	Kilogram
L	Liter
LOD	Limit of detection
LOQ	Limit of quantification
m^2	Square meter
mm/month	Millimeter per month
mg	Milligram
Mg/kg	Milligram per kilogram
Mg/L	Milligram per Liter
n	Number of samples
NS	Non-significant
Pb	Lead
pH	Potential of hydrogen
R^2	Coefficient of determination
SD	Standard deviation
SGR	Specific Growth Rate
t	Cultivation period (days)
THQ	Target hazard quotient
W0	Initial fresh weight
WHO	World Health Organization
Wt	Final fresh weight

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ORIGINAL RESEARCH PAPER

Municipal solid waste bins distribution in urban environment using multi-criteria decision making methods

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ABSTRACT

BACKGROUND AND OBJECTIVES: Amman, Jordan's capital, has experienced rapid urbanization, exacerbating solid waste management challenges. It is apparent that the poor allocation of waste bins in Amman is not merely an operational inconvenience but also a pressing concern with substantial environmental, social, and economic ramifications for the city. The current study's objectives were to apply the analytic hierarchy process to compare alternative bin distributions based on environmental, social, and economic factors.

METHODS: The analytic hierarchy process was used to compare bin distribution alternatives based on environmental, social, and economic factors. Four options were compared: geographic information system-based optimization, smart bin technology using the internet of things, community-based distribution, and centralized and decentralized collection points. Ultimately, sensitivity analysis evaluated the resilience of the analytical hierarchy process model across various weight configurations.

FINDINGS: The results indicate the importance of accessibility, population density, and population health in waste management planning. The primary elements taken into account during the decision-making process included the social factor at 37.7 percent, the environmental factor at 35.5 percent, and the economic factor at 26.8 percent. Also, the analysis findings show that geographic information system-based optimization is the most viable strategy to ensure fair allocation and minimize environmental impacts and operating inefficiencies. The advanced waste bin serves as the second practical strategy, with a significant probability of enhancing collection through real-time monitoring. Conversely, other approaches, including community-based distribution and centralized collection, were found to be less viable and ineffective because of difficulties in implementation and acceptance.

CONCLUSION: The current study highlights the importance of combining geographic information systems and smart bin systems (Internet of Things) to achieve sustainable, economically viable, and socially inclusive waste management in Amman. This comprehensive approach facilitates the achievement of long-term urban planning goals and tackles operational, environmental, and community concerns. Amman can improve solid waste management by adopting scientific, data-driven methods to select waste bin sites.

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INTRODUCTION

Solid waste management (SWM) is a crucial environmental issue in cities, as urban areas generate substantial amounts of solid waste that are often disposed of in both terrestrial and aquatic dumping grounds. Municipal solid waste (MSW) generates multiple environmental, health-related, and social issues throughout the waste pickup, transfer, recycling, and disposal stages. The administration of significant waste quantities in various urban regions worldwide is still not meeting expectations, as the demand for municipal solid waste management services is on the rise (Abubakar *et al.,* 2022; Khan *et al.,* 2022; Apaydın, 2025). Effective management and disposal of solid waste are crucial to overall sustainability and global development. The appropriate disposal and recycling of solid waste are intended to minimize risks to human health, prevent environmental contamination, and reduce unnecessary land use (LU) (Waziri Otun, 2017; Ihsanullah *et al.,* 2022). A multi-criteria decision-making (MCDM) approach enables systematic analysis of various types and amounts of waste, facilitating optimal decision-making for efficient, reliable, and safe collection and disposal services. The amount and importance of waste generated are contingent upon the size of the population, the nature of economic activities, and the extent of recycling efforts. While efforts have been made to minimize waste through technological and regulatory means, waste is expected to remain a major concern worldwide, especially in developing regions where waste management efforts are inadequate and the current distribution systems are ineffective. The primary action in optimizing SWM is to correctly position waste disposal bins to enhance the efficiency of waste collection. Furthermore, the increasing number of dump sites is an unsuitable approach due to land scarcity and environmental constraints, necessitating effective strategies for locating waste bins that meet users' needs and reside in environmentally acceptable areas (Vinti and Vaccari, 2022). The allocation of waste bins can be analyzed from environmental, economic, and social viewpoints, yet a systematic methodology is necessary to pinpoint the most suitable location for waste bin installation that harmonizes these factors within a cohesive framework. Such an approach, combining relevant explicit objectives with significant and accepted trade-offs, moves beyond decisions based solely on intuition and experience, where the inherent advantages and costs of alternatives remain difficult to identify. The pursuit of a solution established on MCDM enhances the effective distribution of solid waste bins through the inclusion of multiple decision factors (Browning *et al.,* 2021; Kumari and Raghubanshi, 2023; Chattham *et al.,* 2025). Efforts to reduce solid waste have become a key element in sustainable urban development and environmental protection (Waziri Otun, 2017). The development of solid waste policies and the effective distribution of waste collection bins can be achieved through MCDM, which can tackle the complexity of waste management systems through multi-criteria analysis. MCDM methods have been employed to select and locate urban waste facilities, to maximize the efficiency and effectiveness of the collection routing, and to facilitate the distribution of urban solid waste collection and treatment systems. Various strategies, such as the analytic hierarchy process (AHP), the technique for order preference by similarity to ideal solution (TOPSIS), and Fuzzy Logic, have been applied in scholarly works to manage the complexities related to decision-making for the allocation of solid waste bins (Hanine *et al.,* 2017; Fang *et al.,* 2023). The literature review shows that multiple MCDM approaches, such as AHP, TOPSIS, and fuzzy logic-based models, have been used to address the solid waste management problem. Earlier applications of AHP and variants have been used for problems such as landfill site selection, waste collection route optimization, and assessment of waste treatment technologies (Apaydin, 2025).

Notwithstanding these advancements, there exists a clear deficiency in the literature, as only a limited number of studies have concentrated on the optimization of waste bin placement in urban settings, and to the author's knowledge, none have evaluated different bin-placement strategies within a city such as Amman. This is to say that the available literature typically compares methodologies individually, rather than comparing methods on a one-to-one basis across a set of similar factors. This paper fills this gap by applying the AHP to compare four municipal bin distribution systems in Amman. The distinctiveness of this work is found in the extensive range of alternatives examined: both conventional and novel methods are evaluated, and contemporary tools are incorporated into the decision-making process. Specifically, two innovative solutions, a geographic information system (GIS)-based optimal bin placement and an IoT-based Smart Bins, are incorporated in the list of options and compared to more traditional means of distribution. This research presents a one-of-a-kind comparative evaluation using GIS analysis and Smart Bin technology as decision options. This innovative approach enables us to establish the most effective bin distribution system in Amman and to evaluate new smart-city technologies against traditional methods. These methods enable stakeholders to consider multiple criteria, including cost, environmental impact, accessibility, and population density, to optimize the placement and allocation of waste bins in urban areas (Ayyildiz and Erdogan, 2024; Abdulhasan *et al.,* 2019; Fateh *et al.,* 2022). These methods enable a structured assessment of opposing criteria, thus promoting more informed and transparent decision-making. Recent studies have demonstrated the effectiveness of hybrid models combining AHP with other MCDM methods to enhance accuracy and reliability in solid waste bin distribution planning (Van Thanh, 2022; Zewdie and Yeshanew, 2023). Amman, the vibrant capital of Jordan, produces approximately 1.2 million metric tonnes of waste annually; nonetheless, this figure is steadily rising due to population growth, coupled with rapid urban development and city expansion accelerating (Abu Qdais *et al.,* 2019; Abu-Qdais *et al.,* 2023). Urban planning changes in the city have brought environmental management and urban sustainability to the forefront by examining population growth, irregular LU, public health concerns, economic influences, environmental processes, and resource management systems. The numerous components preserve harmonious interactions as an integrated system, and the measure of imbalance will perpetually reveal the strength of its weakest component. Amman's structure shows weaknesses in its MSW collection and management system. The unpredictable nature of these services, combined with inadequate urban infrastructure planning, leads the population to adopt new lifestyle habits, resulting in elevated waste production and poor decision-making quality in waste management, which in turn contributes to environmental deterioration (Bui *et al.,* 2023; Sharaf, 2023). A comprehensive understanding of the ongoing patterns of pollution growth among the relevant authorities is essential for achieving significant progress. This understanding will enable them to formulate effective preventive strategies that integrate educational waste-reduction initiatives with targeted treatment techniques prior to the execution of final waste-control measures (Chen *et al.,* 2024). The main aims of the current study are to conduct a thorough evaluation of Amman's solid waste bins distribution and to produce a comprehensive and sustainable SWM plan. The appraisal is significant in shaping sustainable planning initiatives that respond to waste-related environmental problems in metropolitan settings. The study aims to identify and prioritize the optimal solid waste bin distribution strategy for Amman using a multi-criteria AHP approach, and to provide a sustainable planning recommendation based on the findings. This study was conducted in Amman, Jordan, in 2025, for improved urban waste management.

MATERIALS AND METHODS

Solid waste generation in Amman/ study area

Amman has been growing in an irregular manner, typical of many large cities in the region. As people moved from surrounding rural areas to the capital to seek work and economic protection, slums and squatter areas emerged due to a lack of affordable housing and public services (Bataineh, 2022). As Jordan's urbanization rate has increased over the past 60 years (y), the SWM issue has become a significant problem requiring immediate attention. The great Amman municipality administration has responded to urban growth by expanding its area of authority (Al-Nawaiseh *et al.,* 2021; Abu-Ashour *et al.,* 2026). However, due to administrative constraints, it has not been able to meet the potential demand for housing, water and sewage systems, roads, energy, schools, and the solid waste infrastructure. Consequently, the absence of adequate SWM plans in Amman leads to ineffective and chaotic waste management practices, causing numerous areas of the city to be strewn with mixed waste and devoid of municipal waste collection services. For a country at Jordan's level of economic development, Amman generated more solid waste per capita than other cities with similar economic indicators (Abu Qdais *et al.,* 2019; Blagoeva *et al.,* 2023). According to Sarayrah *et al.,* (2024), 11 million Jordanians reside in the country, while 91 percent (%) of its population lives in urban areas. Landfills received 2,649,479 tons of waste in 2022 (Abu-Qdais *et al.,* 2023), which translates to an average of 0.81 kilograms per capita per day (kg/capita/d). Residential waste is collected and transported to landfills, where it is disposed of in accordance with the Jordanian SWM system. The municipality of Amman City alone generates approximately 3,000 tons of MSW daily, accounting for almost 50% of Jordan's overall waste production. The city is dealing with difficulties in waste management, causing ineffective collection and environmental challenges. The main issue arises from inefficient procedures combined with unidentified waste-generating sites.

Analytic hierarchy process

AHP is a measurement method that uses pairwise comparisons and expert judgments to construct priority scales. A specific collection of assessments constitutes the definitive scale for evaluating the extent to which one element influences another in relation to any specified attribute. According to Saaty (2008), AHP employs a well-established method to transform pairwise comparisons into numerical values that determine the priorities of the criteria. Each class is assigned a weight that varies from 10 to 100; these values are subsequently modified according to their weights during the matrix calculation. Table 1 represents the nine-point scale used to quantify pairwise importance. The numbers establish dominance levels between elements when assessing the specified criterion (Saaty, 2008). Utilizing the consistency ratio (CR) for comparing judgments is the final step in the AHP to assess consistency relative to completely random judgment samples. Judgments become unreliable when the CR exceeds 0.1, as such results indicate high randomness, rendering the exercise useless or requiring repetition (Tiba and Azevêdo, 2020). In order to perform an AHP analysis, the following steps are followed:

1. Pairwise comparison matrices:
   a) Constructing matrices for main criteria (for the current study: Environmental, Social, and Economic).
   b) Creating sub-criteria matrices under each main criterion.
   c) Assigning relative importance values using expert judgment.

2. Consistency check:

In order to check the consistency level, the following steps are followed using Eqs. 1 and 2 (Tiba and Azevêdo, 2020):

Table 1: The fundamental scale of absolute numbers for the applied factors (Saaty, 2008)

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
	Less important	←				→	More important	

a) λ_max (Principal Eigenvalue) calculated by multiplying the original matrix with the priority vector.
b) Consistency Index (CI) computed using Eq.1:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

c) CR is calculated using Eq.2:

$$CR = \frac{CI}{RCI} \quad (2)$$

where: RCI = random consistency index obtained from Table 1, and n is the number of attributes.
If CR < 0.1, then the judgments were consistent and valid.

3. Final ranking of sub-criteria:
   a) Global weights obtained by multiplying local sub-criteria weights with their respective main criteria weights.
   b) Final ranking determined based on the computed global weights.

Selecting the optimal locations for solid waste bins requires defining criteria based on environmental, social, and economic factors. These guidelines contribute to ensuring that the positioning of bins is efficient, accessible, and environmentally sustainable. The hierarchy of issues, as established for the current research, is represented in Fig. 1. This illustration includes three criteria, nine sub-criteria, and nine alternatives that will be analyzed through pairwise comparison analysis. A literature review on the decision-making applications of the AHP methodology in SWM informed the selection of both the criteria and sub-criteria used in the current study.

The selected criteria, sub-criteria, and alternatives are discussed below:

I. Environmental criteria

The following sub-criteria, included in the environmental criteria, are intended to help minimize adverse environmental impacts.

1) Land use and land cover (LULC)
   a) Avoid placing bins in protected areas, agricultural lands, and forest zones.
   b) Preferred locations are near urban residential and commercial zones.

2) Slope and elevation
   a) Avoid steep slopes (>10°) to prevent bin instability and collection difficulties.
   b) Preferably flat or gently sloping areas for easy access.

3) Soil type and permeability
   a) Choose areas with low permeability to prevent waste leachate infiltration into the soil.
   b) Avoid placing bins in areas prone to flooding.

II. Social criteria

The social criteria confirm that bins are available and recognized by the community. The following sub-criteria were identified for the social criteria.

1) Population density (PD)
   a) More bins should be placed in high-density residential and commercial areas.
   b) Threshold: Areas with more than 1,000 capital per square kilometers (capita/km^2), should have more frequent bin placement.

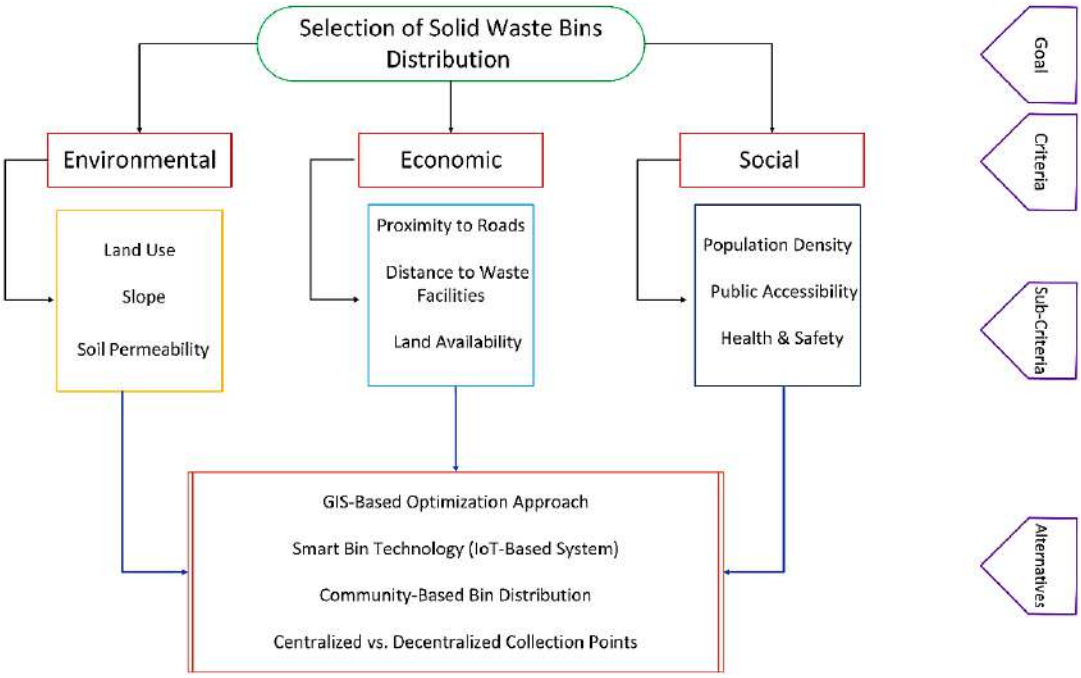

Fig. 1: Hierarchical structure for the selection of solid waste bin distribution

2) Public accessibility

a) Bins should be placed within 100-300 meters (m) of residential and commercial areas.
b) Avoid bins in highly congested pedestrian areas.

3) Health and safety considerations

a) Avoid placing bins too close to hospitals, schools, and food markets to reduce health risks.
b) Bins should be placed at least 50 m away from sensitive locations.

III. Economic and infrastructure criteria

The following sub-criteria are meant to ensure cost-effectiveness and operational efficiency.

1) Proximity to roads and collection routes

a) Bins should be within a distance of 30-50 m of roads for easy collection.
b) Prioritize locations along main roads and waste truck routes.

2) Distance to waste treatment facilities

a) The total transport distance to the landfill or recycling centers should be minimized.
b) Ideal transporting distance to be <10 kilometers (km) from treatment facilities.

3) Land availability and legal constraints

a) Ensure selected locations comply with municipal zoning regulations.
b) Avoid private property or restricted areas.

RESULTS AND DISCUSSION

The AHP pairwise comparison calculations are presented in supplementary material S1; the outcomes demonstrate that social criteria rank as the most important decision-making factor, followed by environmental criteria, and economic criteria rank third. As illustrated in Fig. 2, the outcomes of the AHP calculations reveal that the social factor is the most prominent, possessing an importance weight of 37.7%. The environmental factor ranks next with 35.5%, while the economic factor comes in at 26.8%. Thus, the evaluation process emphasizes social factors above all others, with environmental and economic factors following closely.

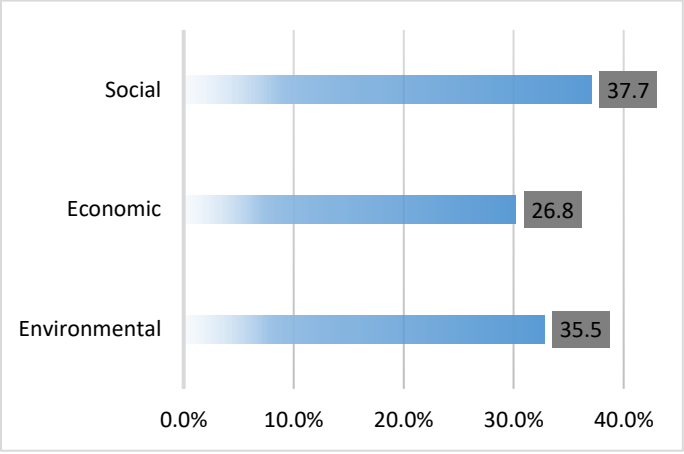

Fig. 2: Results of pairwise comparison for the solid waste bins selection criteria

Decision-makers consider that social criteria are most important in their decision-making process because they significantly influence project success and long-term sustainability. According to the newly established environmental criterion, decision-makers now prioritize environmental sustainability as their second most important consideration. Site selection and operational feasibility are guided by LU, as well as slope (SL) and soil permeability (SP). The economic criterion received a slightly lower rank than the others yet maintained its crucial position. The parameters that evaluate site location in relation to the distance from waste facilities, in conjunction with land availability and nearness to roads, affirm that economic feasibility is still a significant priority. Economic factors remain vital, but environmental and social standards also play a dual role in decision-making. The calculated CR for this part is 0.0086, indicating consistent results since CR < 0.1.

Selection sub-criteria weights

The AHP was applied to the decision-making framework structure based on feedback from a panel of experts with a profound understanding of municipal waste management issues. The panel team featured competent specialists, engineers, and experts from different municipalities, in addition to academic professionals specializing in solid waste management.

AHP pairwise comparison matrix for the Environmental sub-criteria:

According to the related literature and experts' opinions, the pairwise comparisons indicate that LU is more critical than SL, and SL is more critical than SP for the placement of solid waste bins. The assumed pairwise comparison scale is:

1. LU vs. SL → LU is 1.5× more important than SL
2. LU vs. SP → LU is 3× more important than SP
3. SL vs. SP → SL is 2× more important than SP

Table 2 shows the calculated derived weights for each selected sub-criterion. Based on the paired comparison matrix analysis shown in Table 2, the derived weights for the environmental sub-criteria are as follows: LU, 50.00%; SL, 33.33%; and SP, 16.67%. The results of the CR calculations are as follows: (the CR is calculated for the environmental sub-criteria, using the three values for the LU, SL, and SP)

- CI: ≈ 0.001
- Random index (RI) for n=3: 0.58
- CR: ≈ 0.001

Table 2: Paired comparison matrix for environmental sub-criteria

Criteria	LU	SL	SP	Derived weight[1]
LU	1	1.5	3	50.00%
SL	1/1.5	1	2	33.33%
SP	1/3	1/2	1	16.67%

[1]Calculations are represented in S1.

where CR ≈ 0, this indicates that the pairwise comparisons are highly consistent and reliable. Sustainable waste management relies on environmental criteria to minimize potential adverse environmental impacts. Evaluation of environmental sub-criteria based on the literature review and expert opinions suggested the following weight distribution:

The positioning of waste bins necessitates a thorough evaluation of appropriate sites, as it constitutes 50.00% of the outcome priority weight, which influences the safeguarding of protected areas, such as agricultural fields and urban green spaces. Placing waste bins in both commercial and residential zones optimizes waste-collection effectiveness and supports environmentally beneficial treatment. The choice of a suitable site on stable ground is assigned a (33.33%) priority because it ensures efficiency and safety during the collection activities. Waste collection operations and waste transportation become inefficient when waste bins are installed on slopes greater than 10˚ due to instability. The selection of areas with low soil permeability takes a priority weight of (16.67%), which is essential to stop leachate from seeping into deep soil and potentially reaching the near-groundwater resources. It is important to highlight that placing all facilities in locations that are not susceptible to flooding improves the environmental sustainability of the construction project.

AHP pairwise comparison matrix for the economic sub-criteria

Based on general economic considerations and experts' opinions:

- Proximity to roads (PR) is 2× more important than distance to waste facility (DWF)
- PR is 3× more important than land availability (LA)
- Distance to waste facilities is 1.5× more important than LA

Table 3 shows the derived weights calculated for the sub-criteria (PR, DWF, and LA). Based on the paired comparison matrix analysis of the economic criteria presented in Table 3, the derived weights for the economic sub-criteria are: PR, 54.55%; DWF, 27.27%; and LA, 18.18%.

CR calculation

- CI: ≈ 0.001
- RI for n=3: 0.58
- CR: ≈ 0.001

where: CR ≈ 0, since CR is < 0.1, it indicates that the pairwise comparisons are highly consistent, and the judgments are reliable.

Economic considerations focus on securing the highest value for money via compatible infrastructure that ensures durable and efficient operations. Operational costs depend heavily on how easily waste collection trucks can reach the bins (PR, 54.55%). Places situated along main roads reduce costs related to fuel and personnel while speeding up collection operations. A decrease in the DWF results in lower logistical expenses and enhances waste management efficiency (DWF, 27.27%). Treatment facilities should be located within 10 km of the bins' location. The placement of waste bins must adhere to municipal zoning laws and the available public space in order to mitigate legal complications and enhance land utilization (LA, 18.18%).

Table 3: Paired comparison matrix for economic sub-criteria

Criteria	PR	DWF	LA	Derived weight
PR	1	2	3	54.55%
DWF	1/2	1	1.5	27.27%
LA	1/3	1/1.5	1	18.18%

Table 4: Paired comparison matrix for social sub-criteria

Criteria	PD	PA	HS	Derived weight
PD	1	2	3	54.55%
PA	1/2	1	1.5	27.27%
HS	1/3	1/1.5	1	18.18%

AHP pairwise comparison matrix for the social sub-criteria

Based on general social impact considerations, literature review, and experts' opinions:

- PD is 2× more important than Public Accessibility (PA)
- PD is 3× more important than Health & Safety (HS)
- PA is 1.5× more important than HS

Based on the paired comparison matrix analysis for the social criteria as represented in Table 4, the derived weights for social sub-criteria are: PD: 54.55%, PA: 27.27%, and HS: 18.18%.

CR calculation

- CI: ≈ 0.001
- RI for n=3: 0.58
- CR: ≈ 0.001

For one more time, this criterion resulted in a CR ≈ 0.001, meaning that the pairwise comparisons are highly consistent, and the judgments are reliable. Social considerations dictate the criteria for positioning waste bins in locations that are easily accessible to individuals and secure for community members to accept. The weight values for sub-criteria consist of the following breakdown:

The PD, with a priority weight of 54.55% determines that high-density settlements produce more waste, therefore requiring regular bin deployments. The distribution of waste bins begins in areas with a PD exceeding 1,000 capita/km^2. Conversely, PA holds a priority weight of 27.27%, since appropriate bin placement within 100-300 m of residential and commercial areas leads to increased compliance rates. Last but not least, the placement of bins should maintain a minimum distance of approximately 50 m from healthcare facilities, educational institutions, and food market sites to ensure health protection and reduce nuisance odors (HS, 18.18%). Fig. 3 summarizes the resulting weights of sub-criteria under environmental, economic, and social criteria.

Solid waste bin distribution alternatives

The current study examined four bin distribution alternatives according to environmental, social, and economic criteria. The AHP decision alternatives were formulated as four potential bin distribution strategies, taking into account both the current and prospective improvements to Amman's waste collection system. Every option was analyzed across the entire range of requirements and sub-requirements within the AHP model. Under each sub-criterion, the expert panel rated the performance of each alternative against the others (either in direct pairwise comparisons or by rating the alternatives on the factor which were then converted into pairwise comparisons). In this process, the AHP used the judgments of the experts to provide a priority score of all



Fig. 3: The resulting weights of the sub-criteria of environmental, economic, and social criteria

alternatives, which implied overall suitability. An evaluation of these alternative solutions was conducted based on their relative effectiveness, which provided crucial insights into their strengths and weaknesses in the context of waste management in Amman.

The four alternatives assessed are:

1. GIS-based optimization approach: A GIS analysis optimizes urban infrastructure through its ability to precisely position waste collection bins and boost efficiency within the system.
2. Smart bin technology (Internet of Things (IoT)-based system): This technology employs IoT sensors for the surveillance of waste containers, which facilitates the automatic optimization of waste level monitoring and the scheduling of waste collection.
3. Community-based bin distribution: This distribution approach involves public participation in selecting waste bin locations, enhancing both waste segregation practices and recycling activities while fostering adoption.
4. Centralized vs. decentralized collection points: This study explores the manner in which strategic waste collection points allocate waste bins, particularly emphasizing the choice between situating large containers at business centers (centralized collection points) versus installing multiple smaller waste bins throughout residential neighborhoods for convenience purposes (decentralized collection points). The Environmental criterion plays a vital role in making essential decisions aimed at reducing ecological stress during the waste management process by pinpointing the best site locations to prevent contamination, flooding, and land degradation. As presented in Table 5, the site selection process through GIS-based optimization ranks as the best option, with a 34.0% approval rate, as it assesses LU in combination with SL and SP. Identifying appropriate site locations serves two functions: it minimizes damage to land areas, prevents container overflow in densely populated areas, and optimizes collection trips by reducing the need for collection vehicle movements, thereby decreasing carbon dioxide (CO_2) emissions. The sensor-based Smart Bin Technology monitoring system ranks as the second-best option, with a 33.2% approval rate, because it prevents waste overflow and ensures a proper waste collection schedule. The environmental ranking of community-based distribution falls to third favorite, with a 23.9% approval rate, because it relies on public choice rather than scientifically determined site suitability. Expertise in the domain aids in guaranteeing appropriate bin placement; nevertheless, if implemented without care, this choice could lead to sites that might present environmental hazards. Community involvement through this method leads to better waste disposal behavior because it engages people in the process. energy efficiency ranked centralized vs. decentralized collection points

Table 5: Priority weights of different alternatives under the environmental criterion

Alternative	Weight	Rank
GIS-based optimization approach	34.0%	1
Smart bin technology (IoT-based system)	33.2%	2
Community-based bin distribution	23.9%	3
Centralized vs. decentralized collection points	8.8%	4

(8.8%) rank last because this waste management system focuses waste deposits in designated areas, leading to worries about soil and air pollution at those locations. This method of waste management faces challenges in gathering waste throughout the urban region and necessitates the use of larger collection vehicles, which in turn elevates fuel consumption and contributes to air pollution. Table 5 summarizes the priority weights of alternatives under the environmental criterion. The Social criterion measures population density coverage, accessibility, public health, and safety considerations. Public convenience, along with equity and community well-being, is the primary factor in selecting solutions. Table 6 illustrates the position of each alternative according to the social criterion. Within the social criterion, as presented in Table 6, the implementation of GIS-Based Optimization (with a 48.1% weight) stands out as the top choice, as it enables optimized waste bin placement near densely populated areas and convenient paths for users. The placement system allows decision-makers to avoid locating waste-disposal sites in proximity to essential facilities, including hospitals and schools, which are vital for safeguarding public health. The data-driven procedure leads to a fair waste management system that operates efficiently to benefit all members of the urban population. Although smart bin technology (with a 22.0% weight) ranks second most preferred, this system might fail to distribute bins equally across various community sectors. The success of this system's installation depends on selecting suitable installation areas. The community-based distribution, at 16.8% weight, ranks third, possibly due to insufficient public participation to achieve ideal placements. Community involvement generally results in enhanced local engagement; nevertheless, this strategy does not employ scientific techniques to guarantee broad accessibility. Different areas of the community tend to favor certain zones, leading to inefficient waste bin distribution. The lowest-ranking impact category is centralized vs. decentralized collection points, at 13.1%, because residents face challenges when access points are far from their homes. The waste disposal system operates effectively in commercial zones; however, it does not sufficiently meet the needs of residential neighborhoods, where residents necessitate prompt, on-site access to disposal facilities. The economic criterion assesses waste management solutions based on three main factors: the costs of installation and operations as well as the sustainability of long-term financial operations. Table 7 presents the priority weights for the different alternatives under the Economic criterion. As presented in Table 7 the GIS-Based Optimization at 29.3% weight stands as the top choice because its setup expenses may initially be high, but it generates lasting financial benefits through waste collection route optimization that reduces fuel usage. The system minimizes the necessity for supplementary waste collection containers and streamlines waste collection by means of design. Under economic criteria, Smart Bin Technology (IoT-Based System) also share the first position with a weight of 29.3% same as the GIS-Based Optimization option. The introduction of IoT sensors for smart bin setups demands an

Table 6: Priority weights of different alternatives under Social criterion

Alternative	Weight	Rank
GIS-based optimization approach	48.1%	1
Smart bin technology (IoT-based system)	22.0%	2
Community-based bin distribution	16.8%	3
Centralized vs. decentralized collection points	13.1%	4

Table 7: Priority weights of different alternatives under the Economic criterion

Alternative	Weight	Rank
GIS-based optimization approach	29.3%	1
Smart bin technology (IoT-based system)	29.3%	1
Community-based bin distribution	20.7%	2
Centralized vs. decentralized collection points	20.7%	2

initial financial outlay, yet it allows for cost reductions by decreasing superfluous collection operations. This approach provides long-term savings in fuel, labor, and maintenance costs, making it a sustainable financial investment. Community-Based Distribution (with 20.7% weight) ranks second. This solution is affordable because it does not require advanced technology or GIS tools for implementation. Inadequate positioning of waste bins along collection routes may lead to higher operational costs in subsequent periods. The proportion of respondents favoring Centralized versus Decentralized Collection Points, which carries a weight of 20.7%, was tied for second place, alongside unclear financial outcomes. Global waste storage structures reduce collection costs but increase waste management and maintenance expenses due to the accumulation of waste. The use of spread-out, decentralized bins increases collection expenses because they necessitate more frequent pickups. The evaluation system assigns GIS-Based Optimization the top position because it outperforms other methods in waste location selection and operational efficiency while minimizing costs (Belete *et al.,* 2024). The technique offers the most sustainable solution for managing urban waste in Amman. Smart Bin Technology also stands out in environmental and economic terms, making it a promising tool for smart urban development. The implementation of this system necessitates significant capital investments to facilitate widespread adoption. The ranking of community-based distribution is less preferable and less reliable compared to the first two options, as essential decision-making should not usually be replaced by public participation in operations. Utilizing GIS-based planning with community participation can improve public acceptance. This principle also holds true for the Centralized versus Decentralized Collection Points, which are rated equally low as the Community-Based Distribution. Thus, it is evident that Amman requires innovative, sustainable, and reliable alternatives for solid waste management, given its growing waste issues. The results of the AHP evaluation demonstrate that Amman requires a GIS-based optimization approach, along with Smart Bin Technology, to improve its solid waste bin distribution and waste collection performance. Future waste management strategies that incorporate GIS-based site selection along with Smart Bin Technology will enhance operational efficiency and sustainability, ensuring that Amman's waste system remains compatible with urban growth and environmental requirements.

Sensitivity analysis

To examine the strength of the AHP results, a sensitivity analysis has been performed by changing the weights of the primary criteria and

how it affected the ranking of the bin distribution strategies. The assessment indicated that the overall ranking remains consistent even with moderate alterations in weight; however, significant shifts in priorities could alter the preferred method. As an example, with the Economic criterion weight increased twice (0.20) to 0.40 (modeling a situation where cost considerations are as significant as all the other factors added), the overall priority of the Smart Bins strategy decreased by about 15%. In evaluating cost-weight, the Smart Bins option has been relegated in priority, as a more economical method, namely the Population Proportional Distribution, has been placed higher on the list. On the other hand, increasing the Environmental criterion weight by 25 percent (i.e., from 0.40 to 0.50 of the total) improved the Smart Bins option's performance, placing it almost in the same rank as the GIS-Optimized Distribution. If the Environmental weight increased by more than 0.60 (50% above the initial value), the Smart Bins strategy ranked highest. The conclusions drawn from these analyses reveal the moment at which the Smart Bins solution is preferred: when decision-makers view environmental outcomes as 1.5 times more critical than the baseline scenario. In practice, this would imply that when a policy that pays close attention to environmental protection is implemented, e.g., a drastic decrease in carbon prices or a severe anti-pollution policy, the Smart Bin integration would be the optimal option, despite its cost. Conversely, the Smart Bins strategy would forfeit its highly sought-after appeal solely if an undue focus were placed on economic considerations. This sensitivity analysis validates that the suggested approach (GIS optimization in the base scenario) has a strong foundation and also shows under what circumstances a Smart Bin system might be the best solution for waste management in Amman.

Impact of criteria weight adjustments

Multiple scenarios were evaluated by varying the weights of the Environmental, Social, and Economic criteria within reasonable pairwise comparison parameters. The dynamic sensitivity graphs in Fig. 4 show the alternative rankings that result when criterion weights are modified. In the foundational AHP calculations, social factors were assigned a priority of 37.7%, above Environmental factors at 35.5%, and economic elements at 26.8%. Under these circumstances, the GIS-Based Optimization system achieved the top position in all previously discussed criteria.

Scenario 1: Increased weight on environmental factors

The ranking of smart bin technology closer to GIS-based optimization occurred when environmental criteria received significant weight increases, exceeding 40%. Environmental elements facilitate technological solutions for waste management, which improve the effectiveness of waste recovery while promoting environmental conservation.

Scenario 2: Increased weight on social factors

GIS-Based Optimization maintained its dominance as the leading waste management solution when social criteria exceeded 45%, as it strengthens both public access and balanced waste collection patterns across the area. The community-based bin distribution social engagement strategy exhibited certain enhancements, indicating its promise as a sustainable solution when public acceptance is emphasized.

Scenario 3: Increased weight on economic factors

The combination of an increased economic criteria weight (above 35%) resulted in equal placement for smart bin technology and GIS-based optimization, as sensor-based waste management

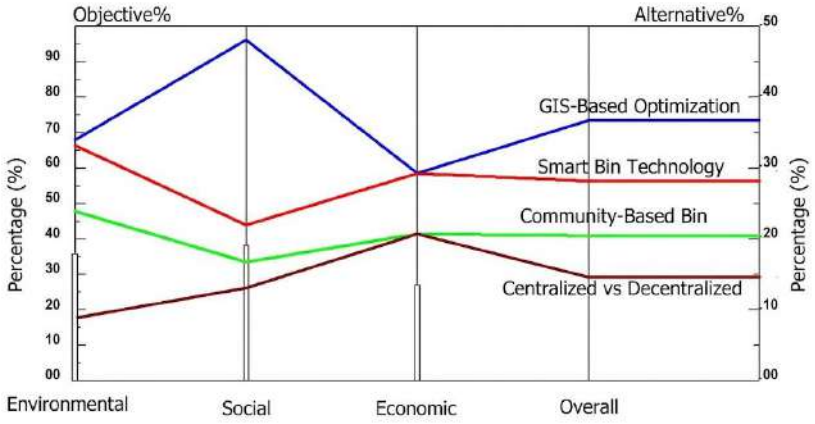

Fig. 4: Dynamic sensitivity graph of the studied criteria and alternatives

systems proved financially efficient. The financial benefits of advanced waste management technologies render them more appealing to industry operators.

Stability of alternative rankings

Every sensitivity-tested scenario confirmed that the GIS-based optimization solution demonstrated the greatest stability and was the optimal choice. The ranking solution preserved a steady position during the weight evaluations of distinct performance factors, consequently illustrating the widespread benefits of data-based waste-bin distribution. Smart bin technology demonstrated outstanding results, placing first (alongside GIS-Based Distribution) when economic considerations and environmental needs became essential factors, proving that technology-based waste management delivers both long-term savings and sustainability advantages. Community-oriented distribution exhibited better results in social-case situations, illustrating how public participation improves waste management systems, even though it is less effective than other methods on their own. The placement of waste bins at centralized points rather than decentralized ones was the least preferred collection method among the suggested methods, regardless of how the weight was shifted, indicating that standard waste bin placement needs improvement for sustainable city waste management practices.

Implications for decision-making

The sensitivity analysis demonstrated that optimization based on GIS results in the most reliable waste bin distribution system, consistently securing its top position in all evaluated scenarios. Smart Bin Technology demonstrates its value as an attractive solution for operational and environmental effectiveness. The integration of GIS-based site selection and real-time smart bin monitoring (IoT bins) represents the most effective solution for waste management systems, combining sustainability improvements with public access convenience and cost-efficiency (Srikanth *et al.,* 2019; Hayat *et al.,* 2023).

CONCLUSION

The current research employed AHP to assess the placement of solid waste bins throughout Amman city (Jordan) in terms of environmental sustainability, alongside social and financial implications. Social elements have emerged as the foremost determinants in the decision-making process, highlighting the significance of public

accessibility, in addition to density and safety standards. The second most important ranking identified the environmental considerations, highlighting the need for strategic waste bin placement to protect natural ecosystems and decrease environmental impact. The economic aspects played a crucial role in determining the financial feasibility of waste management decisions, as localities selected waste facilities based on their accessibility to roads and other infrastructure. On the other hand, evaluating different collection scenarios revealed that GIS-based optimization proved to be the most effective solution, leveraging spatial and infrastructural parameters to conduct data-driven location optimization of waste bins. Smart bin technology has reached a status that is nearly equivalent to GIS-based optimization. Smart bin technology shows promise in optimizing operational efficiency through automated waste collection, supported by real-time monitoring. Public engagement is important, yet the analysis performed is secondary to scientific decision-making, given that community-based distribution and centralized versus decentralized collection points received the lowest rankings. Sensitivity analysis under the AHP model evaluated the robustness of GIS-based optimization, which consistently ranked highest across different weight changes, substantiating its status as Amman's most suitable waste management approach. The findings highlight the importance of institutionalizing GIS-based spatial planning within municipal operations as a routine decision-support tool. This requires periodic updating of spatial and demographic datasets, cross-departmental coordination, and integration with existing collection routes to ensure sustained accuracy and efficiency. The implementation of smart bin deployment ought to occur in phased stages that correspond with municipal budgeting cycles, along with training for technical personnel in GIS and IoT data management systems. From a governance perspective, successful implementation depends on clear institutional responsibilities within the Greater Amman Municipality, regulatory support for digital infrastructure integration, and continuous public awareness initiatives to enhance community acceptance and behavioral compliance. Rather than presenting a purely technical optimization model, this study provides a structured, actionable planning framework that supports evidence-based municipal decision-making and long-term, sustainable urban waste management.

AUTHOR CONTRIBUTION

R.M.Z. Alqaralleh conceived, designed, and conducted the experiment, as well as overseeing sample collection and analytical measurements, and preparing the manuscript draft.

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CONFLICT OF INTEREST

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

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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

%	Percentage
°	Degree
λ_max	Principal Eigenvalue
AHP	Analytic hierarchy process
capita/km²	Capita per square kilometers
CI	Consistency index
CR	Consistency ratio
DWF	Distance to waste facilities
GIS	Geographic information system
HS	Health and safety
IoT	Internet of things
kg/capita/d	Kilograms per capita per day
km	Kilometer
LA	Land availability
LU	Land use
LULC	Land use and land cover
m	Meters
MCDM	Multi-criteria decision making
MSW	Municipal solid waste
n	Number of attributes
PA	Public accessibility
PD	Population density
PR	Proximity to roads
RCI	Random consistency index
RI	Random index
S1	Supplementary material
SL	Slope
SP	Soil permeability
SWM	Solid waste management
TOPSIS	Technique for order preference by similarity to ideal solution
y	Years

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ORIGINAL RESEARCH PAPER

Behavioral determinants of pesticide use compliance among Allium fistulosum farmers

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ABSTRACT

BACKGROUND AND OBJECTIVES: Allium fistulosum (welsh onion) constitute a flagship agricultural product of Cibeureum Village Sukanagalih, Pacet District, Cianjur Regency, West Java, Indonesia. The presence of pests compels farmers to apply high quantities of pesticides, which poses numerous health hazards and environmental consequences. It is essential to alter these practices to motivate farmers to embrace sustainable pesticide use. The study objectives were to determine Allium fistulosum farmers' knowledge, attitude, behavior, and their correlation regarding pesticide use; and identifies insecticide types, active ingredients, and residues in Allium fistulosum from Cibeureum Village, Indonesia.

METHODS: In this cross-sectional study, interviews, questionnaire, and field observation were conducted on 35 Allium fistulosum farmers in Cibeureum Village; and high-performance liquid chromatography-tandem mass spectrometry was used to detect Allium fistulosum insecticide residues

FINDINGS: The study revealed that Allium fistulosum farmers applied excessive doses of insecticide; accordingly, 0.008 milligrams emamectin benzoate residues per 1 kilogram of plant sample were found. A significant number of farmers were well-versed in the dangers posed by hazardous substances in pesticides and the necessity of utilizing personal protective equipment. This resulted in a conscientious approach to pesticide usage, including the purchase of pesticides with explicit labels from licensed retailers, refraining from other activities and donning masks during application, and subsequently ensuring personal hygiene and storing pesticides in distinct rooms post-application. Nevertheless, the correlation between knowledge and attitude is 0.486 (moderate), as well as between attitude and behavior is 0.471 (moderate). In practical application, the pesticide dosage used by farmers often does not comply with the recommended levels.

CONCLUSION: Farmers with responsible pesticide-use knowledge cannot definitively reflect their attitude and behavior regarding the safe use of pesticides. The practice of responsible pesticide use among farmers has been influenced by their experiences, leading to the formation of inherited agricultural practices and a habit that is socially patterned. This led to misconceptions that higher dosages of pesticides could increase agricultural productivity. In the actual condition, the accumulation of emamectin benzoate residue were found on Allium fistulosum. Therefore, it is essential for improving farmers' pesticide-use knowledge, attitude, and behavior, followed by policy that could improve farmers welfare.

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42	6	9

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INTRODUCTION

Allium fistulosum, commonly known as welsh onion, is a leading horticultural commodity, with growing market demand. Various nutritional, health, and culinary benefits make *A. fistulosum* highly sought after by the public and widely cultivated in East Asia and Southeast Asia, including Siberia, China, Japan, the Republic of Korea, Vietnam, Philippines, Malaysia, and Indonesia (Kim *et al.*, 2023). *A. fistulosum* production in Cianjur Regency, West Java, Indonesia increased from 281,942 quintal (q) in 2018 to 289,467 q in 2019, 318,505 q in 2020, and 415,210 q in 2021 (Statistik, 2020; Statistik, 2022). Even with the economic advantages, farmers are confronted with the risk of crop loss due to armyworm (*Spodoptera exigua*) invasions, which became evident on the seventh days after planting (dap). *S.exigua* life cycles from laying eggs to adult stages are influenced by climate change, rainfall, air quality, and light (Supartha *et al.*, 2022). Many farmers are largely dependent on pesticides, frequently using them in an uncontrolled manner and possessing insufficient understanding of the risks involved with pesticide use (Mehmood *et al.*, 2025). This practice is found in Cibeureum Village, Pacet District, Cianjur Regency, West Java, Indonesia; most farmers applied excessive dosage of insecticides, namely more than three times per vegetable planting cycle (Noriko *et al.*, 2023). Farmers are utilizing an excessive amount of pesticides to combat insect and non-insect pests, including fungi, weeds, rodents, and plant diseases that cause crop loss. Inappropriate use of pesticides has threatened humans, animals, non-target plants, and the environment (Ahmad *et al.*, 2024). Pesticide disrupts the physiological functions of the body's organs and concurrently poses a threat to the environment when residues are absorbed by the soil, transported by water, and dispersed by wind (Riyaz *et al.*, 2022). Therefore, the maximum residue limit (MRL) has been established for food safety standard, particularly for agricultural products (Zhang, 2025). Pesticide exposure may occur directly during application in the workplace or indirectly from contaminated food and water, increasing the long-term risks of respiratory disorders and genetic changes (Shekhar *et al.*, 2024). Pesticide short-term exposure causing dermal irritation, sore eyes, dizziness, nausea, and diarrhea. The lack of public attention to the symptoms emphasizes the critical need to improve farmers' knowledge, attitudes, and behaviors related to pesticide application. Farmers' knowledge influences their environmental awareness through their attitude and behavior (Sabran and Abas, 2021). Knowledge is correlated with farmers' comprehension regarding pesticide hazardous substances and application, therefore mitigating environmental pollution and decreasing public health risks (Oshingbade *et al.*, 2025; Rashid *et al.*, 2026). Consequently, a positive correlation exists between farmers' knowledge, attitudes, and behaviors regarding the sustainable use of pesticide. Previous studies have observed the correlation between farmers' knowledge, attitude, and behavior/practice in general using questionnaire, but it is limited to investigate the factors influencing their practice, e.g., from Shahidullah *et al.* (2023) and Karki *et al.* (2025). The difference and uniqueness of this study compared to the previous studies is focused on farmers who cultivate *A. fistulosum* in villages which become the distribution centres of horticultural products and the pesticide residue analysis in *A. fistulosum*. The leaves of this plant are utilized in almost daily dishes, leading to worries about the buildup of pesticide residues that are often applied by farmers. This study measured the knowledge, attitudes, and behavior of pesticide use through a questionnaire referring to Article 75 of Law of the Republic of Indonesia Number 22 of 2019, which regulates 'Sustainable Agricultural Cultivation Systems'; and Government Regulation of the Republic of Indonesia Number 6 of 1995 concerning 'Plant Protection'. This study evaluated the correlation

coefficient between different variables to examine the elements that affect farmers' behaviors regarding pesticide use. The analysis was not only based on the results of questionnaires and interviews, but also through the field observations to confirm the actual behaviour/practices of farmers. To verify the effects of pesticide application on *A. fistulosum*, an analysis of pesticide residues was performed on the plants. According to the outlined issues, a study is required to determine *A. fistulosum* farmers' knowledge, attitude, behavior, and their correlation regarding their pesticide use. Furthermore, the residue analysis was performed on the *A. fistulosum* plant, focusing on the type of pesticide utilized to substantiate the empirical evidence regarding the excessive pesticide use by farmers. The study findings are expected to provide safe pesticide practices for farmers, consumers, and the environment through the implementation of responsible pesticide use behavior. The findings can be used as policy recommendation for sustainable agriculture. This study was conducted in Cibeureum Village Sukanagalih, Pacet District, Cianjur Regency, West Java, Indonesia in 2023.

MATERIALS AND METHODS

The study area and data collection

The study was carried out involving the complete population (N) of *A. fistulosum* farmers operating in Cibeureum Village Sukanagalih, specifically 37 farmers (Fig. 1). This amount of study population represents the farmers in other Village around the study area due to similar tendency in using pesticide, therefore, it is potentially to generalize. The study respondent (n) was determined using the Eq. 1 (Karki *et al.*, 2025):

$$n = \frac{\mathrm{N}}{1+\mathrm{N}(e^2)} \quad (1)$$

where, N represent the population using the 0.05 or 5 percent (%) margin of errors (e). The total of 35 individuals were selected as a sample along with several inclusion criteria, e.g., farmers who consented to participate as respondents, resident lived in Cibeureum Village Sukanagalih, owned or managed land in Cibeureum Village Sukanagalih, and were active or former *A. fistulosum* growers. The two remaining farmers are not included as they fail to meet one of the criteria for inclusion, namely, residency in Cibeureum Village Sukanagalih. This cross-sectional quantitative study used primary data from farmers' interviews and a questionnaire, the secondary data from a literature study. Socio-demographic variables including farmers' age, education, experience, farm size, and training were observed as contributing factors. This study is confined to investigating the relationship between knowledge of pesticide use and behavior; knowledge and attitude; as well as the relationship between attitudes and behaviors. The data was collected to understand the factors contributing to the existing condition without examine the pre and post intervention (for instance, measured farmers' pesticide-use knowledge after participating in workshop). Data consistency was verified through field observation for all farmers, particularly for farmers' pesticide-use behavior and laboratory analysis for emamectin benzoate residue detection in *A. fistulosum*. During the questionnaire completion by farmers, each valid question is explained by researcher to prevent misinterpretation and the results are confirmed to the farmers. The alignment between the outcomes of farmers' questionnaires and their pesticide-use practices was analyzed through field observations conducted without any interference. Along with the inclusion criteria as part of purposive sampling, these aims to ensuring the research accuracy. In this study, all respondents participation was voluntary without intervention and their name or private information is treated confidentially. In Table 1, each questionnaire item was assigned a five-point Likert scale. *A. fistulosum* plant and flowers in Cibeureum Village are presented in Fig. 2.

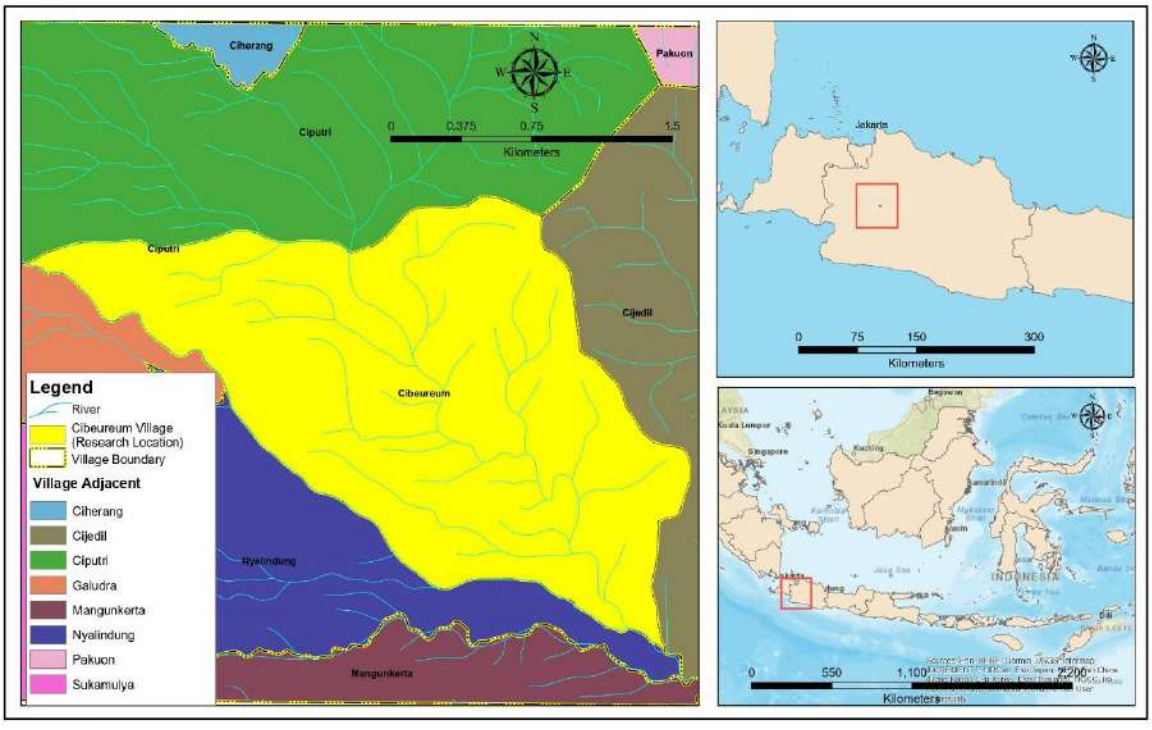


Fig. 1: Geographical location of the study area in Cibeureum Village Sukanagalih, Pacet District, Cianjur Regency, West Java, Indonesia



(a) *(b)*

Fig. 2: (a) *Allium fistulosum* plant (A. Flowers; B. Leaves; C. Pseudostem; D. Roots) (b) Flowers of *Allium fistulosum*

Table 1: Likert-scale scoring

Likert-scale description		
Knowledge	Attitude	Behavior
Highly knowledgeable (HK)	Strongly agree (SAG)	Always (A)
Knowledgeable (K)	Agree (AG)	Often (O)
Moderately knowledgeable (MK)	Neutral (NT)	Occasionally (OC)
Poorly knowledgeable (PK)	Disagree (D)	Rarely (R)
Not knowledgeable at all (NK)	Strongly disagree (SD)	Never (NV)

Table 2: Respondent achievement categories (Zen *et al*., 2022)

No.	RAL percentage	Category
1	85% – 100%	Excellent
2	66% – 84%	Good
3	51% – 65%	Fair
4	36% – 50%	Poor
5	0% – 35%	Very Poor

The Likert-scale for each respondent was calculated as the respondent's achievement level (RAL) to assess comprehension of each questionnaire item, using Eq. 2 (Rahmawati et al., 2023): Subsequently, the results were categorized based on the RAL percentage (Table 2).

$$RAL = \frac{\text{average score} \times 100\%}{\text{maximum score}} \quad (2)$$

Sampling and testing

The whole *A. fistulosum* plant, including roots, was collected using a simple random sampling method by collected 1 kilogram (kg), respectively, from 6 point in 3 different elevations on hillslopes with a 40% gradient. Samples 1-2 were taken from the highest slope with ±15 meters (m); samples 3-4 from the middle slope (±7-8 m); and samples 5-6 from the lowest slope (0 m). This sampling procedure was executed as a cross-sectional study, with *A. fistulosum* samples being collected throughout the harvest period. According to the pests infestation of armyworms and thrips in *A. fistulosum*, farmers only used insecticide containing emamectin benzoate. The pesticide residue analysis conducted in the accredited laboratory with ISO/IEC 17025:2017 quality system at Direktorat Jenderal Tanaman Pangan: Balai Pengujian Mutu Produk Tanaman, located in Jl. Aup No.3, RT.9/RW.10, Pasar Minggu, South Jakarta. The detection of emamectin benzoate residue in *A. fistulosum* conducted using Quick, Easy, Cheap, Effective, Rugged and Safe (QuEChERS) method; clean-up; and high performance liquid chromatography-mass spectrometry (HPLC-MS/MS). During the sample analysis, each sample of *A. fistulosum* has double replications. The 15 grams (g) of homogeneous samples were extracted using 15 milliliters (mL) acetonitrile, then salt and extractive buffer were added, and the mixture was homogenized and centrifuged. Sample clean-up was conducted using dispersive solid phase extraction (d-SPE) with Primary secondary amine (PSA) 400 milligrams (mg), C18 400 mg, magnesium sulphate ($MgSO_4$) 1200 mg. The sample extract was subjected to evaporation using nitrogen (N_2) at a temperature of 30 degrees Celsius (°C), subsequently reconstituted with acetonitrile and 0.15% formic acid, and the resulting mixture was filtered prior to analysis. The quantitative analysis were conducted using HPLC-MS/MS in Ethylene Bridged Hybrid C18 (BEH C18) column 2.1 centimeters (cm) × 100 millimeters (mm) × 1.7 micrometer (µm), 0.1% formic acid for water mobile phase and acetonitrile with gradient elution system, column temprature (40°C), and 10 microlitre (µL) injection volume. The quatification was performed utilizing external standard calibration, while the quality assurance assessment was carried out through 'blank' analysis and spike sample (recovery test). The obtained test results were analyzed in accordance with Regulation of the National Food Agency of the Republic of Indonesia Number 15 of 2024, which regulates "The maximum residue limits of pesticide in fresh food products of plant origin". The other regulation is following Codex Alimentarius of The Food and Agriculture Organization (FAO) and The World Health Organization (WHO) regarding emamectin benzoate maximum residue limits (FAO and WHO, 2023).

Questionnaire items validity and realibility

Questionnaire items were designed based on the guidelines in Article 75 of Law of the Republic of Indonesia Number 22 of 2019, which regulates "Sustainable Agricultural Cultivation Systems"; and Government Regulation of the Republic of Indonesia Number 6 of 1995 concerning "Plant Protection". Prior to the data collection, a validity test for the statistics was performed on 21 questionnaire items that had been trialed with

farmers. Along with a validity criterion of Pearson correlation coefficient (r) $r_{count} > r_{table}$ and Significance (Sig.) (2-tailed) < 0.05, the total of 16 questionnaire items is valid, and 5 items are replaced since not valid. The validity test was conducted again with farmers, resulting in 19 valid questionnaire items. These items comprise include 5 for assessing knowledge, 6 for evaluating attitude, and 8 for analyzing the behavior of *A. fistulosum* farmers concerning pesticide use. Furthermore, a reliability test was conducted on these valid questionnaire items using Cronbach's Alpha coefficient (Cronbach's Alpha value > 0.60). According to the reliability test results, all questionnaire items are reliable for measuring farmers' knowledge, attitude, and behavior; Therefore, questionnaire completion by farmers can be implemented.

Data analysis

The questionnaire data undergo analysis using SPSS Statistics. The collected questionnaire data will analyzed using univariate and bivariate analysis. The univariate analysis describes *A. fistulosum* farmers' knowledge, attitude, and behavior in using pesticide, whereas their questionnaire score results are distributed based on the RAL's percentage. Furthermore, the results obtained will undergo processing for subsequent analysis through bivariate analysis to investigate the correlation between two variables. According to the scales of measurement, this study has nominal data. Therefore, 2 × 2 cross-tabulation analysis and the Fisher's exact test were conducted to reveal the correlation between variables with 95% confidence interval (CI) and $p < 0.05$. The Fisher's exact test was applied to the entire population of *A. fistulosum* farmers in Cibeureum Village, considering a sample size ranging from 20 to 40, with an expected count < 5 in 2 × 2 cross-tabulation. The correlation coefficient obtained were interpreted into five correlation levels, i.e., 0.00 to 0.199 (very low); 0.20 to 0.399 (low); 0.40 to 0.599 (moderate); 0.60 to 0.799 (strong); and 0.80 to 0.100 (very strong).

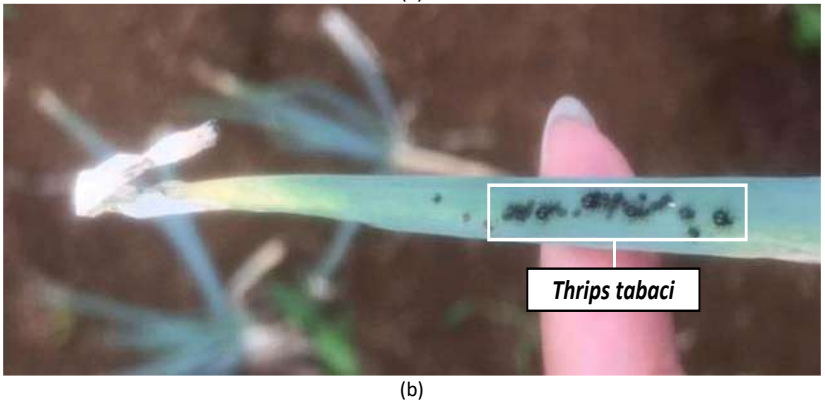
RESULTS AND DISCUSSION

Insecticide types and content analysis

The interview with farmers showed that the most common pests infesting *A. fistulosum* in Cibeureum Village are armyworms and thrips (Fig. 3). Armyworms attack *A. fistulosum* on the inner leaf surface and outer leaf epidermis (Supartha *et al.*, 2022). Thrips (*Thrips tabaci*) compromise plants by inflicting the leaves, flowers, and fruit; introducing poison; drawing out the contents of mesophyll cells; and spreading viral infections (Twardowski *et al.*, 2024). Accordingly, *A. fistulosum* farmers in Cibeureum Village used insecticide containing emamectin benzoate, which effectively eliminate insects, parasitic worms, and spiders without harming non-target organisms (Cerna-Chávez *et al.*, 2024). Emamectin benzoate is an insecticide employed to manage agricultural and forestry pests. It acts by targeting high-affinity γ-aminobutyric acid receptors (GABA-R) and glutamate-gated chloride channels (GluCls) to eliminate insects. This mechanisms improved membrane chloride ion permeability and affects the nerve signal of insects that causing death (Liu *et al*., 2022). The study reveals that farmers consistently utilized pesticides from the early phases of planting, despite the lack of indications of pest presence. Farmers applied insecticides once a week from seventh (dap) until one week before harvesting in 75 days (one cropping cycle), using a 16 liters (L) sprayer for 500 square meters (m^2). Two table spoon (± 30 mL) of insecticide used for one sprayer tank, subsequently farmers also mixing it with adjuvants and vitamins to prevent runoff and drift, regardless of recommended dosage. Pesticide poisoning correlates with lower cholinesterase levels that hydrolyze acetylcholine, posing an increased risk for those exposed to pesticides, particularly among farmer (Nuryati *et al*., 2022).



(a)



(b)

Fig. 3: (a) armyworms (*Spodoptera exigua*); (b) thrips (*Thrips tabaci*) found in *Allium fistulosum*

Residue levels in A. fistulosum

The residue analysis of emamectin benzoate in 6 samples of *A. fistulosum* produced by Cibeureum Village farmers was 0.008 milligrams per kilogram (mg/kg) of plant sample. According to the Regulation of the National Food Agency of the Republic of Indonesia Number 15 of 2024, MRL of emamectin benzoate in *A. fistulosum* is 0.002 mg/kg. However, in Codex Alimentarius of FAO/WHO, the MRL of emamectin benzoate of *A. fistulosum* is not mentioned, but in the same genus, namely *Allium schoenoprasum* (chive) is 0.01 mg/kg. A study indicated that reduced levels of emamectin benzoate residues were observed between 1 to 5 days following application and were not found on the 7th day (Ali *et al.*, 2025). Nevertheless, there are worries about the rampant application of pesticides without proper policy oversight; it may elevate the likelihood of residue accumulation in vegetation and the surrounding ecosystem. Pesticide residue is dispersed in the air, soil, and water; then it accumulates in soil, absorbed by plants, degraded by microorganisms, washed away by rainwater, and evaporates; therefore, increasing potential exposure to non-target organisms (Riyaz *et al.*, 2022). Nonetheless, this study found that there was no additional exposure to pesticides in the environment (including soil, water, or sediment); the analysis for residue detection was carried out on the complete plant, despite the fact that the leaf is commonly ingested by human.

Farmers knowledge of pesticide uses

Questionnaire data in Table 3 and Fig. 4 indicate farmers' high knowledge level regarding hazardous substance in pesticide (94%) and wearing personal protective equipment (PPE)

Table 3: The Distribution of farmers' pesticide-use knowledge in Cibeureum village

No.	Knowledge	NK	PK	MK	K	HK	n	RAL (%)	Category
1	Pesticides contain hazardous substances to eliminate armyworms	0	0	0	10	25	35	94	Excellent
2	PPE is required while applying pesticides	0	0	3	18	14	35	86	Excellent
3	Pesticide usage should not exceed the prescribed dosage on the label	2	16	6	5	6	35	58	Average
4	A recommended pesticide has an authorized brand and certification	7	7	10	9	2	35	55	Average
5	Pests are controlled naturally through IPM	19	9	0	6	1	35	38	Poor

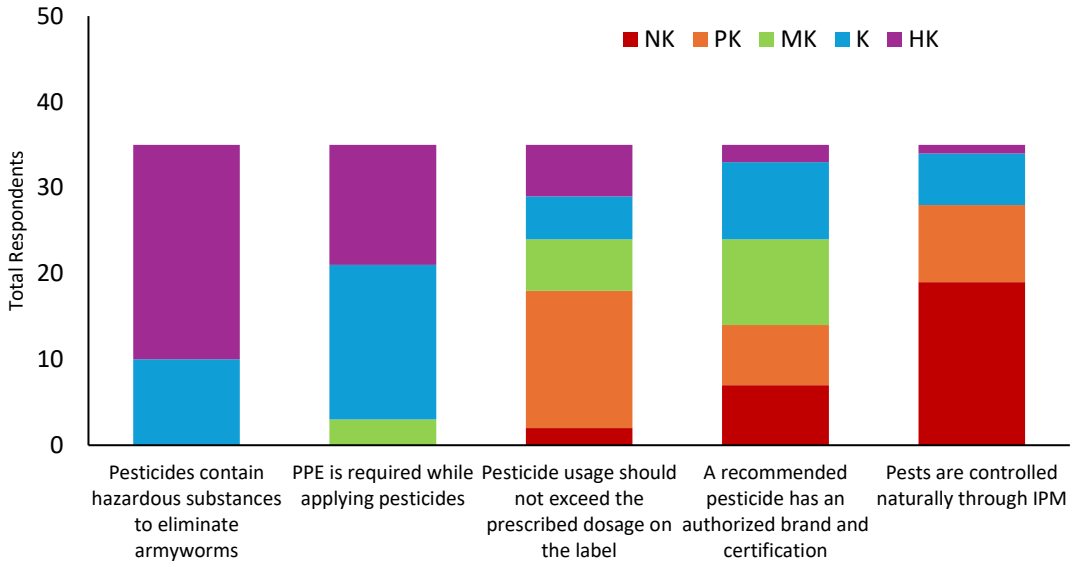


Fig. 4: The visualization of farmers' pesticide-use knowledge distribution

during application (86%). Nonetheless, awareness of utilizing approved pesticide brands (55%) at the recommended dosage (58%) was moderate, while understanding of integrated pest management (IPM) (38%) was low. Natural pest management or IPM, represents an alternative strategy integrating physical and mechanical methods to control pests, as stated in Indonesian Government Regulation Number 6 of 1995.

Farmers attitude of pesticide uses

In Table 4 and Fig. 5, farmers exhibited a favorable attitude by abstaining from other tasks during pesticide application (91%), with the subsequent actions being the wearing of PPE (78%) and choosing pesticides that have clear labels and instructions (66%). However, attitudes adhering to recommended dosages (44%) and understanding the risks of excessive use (50%) were suboptimal, resulting in less effective natural pest management (38%).

Farmers behavior of pesticides use

In Table 5 and Fig. 6, a significant majority of farmers demonstrated a strong positive behavior by acquiring pesticides from licensed retailers (95%), refraining from other activities during application (90%), keeping pesticides in designated rooms (84%), using masks (79%), and upholding personal hygiene (74%). However, some farmers demonstrate the weakest behavior in controlling caterpillars with IPM (40%) and using pesticides within recommended dosage (38%) due to noncompliance with instructions (42%). These results are consistent with the field observation of farmers behavior.

Table 4: The Distribution of farmers' pesticide-use attitude in Cibeureum village

No.	Attitude	SD	D	NT	AG	SAG	n	RAL (%)	Category
1	Pesticides can be dangerous, toxic, and hazardous to health if excessively used	7	15	5	4	4	35	50	Poor
2	It is prohibited to perform other activities while applying pesticides	0	1	0	13	21	35	91	Excellent
3	It is important to wear PPE during pesticide application	3	4	0	15	13	35	78	Good
4	Pesticides must be used in accordance with the recommended dosage on the label	9	17	3	5	1	35	44	Poor
5	Pesticides must have a legitimate brand, clear label and instructions	0	14	3	11	7	35	66	Good
6	Pest control without pesticides is safer for humans and the environment	13	15	5	1	1	35	38	Poor

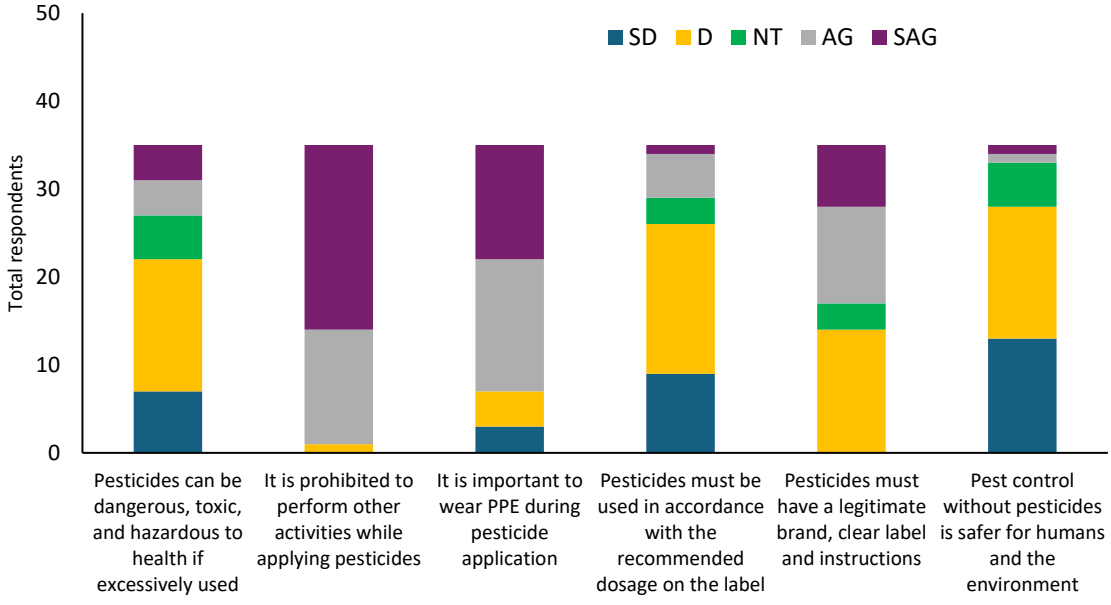


Fig. 5: The visualization of farmers' pesticide-use attitude distribution

Table 5: The Distribution of farmers' pesticide-use behavior in Cibeureum village

No.	Behavior	NV	R	OC	O	A	n	RAL (%)	Category
1	Avoid eating, drinking and smoking while working with pesticides	1	0	2	10	22	35	90	Excellent
2	Maintaining personal hygiene following pesticide application	0	4	13	8	10	35	74	Good
3	Wearing a mask during pesticide application	2	5	1	11	16	35	79	Good
4	Storing pesticide and spray equipment in a separate room	0	1	9	7	16	35	84	Good
5	Purchasing pesticides from authorized stores	0	0	0	8	27	35	95	Excellent
6	Follow the recommended dosage on the label	21	5	3	3	3	35	38	Poor
7	Read the usage instructions before using the pesticide	21	5	3	3	3	35	42	Poor
8	Manual removal of the caterpillars before they reproduce as part of IPM	19	7	2	4	3	35	40	Poor

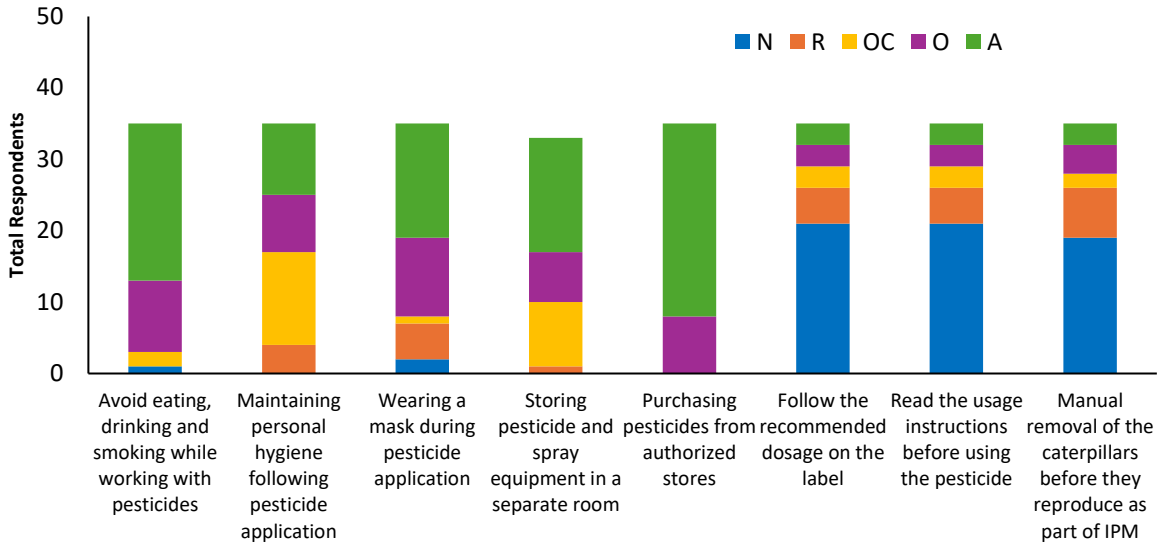


Fig. 6: The visualization of farmers' pesticide-use behavior distribution

The correlation between knowledge and pesticide use behavior

In Table 6, 22 farmers showed responsible behavior and comprehensive knowledge (81.5%), conversely, 5 farmers had comprehensive knowledge, yet were not responsible (18.5%). Furthermore, 4 farmers (50%) are deemed responsible, yet they failed to show extensive knowledge; therefore, 4 farmers (50%) engaged in irresponsible conduct and inadequate knowledge. The Fisher's exact test showed probability value (*p-value*) = 0.162 or more than 0.05, indicating farmers' knowledge and behavior have non-significant correlation. The non-significant correlation occurs while knowledge that shaped behavior need generated by habit based on experience (Gardner *et al.*, 2022). The findings of this study indicated that farmers have a considerable level of knowledge regarding pesticides as chemicals for pest control, despite there exists a misunderstanding that increasing the dosage enhances their effectiveness. This aligns with Akkouch *et al.*, (2025) findings, where most farmers believed that the higher dose of pesticide could protect the plant from pest infestation, thus increasing crop yields. Although farmers have adequate knowledge, this alone is insufficient to motivate responsible pesticide-use behavior (Istriningsih *et al.*, 2022). The disparity between knowledge and behavior is linked to misconceptions regarding pesticide use, influenced by internal factors such as age, education, occupation, and expertise, as well as external factors such as socioeconomic status, environment, and information (Pratama *et al.*, 2022). The majority of farmers in this study aged 30-49 years, only completed the primary school education, having >15 years of experience in farming and currently managing 500 m^2 of land, and never attend IPM training. Education is a key factor that influences farmers' awareness in the adoption of good agricultural practices (GAP) (Akkouch *et al.*, 2025). Moreover, experience is a major factor that develops farmers' knowledge, attitude, and behavior in farming. Farmers are of the opinion that traditional agricultural methods can safeguard plants from pest attacks; however, currently, due to the pressures of climate change and the deterioration of environmental carrying capacity make pesticide use indispensable. Subsequently, the household economic needs and market demand of *A. fistulosum* led farmers to habitually applied excessive dose of pesticide, preventing agricultural loss due to pests attack.

Table 6: The correlation between farmers' pesticide-use knowledge and attitude in Cibeureum village

Category	Responsible pesticide-use atittude		Irresponsible pesticide-use attitude		Total		p-value
	n	%	n	%	n	%	
Comprehensive knowledge	26	96.3	1	3.7	27	100	0.006
Poor knowledge	4	50	4	50	8	100	
Total	30	85.7	5	14.3	35	100	

Consequently, 0.008 mg emamectin benzoate residue found in 1 kg of *A. fistulosum* sample. The environmental impacts did not feel yet, therefore led farmers to underestimate excessive pesticide use. These matters are supported the non-significant correlation between pesticide-use knowledge and behavior. Overall, the study in Cibeureum Village reveals that there is no correlation between farmers' understanding and their behavior regarding pesticide application, shaped by socially determined habits, inherited farming practices, and economic necessities.

The correlation between knowledge and pesticide use attitude

According to Table 7, 26 respondents (96.3%) demonstrate a comprehensive knowledge and responsible attitude regarding pesticide use; one respondent (3.7%) had a comprehensive knowledge, yet the attitude remains inconsistent. However, there are 4 respondents who exhibit inadequate knowledge and a responsible attitude (50%), while the remaining 4 respondents display both inadequate knowledge and an irresponsible attitude (50%). The Fisher's exact test yielded a p-value = 0.006 or less than 0.05 with a correlation value of 0.486 (moderate), a significant correlation observed between farmers' responsible pesticide-use knowledge and attitude (Table 8). Knowledge is defined as a personal understanding associated with the information one has acquired or directly perceived, and it is not confined to symbol recognition (Shahidullah *et al.*, 2023). Attitude refers to a person's psychological tendencies toward an object that shape their knowledge and behavior (Pratiwi *et al.*, 2022). According to the study, farmers' attitude in Cibeureum Village is based on their knowledge, encouraging the adoption of a responsible pesticide-use attitude. Consistent with Rashid *et al.* (2026), knowledge positively correlated with attitude, promoting sustainable use of pesticides. In this study, most farmers demonstrated a positive attitude during pesticide application by wearing PPE; avoiding other activities; and reading labels, reflecting their comprehensive knowledge. As stated by Gugenishvili and Laine-Kronberg (2025), the greater the amount of information or knowledge acquired by an individual, the more robust their attitude is likely to be. Moreover, Porusia *et al.* (2025) found that farmers with a better understanding of pesticides tend to have positive attitudes concerning their use; therefore, pesticide knowledge has a significant influence on farmers' attitudes. Conversely, some farmers did not necessarily exhibit a responsible attitude despite possessing comprehensive knowledge. In this study, the inconsistency between comprehensive knowledge and attitude regarding compliance with pesticide use dosage are driven by several factors. The inherited agricultural practices to protect plants before pest infestation led farmers to believe in using pesticide, even with irrational dosage. Furthermore, behaviors of farmers significantly influence their practices regarding the use of pesticides, especially for commodities with high market demand such as *A. fistulosum*. This indicated that comprehensive knowledge itself does not necessarily change their pesticide-use attitude. Al-Sarar *et al*. (2025) reported that 65.1% farmers relied on peer information from relatives and social media platforms instead of reading the labels while using pesticides. This potentially causing environmental pollution. In this study, farmers blended an insecticide containing the active component

Table 7: The correlation analysis of farmers' pesticide-use knowledge and attitude in Cibeureum village

Measurement Level	Measure	Value	Approximate Significance
Nominal × Nominal	Contingency Coefficient	0.486	0.001
—	N of Valid Cases	35	—

emamect in benzoate with vitamins and adjuvants based on a self-formulated mixture and assumed that higher doses increase agricultural productivity. These findings are aligned with Kapeleka (2024) which reported that the higher dose of pesticide, the more productive their agriculture would be. The excessive application of pesticides results in the contamination of soil, interfering with enzyme activity and nitrogen fixation, and it also taints groundwater through leaching (Riyaz *et al.*, 2022). This potentially reduces soil fertility, *A. fistulosum* yield, and water safety. As stated by Kaur *et al.* (2022), farmers are acknowledge that pesticide has impacts on the environment, yet overlook the health impacts. This indicates that farmers are concerned of pesticides exposure pathways but unwilling to adopt safe procedures due to limited knowledge of specific health risks (Aschale *et al.*, 2024). Insufficient knowledge in farmers correlates positively with a careless attitude and is influenced by several elements, including age, education, agricultural training, and the scale of the farm (López-Hernández *et al*., 2021; Mulugeta *et al.*, 2024). Improving farmers' knowledge is essential to promote a responsible pesticide-use attitude and behavior.

The correlation between attitude and pesticide use behavior

Table 9 showed that 26 farmers (86.7%) have responsible attitude and behavior in using pesticide, and 4 respondents demonstrated a responsible attitude, yet did not behave wisely (13.3%). Subsequently, all 5 respondents (100%) demonstrate an irresponsible attitude and behavior towards pesticide use. Fisher's exact test result obtained a *p-value* < 0.001 followed by a correlation value of 0.471 (moderate), showing that there is a significant correlation between farmers' responsible pesticide-use attitude and behavior (Table 10). Most of the *A. fistulosum* farmers in Cibeureum Village already possess a responsible pesticide-use attitude and behavior, although some farmers demonstrated irresponsible pesticide-use. Attitude embodies the combination of cognitive, affective, and conative elements; as evidenced by the ways in which individuals comprehend, experience, and react to an object (Pratiwi *et al.*, 2022). A positive attitude serves as the farmers' preliminary perspective on responsible pesticide use (Thangjam and Jha, 2024; Aye *et al.*, 2024). This study showed that attitudes have a stronger influence on shaping responsible pesticide-use behavior, compared with just relying on knowledge. Farmers' exhibit a strong commitment to refraining from engaging in other activities and recognize the significance of wearing complete PE when handling pesticides. Furthermore, this study revealed that most farmers were observed wearing incomplete personal protective equipment (only masks, gloves, and boots) while spraying, thereby reinforcing their commitment to a responsible attitude and behavior regarding pesticide use. Based on the interview results, several health symptoms were mentioned by farmers after they applied pesticide, i.e., dizziness, nausea, and shortness of breath. According to Istriningsih *et al.* 2022 findings, farmers have experienced mild and severe acute poisoning symptoms. The body can be exposed to pesticides through the (dermal), respiratory tract, and mouth (oral) (Tudi *et al.*, 2022). Therefore, farmers must wear PPE to protect the entire body from chemical, biological, and physical hazards in the workplace (Aksüt and Eren, 2024). Farmers display commendable

Table 8: The correlation between farmers' pesticide-use attitude and behavior in Cibeureum village

Category	Responsible pesticide-use behavior		Irresponsible pesticide-use behavior		Total		p-value
	n	%	n	%	n	%	
Responsible pesticide-use attitude	26	86.7	4	13.3	30	100	0.000
Irresponsible pesticide-use attitude	0	0	5	100	5	100	
Total	26	74.3	9	25.7	35	100	

Table 9: The correlation analysis of farmers' pesticide-use attitude and behavior in Cibeureum village

Measurement Level	Measure	Value	Approximate Significance
Nominal × Nominal	Contingency Coefficient	0.471	0.002
—	N of Valid Cases	35	—

conduct by obtaining pesticides from authorized outlets, practicing personal cleanliness post-application, and storing pesticides in a separate area. Pesticides must be stored in locked and well-ventilated areas to prevent accidental poisoning in humans (Karki *et al.*, 2025). Farmers disturbed by pesticide odors become more critical to adopt protective attitudes and behaviors towards the poisoning risk of pesticide. Therefore, it is necessary to expose the framework for awareness regarding the safety use pesticide (Aye *et al.*, 2024). The findings revealed that a number of farmers consistently utilized IPM practices, including the hand-picking of caterpillars and the removal of diseased plant parts to ward off pests. Shrestha *et al*. (2024) found that only 37% of the total respondents are adopting the IPM, with an average age of 43.62. A different study from Sun *et al*. (2022) demonstrates that most farmers aged <55 are willing to adopt the IPM compared with farmers aged >55. Additionally, many older farmers are resistant to the implementation of IPM, primarily due to their reliance on traditional agricultural practices and insufficient knowledge about the health and environmental risks associated with pesticide exposure. Therefore, raising farmers awareness on pesticide use is necessary. This can be achieved through evidence-based interventions, e.g., provide recommendations to the village authorities in order that farmers could receive pesticide-use education through the collaboration between University and The Agricultural Agency.

CONCLUSION

Based on a study conducted in Cibeureum Village Sukanagalih, Pacet District, Cianjur Regency, West Java, Indonesia, farmers cultivating *A. fistulosum* were found using insecticide containing emamectin benzoate to control armyworms and thrips. *A. fistulosum* received weekly applications of insecticides, a sticker adjuvant, and vitamins at excessive dosages from the seventh day after planting (DAP) until one week prior to harvest, over a 75-day period, using a 16 L sprayer to treat a 500 m² area. Farmers in Cibeureum Village only using a single type of insecticide contains emamectin benzoate and 0.008 mg residue was found on 1 kg of *A. fistulosum* sample grown in three different elevations of hillslope. Nevertheless, this study focused on investigating the specific risks linked to the single insecticide type employed by *A. fistulosum* farmers. As a result, each sample of *A. fistulosum* is replicated twice at each elevation sampling, and the residue analysis tests may aid in representing represent the *A. fistulosum* population in Cibeureum Village. The similarity of residue content in three different elevations indicated residue accumulation in *A. fistulosum*. These results illustrate the relationship between the knowledge, attitude, and behavior of farmers in Cibeureum Village regarding pesticide use, especially insecticides. The Knowledge and attitude demonstrate a moderate correlation with a p-value = 0.006 and a correlation coefficient of

0.486. A responsible approach to pesticide usage indicates the level of knowledge among farmers, although this is not universally applicable. Despite being aware of the dangers posed by pesticides, the amounts applied often exceed the suggested limits. This supports the study findings of limited knowledge among farmers regarding natural pest management using IPM (38%); Thereby, contributes to shaping their attitude for not adopting pest control without using pesticides (38%), resulting in failure to comply with pesticide recommended dosage (44%) and posing health risks due to pesticide hazard and toxicity (50%). Moreover, a significant correlation was observed among farmers' attitude and behavior, with a p-value < 0.001 followed by a correlation coefficient of 0.471, which highlights a moderate correlation. This signifies that the optimistic outlook of farmers affects their conscientious behavior in pesticide application, which encompasses avoiding additional activities and wearing personal protective equipment during the process. However, some farmers are still lacking responsible pesticide-use attitude; this is reflected in behavior of refraining them from adopting IPM for manual removal of pests, e.g., caterpillars (40%). As consequences, farmers demonstrated non-compliance behavior in using pesticide with recommended dosage (38%) due to their failure of reading instructions for use before application (42%). According to the study, farmers' knowledge and behavior (p = 0.162) have non-significant correlation. This reveals farmers' knowledge-behavior gap due to pesticide-use misconception based on experience; farmers remain convinced that higher doses increase agricultural productivity. Cibeureum farmers, influenced by socially established habits within their peer group, tend to apply pesticides in excessive amounts, particularly at the beginning of the planting process and when pest infestations are not present. Misconception reflected from inherited agricultural practices among farmers should be addressed through a field demonstration associated with sustainable pesticide use that could increasing agricultural productivity. This initiative aims to promote a sensible pesticide use policy by anticipating farmers' actions concerning the excessive application of pesticides, which presents a risk of residue buildup in the environment, especially in the environment, particularly in *A. fistulosum* plant. The future research plans are examining the behavioral change in farmers' regarding pesticide use after given field demonstration and conducting further research on farmers growing other crops, such as *Brassica rapa* (bok choy), *Capsicum annuum* (red chilli), and *Solanum lycopersicum* (tomato), including it is pesticide residue test in environment.

AUTHOR CONTRIBUTIONS

N. Noriko has contributed as a research supervisor in designing and monitoring the entire research, supervising the second and third authors, interpreting the results, drafting and reviewing the manuscript. A. Damayanti has been involved in data acquisition regarding pesticide-use among farmers, statistical analysis, literature review, and drafting the manuscript. F. Salsabila engaged in data acquisition for pesticide analysis used by farmers, statistical analysis, literature review, and drafting the manuscript. K.M. Rahayu contributed to providing research insight, technical guidance, and reviewing the manuscript. R.L. Puspitasari performed the technical support, questionnaire validation, and gave a critical revision to the manuscript. R.N.B. Mulyanto has drafting and proofreading 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
^oC	Degrees Celsius
µL	Microlitre
µm	Micrometer
A	Always
A. fistulosum	*Allium fistulosum* (welsh onion)
AG	Agree
BEH C18	Ethylene bridged hybrid C18
CI	Confidence Interval
cm	Centimeters
D	Disagree
dap	Days after planting
d-SPE	Dispersive solid phase extraction
e	Margin of errors
e.g.	For example
etc	And others
FAO	The Food and Agriculture Organization
g	Grams
GABA-R	High-affinity γ-aminobutyric acid receptor
GluCls	Glutamate-gated chloride channels (GluCls)
HPLC-MS/MS	High performance liquid chromatography-mass spectrometry
HK	Highly knowledgeable
i.e.	That is
IPM	Integrated pest management
K	Knowledgeable
kg	Kilogram
L	Liters
m	Meters
mg	Milligrams
mL	Milliliters
mm	Millimeters
m^2	Square meters
MRL	Maximum residue limit
$MgSO_4$	Magnesium sulphate
mg/kg	Milligrams per kilogram

MK	Moderately knowledgeable
N	Population
N_2	Nitrogen
n	Respondent
NK	Not knowledgeable at all
NT	Neutral
NV	Never
O	Often
OC	Occasionally
PPE	Personal protective equipment
PK	Poorly knowledgeable
PSA	Primary secondary amine
p-value	Probability value
q	Quintal
QuEChERS	Quick, easy, cheap, effective, rugged and safe
R	Rarely
r	Pearson correlation coefficient
RAL	Respondent's achievement level
SAG	Strongly agree
SD	Strongly disagree
Sig.	Significance
WHO	World Health Organization

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ORIGINAL RESEARCH PAPER

An extensive inventory of municipal open waste burning nationwide based on machine learning analysis

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ABSTRACT

BACKGROUND AND OBJECTIVES: Residential open waste burning remains a major environmental and climate challenge in Indonesia. Th study objectives were to conduct a comprehensive nationwide assessment of open burning by measuring its prevalence, recognizing spatial patterns, examining material composition, and revealing the behavioral influences that contribute to it. The ultimate objectives of this study were to generate evidence-based insights that can inform targeted policies and interventions to reduce open waste burning and its associated impacts.

METHODS: The study integrates multiple approaches, including national datasets, a large-scale household survey, spatial analysis, and topic modelling of qualitative responses. The estimation of waste burning activities was conducted through a framework derived from the Intergovernmental Panel on Climate Change's activity and emission inventory, with a crucial improvement that integrated the official administrative classifications of Indonesian villages and cities to more precisely allocate uncollected waste fractions at the subnational level. Primary data were collected via an online questionnaire, yielding 722 valid responses distributed across major regional clusters in Indonesia, including Java, Sumatra, Kalimantan, Sulawesi, Bali–Nusa Tenggara, and eastern regions, characterizing household waste generation, disposal practices, and behavioral drivers.

FINDINGS: The results indicate that in the reference year, approximately 26.6 million tonnes of municipal waste were estimated to be openly burned in Indonesia, corresponding to about 23.3 million tonnes of carbon dioxide equivalent emissions. Residential combustion represents approximately 70 percent of the overall waste incinerated, significantly surpassing the contributions from landfill fires. Spatial analysis revealed strong clustering of open waste burning in densely populated provinces, particularly on Java Island, with notable intra-provincial variation at the district level. Analysis of material composition revealed that dry and combustible components, including plastics, paper, wood, and garden waste, were disproportionately present in the incinerated waste. Latent Dirichlet Allocation topic modelling identified inadequate waste collection infrastructure and household convenience as dominant drivers of open burning.

CONCLUSION: This study illustrates that open burning is a prevalent and serious concern in Indonesia, leading to considerable climate and environmental consequences. Given that residential burning constitutes approximately 70% of the 26.6 million tonnes incinerated annually, targeted improvements in household waste collection services present significant opportunities to decrease emissions.

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INTRODUCTION

Municipal solid waste management remains a persistent challenge in many low- and middle-income countries, particularly where rapid urbanization, population growth, and infrastructure development are not well-aligned (Haregu *et al.*, 2017). Over the last decade, waste generation in Indonesia has grown considerably, whereas the systems for waste collection and treatment continue to grapple with challenges regarding coverage, capacity, and affordability in the realm of waste management (Middha and Horne, 2024; Fatimah *et al*., 2020). Consequently, a significant fraction of municipal waste is managed outside formal systems, leading to environmentally harmful practices such as uncontrolled dumping and open waste burning (OWB) at the household and community levels (Chavan *et al*., 2022). Residential OWB are of particular concern because of their contribution to local air pollution, human health risks, and climate change. The uncontrolled incineration of various household refuse discharges particulate matter, toxic substances, and greenhouse gases, which encompass short-lived climate pollutants like black carbon (Mathew *et al*., 2024). Although exposure to pollutants such as particulate matter is widely associated with respiratory and other adverse health outcomes, this study focuses on emission quantification and climate impact indicators at the national scale and does not conduct a detailed human health exposure or risk assessment. The broader literature acknowledges the potential disproportionate effects on vulnerable groups, including children and the elderly; however, this study did not conduct a specific evaluation of these impacts. Despite national regulations prohibiting open burning and policy commitments to improve waste management performance, OWB remains widely practiced, especially in areas with limited waste collection services. Consequently, comprehending the extent, spatial arrangement, and fundamental factors influencing residential OWB is essential for formulating effective mitigation strategies and advancing national environmental and climate objectives (Ogut *et al.,* 2024). Previous studies have attempted to quantify waste-burning activities and their emissions on global, regional, and national scales. The Intergovernmental Panel on Climate Change (IPCC) provides methodological guidance for estimating emissions from OWB, forming the basis of many national inventories. Global and regional evaluations have underscored that the burning of residential and informal waste can represent a significant, albeit frequently overlooked, contributor to air pollutants and climate-forcing emissions (Ramadan *et al*., 2022a; Velis *et al*., 2021). In Indonesia and Southeast Asia, several studies have documented the prevalence of OWB and their environmental impacts (Ramadan *et al*., 2025; Wiedinmyer *et al*., 2014). Research has shown that OWB is closely linked to inadequate waste collection coverage, informal settlement patterns and limited access to waste treatment facilities. Recent studies based on inventory data have improved emission estimates by incorporating waste composition, combustible fractions, and refined activity data, illustrating that emissions from residential burning can overshadow those from landfill fires at the national level (Jakhar *et al.*, 2023; Ramadan *et al*., 2023). Although this study builds upon the inventory framework of Ramadan *et al.* (2025), it quantitatively differs by reallocating uncollected waste fractions using official village–city classifications, incorporating updated national datasets for improved subnational emission estimates, and integrating household survey data to link spatial patterns with behavioral drivers. Nevertheless, a significant number of current studies depend heavily on generalized assumptions regarding the characteristics of rural and urban areas, uniform waste collection efficiencies, and proxy indicators for household behavior (Chaudhary *et al.*, 2021; Wiedinmyer *et al.,* 2014). While several national case studies have assessed open

waste burning and its emissions (Wiedinmyer *et al*., 2014), most focus primarily on activity data and emission estimation (Chaudhary *et al.*, 2022; Thompson *et al.*, 2024). Consequently, there is limited empirical evidence linking national-scale emission estimates with household decision-making processes and perceived constraints. This study advances the current body of knowledge in several ways. Furthermore, it is significant to highlight that existing national inventory infrequently incorporate classifications of subnational administrative settlements to improve activity data. They also fail to consistently merge emission modeling with empirically obtained behavioral evidence to explain spatial heterogeneity. As a result, the methodological linkage between inventory refinement and household-level drivers remains insufficiently developed. Unlike general rural–urban categories that are usually based only on population density, the official village–city (*desa–kota,* in local language) classification reflects administrative status and how public services are managed. This difference is important because waste collection coverage, infrastructure development, and local enforcement are organized according to administrative areas. Through the application of official village and city classifications, this study optimizes the distribution of uncollected waste fractions and mitigates potential bias in subnational emission estimates. First, it refines existing waste burning inventory approaches by integrating official village–city classifications from the Indonesian Statistical Agency (BPS), allowing for a more accurate representation of settlement characteristics and waste collection conditions than conventional rural–urban assumptions. Second, this study combined national datasets with primary household survey data from 722 valid respondents, enabling triangulation between top-down statistics and bottom-up behavioral evidence. Third, machine learning–based topic modelling as latent dirichlet allocation (LDA) was applied to systematically identify the dominant reasons behind residential OWB practices and the strategies perceived by households as most effective for reducing OWB. This strategy goes beyond simple descriptive surveys by uncovering latent themes within open-ended responses, thus delivering a data-informed comprehension of the behavioral and institutional drivers. Finally, by linking spatially explicit waste burning estimates with climate impact indicators, this study offers an integrated perspective that connects household behavior, regional waste management performance, and emission outcomes. The primary aim of this study was to quantify, spatially characterize, and explain residential OWB practices in Indonesia, with a focus on identifying effective pathways for mitigation. This study is formulated as a national cross-sectional analysis grounded in the most up-to-date consolidated datasets and does not intend to examine temporal trends in OWB over an extended period. The analysis is based on aggregated annual data and does not explicitly assess potential seasonal variations in OWB activities, such as differences between dry and rainy seasons. The primary objective of this study is to 1) evaluate the burning activities associated with residential and landfill waste at the provincial and sub-provincial levels, employing a revised activity and emission inventory framework; 2) assess the spatial distribution and climate impact of waste burning across Indonesia; 3) characterize household waste generation, disposal practices, and infrastructure availability based on a large-scale questionnaire survey; and 4) determine the primary factors influencing residential OWB and explore possible mitigation strategies using topic modelling of open-ended survey responses. By achieving these objectives, this study aims to provide evidence-based insights to support more targeted waste management interventions and policy actions to reduce OWB and its associated environmental and climate impacts. This study was conducted in Indonesia in 2025.

MATERIALS AND METHODS

Study context and data sources

This study uses national waste management datasets as input parameters for emission inventory calculations. Data were obtained primarily from the National Waste Management Information System (SIPSN) operated by the Ministry of Environment and Forestry, as well as from the Indonesian Statistical Agency (BPS). National waste generation is reported to range from 19 to 60 million tons annually, depending on the coverage of reporting and the year in question, with management rates falling between roughly 34–39 percent (%). For the reference year 2023, SIPSN records indicate total waste generation of 56.6 Mt, of which about 39% was formally managed. These figures underscore that despite regulatory frameworks, such as the Presidential Regulation on national waste management targets, which aim for significantly higher management rates (70%), implementation remains incomplete. In the context of waste composition, the SIPSN categorization reveals that organic waste, encompassing food and backyard waste, accounts for the predominant share of the Indonesian waste stream, often noted to be around 40% or more. This is succeeded by plastics and other components, reflecting standard household and market waste patterns. This composition profile has direct implications for waste-handling strategies, as a high organic content suggests opportunities for composting and valorisation, whereas significant plastic and mixed fractions present ongoing challenges for recycling systems. Despite considerable production volumes and evolving infrastructure (for instances, landfill facilities, reduce reuse recycle facilities, and waste banks), the observed pace of scaling and integration into municipal systems is uneven across regions, indicating the continued need for policy emphasis on service expansion, segregation at source, and resource recovery pathways.

Data collection

Data collection in this study combined a literature survey compilation and an online survey to comprehensively characterize waste-related conditions in Indonesia. The literature and database review followed a structured search strategy. Official datasets were identified through systematic screening of national statistical portals (BPS and SIPSN), while supporting academic references were selected using keyword combinations such as “open waste burning”, “municipal solid waste Indonesia”, and “emission inventory OWB” in major scientific databases. Only peer-reviewed articles, official government statistics, and reports published between 2010–2025 were included. Sources lacking methodological transparency or national relevance were excluded. The literature survey data were acquired through a methodical review of literature and databases, leveraging official statistics from the Indonesian Statistical Agency (BPS), SIPSN, and regional gross rate domestic product (GRDP) databases to capture spatial, demographic, socio-economic, and waste management indicators at the regency and city levels. The data presented established the basis for evaluating waste generation, management efficiency, waste composition, and related derived indicators through computational methods. In parallel, primary data were collected through an online questionnaire survey designed to capture household-level waste generation characteristics, waste management practices, infrastructure availability, and contextual perceptions. The structure of the questionnaire adhered to a predetermined design that included eligibility screening, respondent profiling, household waste characteristics, management practices, and perceptions related to policy. It was implemented through a cluster-based regional approach. The integration of national datasets and primary survey data enabled triangulation between national-level waste statistics and household-scale conditions, strengthening the robustness of

the analysis. Discrepancies in the totals reported by SIPSN (for instance, 19.3 Mt compared to 56.6 Mt) indicate differences in the extent of reporting across various regencies and cities, as well as the completeness of data for each year. For emission estimation, the study consistently uses the consolidated 2023 national dataset (56.6 Mt) to ensure comparability. For regencies not fully covered in SIPSN reporting, waste generation values were approximated using population-based extrapolation derived from BPS demographic statistics and regional per capita waste generation rates.

Data collection for OWB profiling

All emission estimates in this study refer to the reference year 2023, based on the most recent consolidated national datasets available at the time of analysis. Table 1 outlines the data sources employed to evaluate waste-related activities throughout the administrative regions in Indonesia. Spatial and administrative variables, including regency and city names, land area, population, and the number of villages and cities, were primarily derived from official statistics published by the Indonesian Statistical Agency (BPS). These datasets present the crucial geographical and demographic structure needed to delineate regional disparities and to assist in further calculations. Indicators such as population density and the proportion of villages to cities were derived through calculations based on the original statistical data. Socio-economic indicators, particularly GRDP at constant prices (2022), were obtained from regional GRDP databases to represent economic conditions that may influence waste generation and management performance. The GRDP was not explicitly factored into the equations used for emission calculations. Rather, it served as a contextual reference to understand regional disparities in waste generation and management performance in the discussion section. These socio-economic variables, including regional economic indicators, education level, and urban–rural classification, were used for descriptive and contextual interpretation. Nevertheless, the research does not conduct inferential statistical modeling to measure causal connections between socioeconomic factors and practices related to open waste burning. Waste generation data, including total annual waste generation and waste management or collection efficiency, were sourced from the SIPSN website. Per capita waste generation rates were subsequently calculated using population data, enabling comparability across regions with different population sizes. Additional parameters relevant to waste flow characterization were estimated through a combination of reported data and calculated assumptions. The fraction of uncollected waste ($f_{uncollected}$) was calculated as 1 minus the reported waste collection or management efficiency for each administrative unit based on SIPSN data. In regions where comprehensive reporting is absent, values were approximated by utilizing population-weighted averages within the corresponding regional cluster. The combustible fraction (B_{frac}) was derived from reported waste composition data by summing combustible components (e.g., plastics, paper, textiles, wood, and yard waste) and excluding inert fractions such as metals and glass. These include the fraction of uncollected waste, detailed waste composition fractions, and the combustible portion of municipal solid waste. The emission factors utilized in the following analyses were derived from reputable literature sources to guarantee methodological consistency and comparability with previous studies. The emission factors from Ramadan *et al.* (2025) are IPCC-aligned and represent typical uncontrolled mixed municipal waste burning conditions. Uniform factors were applied across provinces to ensure national comparability and methodological consistency. Collectively, these datasets offer a cohesive foundation for evaluating regional waste management circumstances and facilitating quantitative analysis of waste-related endeavors at both national and subnational levels.

Table 1: Data sources for estimated waste burned activity

Data	Sources
Name	Statistical Agency data per province 2023
Area (kilometer squares/km^2)	Statistical Agency data per province 2023
Population (people)	Statistical Agency data per province 2023
Number of villages by administration	Village and city classification data, Statistical Agency 2020
Number of cities by administration	Village and city classification data, Statistical Agency 2020
Percentage of villages to cities by administration	Calculation
Number of villages	Village and city classification data, population data per village, Statistical Agency 2020
Number of cities	Village and city classification data, population data per village, Statistical Agency 2020
Percentage of villages to cities	Calculation
Regional density (people/km^2)	Calculation
GRDP at constant prices (2022) (Rupiah/Rp)	GRDP Data
Waste generation in 2022 (t/y)	SIPSN website
Waste generation per capita (kilogram per day (kg/d))	Calculation
Waste collection/management efficiency (%)	SIPSN website, Waste management percentage
Fraction of uncollected waste (%)	Calculation
Fraction of waste composition (%)	SIPSN website
Combustible waste (%)	Calculation
Emission factors	Ramadan *et al.* (2025)

Questionnaire design and sampling method

This study employed a cross-sectional questionnaire survey administered online to capture household-level waste management conditions and perceptions in Indonesia. The online-only approach may introduce socio-economic bias, as participation requires internet access and digital literacy; this limitation is acknowledged in the interpretation of results. The questionnaire was formulated based on a systematic design that encompasses respondent eligibility, socio-demographic characteristics, household waste generation and composition, waste management practices, availability of community waste infrastructure, awareness of waste-related programs, and the challenges and solutions perceived by respondents. Prior to full deployment, the questionnaire structure and wording were reviewed internally and pilot-tested to ensure clarity and logical flow. Internal consistency of key multi-item sections was assessed using Cronbach's alpha, indicating acceptable reliability. The concluding instrument integrated closed-ended questions for quantitative assessment along with chosen open-ended questions to obtain contextual explanations and qualitative insights. Although the questionnaire assessed the availability of formal waste infrastructure such as waste banks and material recovery facilities (MRFs), it did not explicitly collect quantitative information regarding the role of informal recycling activities or waste pickers in influencing household decisions to burn waste. Therefore, the potential influence of informal recycling networks is discussed indirectly through reported waste management practices rather than through direct measurement. Furthermore, the questionnaire gathered data on various on alternative waste management practices reported by households, including composting, recycling, and formal collection services. Nevertheless, the study did not perform a comprehensive technical or economic feasibility assessment of alternatives such as composting systems, incineration with energy recovery, or recycling adoption potential; these were evaluated descriptively relying on reported practices and perceived preferences rather than through quantitative feasibility modelling. Perceived constraints, including high transportation costs and limited access to collection services, were captured in the survey

and interpreted as structural factors influencing household waste management decisions. Questionnaire design can be seen in Table 2. Data gathering was executed utilizing an online survey platform, yielding a total of 1,025 responses. To mitigate duplicate submissions, the survey platform restricted multiple entries from the same device/IP and responses were screened for identical patterns. To ensure analytical relevance, a multi-stage screening process was applied. First, respondents who reported never observing or engaging in open waste burning were excluded from the behavioral driver analysis. Nonetheless, these responses were preserved within the larger dataset and were not utilized to exaggerate national prevalence estimates. Second, responses with substantial missing data, inconsistent answers, or incomplete key sections were removed. Following this filtering process, 722 questionnaires were deemed valid and retained for further analysis, representing approximately 70.4 % of the total collected responses. To account for Indonesia's geographical diversity, the survey sample was clustered by region following the predefined clustering framework outlined in the study protocol. Participants were categorized into significant regional clusters/ islands (for instance, Java, Sumatra, Kalimantan, Sulawesi, Bali–Nusa Tenggara, and Maluku–Papua), facilitating equitable representation and comparative analysis across regions. This cluster-based methodology allowed for the detection of spatial disparities in the characteristics of household waste generation, the accessibility of services, and the practices of waste management, while also preserving a sufficient sample size within each cluster for analysis. No formal power calculation was conducted, as the study was designed for descriptive and exploratory analysis rather than inferential hypothesis testing. As the questionnaire was administered online, households without stable internet access or sufficient digital literacy may have been less likely to participate, particularly in remote or rural areas. Despite attempts to disseminate the survey throughout various regional clusters, the sample may not completely reflect populations with restricted connectivity. This limitation should be considered when interpreting the survey-based findings. Participation was voluntary, informed consent was obtained at the beginning of the survey, and no personal identifiers were collected.

Data analysis

The quantitative survey data were analyzed using descriptive statistical methods, including frequency distributions, percentage calculations, and regional comparisons based on predefined clusters. No inferential statistical tests or regression modelling were utilized, since the objective of the study was to describe patterns rather than test causal hypotheses. Spatial and material composition data were processed through aggregated calculations at provincial and subnational levels. Qualitative responses were analysed using Latent Dirichlet Allocation (LDA) as described below. The study did not aim to determine statistically significant relationships among variables; instead, its robustness was reinforced through triangulation between national datasets and primary survey responses, consistency with established inventory methodologies, and systematic validation steps within the topic modelling process (for instance, topic coherence evaluation and multidimensional scaling stress assessment). This approach ensures analytical transparency while aligning with the descriptive and inventory-based objectives of the study. No formal uncertainty propagation such as, Monte Carlo simulation was performed. Waste generation, collection efficiency, and emission factors were treated as deterministic inputs; therefore, combined uncertainty ranges were not calculated. The findings represent central inventory estimates rather than outputs based on probability. The village–city classification assumes homogeneity within each administrative category. The gradients found in peri-urban areas and the variability within categories were not modeled in detail, potentially resulting in a simplification of

Table 2: Questionnaire design

Section	Objective	Key Variables / Indicators	Question Type	Measurement Scale / Response Options
Pre-screening	Identify eligible respondents who have exposure to open burning of household waste	Experience observing open burning; experience practicing open burning	Closed-ended	Nominal (Yes / No / Do not know)
Respondent Profile	Capture socio-demographic characteristics of respondents	Age; gender; education level; occupation; household head status; place of origin and current domicile	Closed-ended	Nominal and ordinal categories
Household Characteristics	Describe household context related to waste generation	Household size (number of residents)	Closed-ended	Discrete numerical
Waste Generation	Estimate household waste quantity	Daily waste generation per household	Closed-ended (estimation)	Ordinal (volume categories in liters / bag size equivalents)
Waste Composition	Characterize types of household waste generated	Food waste; garden waste; paper; plastics (soft & rigid); textiles; glass; metals; hazardous waste; nappies; residue	Closed-ended	Percentage distribution (%); zero value allowed ("not available")
Waste Management Practices	Identify existing waste handling and disposal methods	Waste collection by private/DLH services; open burning; dumping; burial; composting; others	Closed-ended (multiple choice)	Nominal
Uncollected Waste Handling	Understand coping strategies when collection services are absent	Alternative waste disposal methods	Closed-ended	Nominal
Waste Infrastructure Availability	Assess access to community-based waste facilities	Presence of waste bank; presence of MRF	Closed-ended	Nominal (Yes / No / Do not know)
Awareness & Capacity Building	Measure exposure to waste-related education and outreach	Participation in socialization, training, or awareness activities	Closed-ended	Nominal (Yes / No)
Perceived Impacts of Open Burning	Explore perceived positive and negative impacts of open burning	Environmental, health, economic, and practical impacts	Open-ended	Qualitative (thematic analysis)
Regulatory Awareness	Assess awareness of legal restrictions on open burning	Knowledge of existing regulations	Closed-ended	Nominal (Yes / No / Do not know)
Drivers of Open Burning	Identify structural and socio-economic drivers	High transport costs; lack of collection services; cultural practices; other reasons	Mixed (closed-ended with explanation)	Nominal + short qualitative justification
Persistence Factors	Explore additional motivations sustaining open burning practices	Other underlying or contextual reasons	Open-ended	Qualitative
Policy & Management Recommendations	Capture community-based solutions and expectations	Preferred waste management methods; suggested strategies and interventions	Open-ended	Qualitative

spatial data. Double counting between residential burning (W_{Bres}) and disposal-site burning (W_{Bdump}) was avoided by separating uncollected waste fractions (allocated to WBres) from collected waste fractions subject to disposal-site burning (allocated to W_{Bdump}). Carbon dioxide (CO_2) equivalent values were calculated using 100-year global warming potential (GWP100) values consistent with IPCC AR6 recommendations. The findings related to spatial clustering are presented in a descriptive manner; formal spatial autocorrelation metrics (for instance, Moran's I) were not employed, as the focus of the analysis was on the spatial distribution derived from inventory rather than statistical spatial inference. Independent atmospheric measurements or field-based validation data were not available; validation was conducted through methodological consistency with IPCC guidelines and comparison with published national inventory studies. The allocation of uncollected waste to open burning follows established inventory practice; however,

only the combustible fraction is assumed to be burned, not the entire uncollected amount. The evaluation is fixed and restricted to the reference year 2023. Temporal dynamics and interannual variability were not assessed.

Activity and emission profile of municipal OWB in Indonesia

The estimation of waste burning activity and associated emissions in this study followed the updated activity inventory methods and emission inventory framework developed by Ramadan *et al.* (2025), which are based on refinements of the 2006 IPCC Guidelines for OWB. The methodological framework, which encompasses the distinction between residential burning and incineration at disposal sites, the utilization of uncollected waste fractions, and the implementation of pollutant-specific emission factors, was preserved to maintain consistency and comparability with both regional and international inventories. However, a key modification was introduced in the determination of settlement characteristics, where the distinction between villages and cities was defined explicitly using official Indonesian administrative classifications from the Statistical Agency report rather than relying solely on generic rural–urban assumptions. In this study, residential waste burning was estimated by differentiating waste generation and collection characteristics between villages (*desa*) and cities (*kota*). Villages were assumed to have lower collection coverage and higher likelihood of unmanaged waste disposal, while cities were characterized by higher, but still incomplete, collection services. This categorization enabled a more precise assignment of uncollected waste fractions at the subnational level. Waste burning at disposal sites (WB_{dump}) was estimated assuming that uncontrolled dumping and associated burning primarily occur at formal or semi-formal disposal facilities, which are predominantly located in urban administrative areas according to national waste infrastructure distribution data. Greenhouse gas emissions, short-lived climate pollutants, and various primary air pollutants were assessed by taking the total waste burning (WB) and multiplying it by the emission factors specific to each pollutant, as well as the combustible fraction of municipal solid waste, following the emission inventory equations established by Ramadan *et al*. (2025) (Table 3). Sensitivity is expected to be most influenced by assumptions on uncollected waste fractions and the selected emission factors, which are highlighted as key sources of variability. By explicitly incorporating village–city characteristics based on BPS data, this approach reduces potential overestimation associated with uniform rural–urban assumptions and provides a more context-sensitive representation of waste burning activities in Indonesia. Like all emission estimates based on inventory, the findings are influenced by uncertainties related to activity data, emission factors, and assumptions concerning uncollected waste fractions. Potential underreporting or unobserved small-scale burning activities cannot be entirely excluded. However, the methodology relies on established IPCC-based inventory frameworks and nationally aggregated datasets rather than solely on self-reported burning behavior, which enhances the robustness and comparability of the estimates. This study did not include a formal uncertainty propagation analysis, for instance, confidence intervals. The reported emission values therefore represent deterministic central estimates based on the best available national datasets and literature-derived emission factors and should be interpreted accordingly. Accordingly, the reported values of 26.6 million tonnes of waste burned and 23.3 million tonnes CO_2 equivalent emissions should be interpreted as indicative national-scale estimates derived from standardized inventory procedures, rather than as exact measurements with quantified confidence intervals.

Table 3: Equations used in estimating emission

Parameter	Equations	Sources
The amount of MSW that was openly burned at the residential area	$W_{Bres} = MSW_p \; x \; [(P_{rural} x \; f_{uncollected(rural)}) + (P_{urban} x f_{uncollected(urban)})] \; x \; B_{frac}$	Ramadan *et al.*, 2022a
The amount of MSW that was openly burned at the disposal site	$W_{Bdump} = MSW_p \; x \; P_{urban} \; x \; f_{collected(urban)} \; x \; \lambda \; x \; B_{frac}$	Wiedinmyer *et al.*, 2014
Total MSW burned	$W_B = W_{Bres} + W_{Bdump}$	Ramadan *et al.*, 2023
Total CO_2 emissions	$Total \; CO_2 \; Emissions \; (CO_{2T}) = W_B \; x \; \sum_j (WF_j \; x \; dm_j \; x \; CF_j \; x \; FCF_j) \; x \frac{44}{12}$	Ramadan *et al.*, 2025
Total CH_4, N_2O, BC, SO_2, PM_{10}, $PM_{2.5}$, CO, NO_x emissions	$Total \; x \; emissions = W_B \; x \; EF_{CH_4} \; x \; \delta$	Heston *et al.*, 2023
Total climate impact BC, CH_4, N_2O	$Climate \; impact \; of \; x = x_T \; x \; GWP_x$	Pathak *et al.*, 2023

Text data analysis and topic modelling

To ascertain the fundamental causes of household waste incineration practices and to investigate possible strategies for their reduction, qualitative responses from the questionnaire were examined utilizing topic modeling techniques applied in the orange data mining software (Fig. 1). Open-ended responses related to motivations for waste burning and suggested mitigation strategies were first compiled into a structured text corpus by exporting responses into a comma-separated values (CSV) format. This corpus was subsequently imported into orange for text processing and analysis. Prior to modelling, the text data underwent a standardized preprocessing workflow, including tokenization, conversion to lowercase, removal of punctuation and numerical characters, stop-word elimination, and lemmatization to reduce words to their base forms (Table 4). These measures were implemented to enhance semantic coherence and minimize noise within the textual dataset. The cleaned corpus was then used as the input for Latent Dirichlet Allocation (Heston *et al.*, 2023), an unsupervised probabilistic topic modelling method that identifies latent thematic structures based on word co-occurrence patterns across documents. The total number of topics was ascertained iteratively by evaluating both topic coherence and interpretability, which guaranteed that the derived topics effectively captured the main narratives found in the answers provided by the respondents. Topic coherence (Cv) scores were calculated for models ranging from 3–10 topics, and the selected model showed the highest coherence score (Cv = 0.51), balancing interpretability and thematic separation. LDA assumes a bag-of-words representation and conditional independence between terms; these assumptions may simplify semantic structure but remain standard practice in exploratory topic modelling. The concluding corpus included 722 valid open-ended responses that served as separate documents within the LDA model. Model stability was assessed by running the LDA model multiple times with different random seeds; dominant topic structures remained consistent. Stop-word lists were based on the standard Indonesian language corpus available within the orange text-mining library, supplemented by manual removal of domain-irrelevant terms. All preprocessing and modelling were conducted in Indonesian. The topic was interpreted and reported in English after the modeling phase to mitigate any potential translation bias during computational analysis. To support interpretation and validation of the topic structure, latent Dirichlet allocation visualization (LDAvis) was employed to visualize topic saliency and term relevance, while multidimensional scaling (MDS) was used to map inter-topic distances in a two-dimensional space. The assessment of the MDS representation's quality was conducted through Kruskal's stress value, where values under 0.05

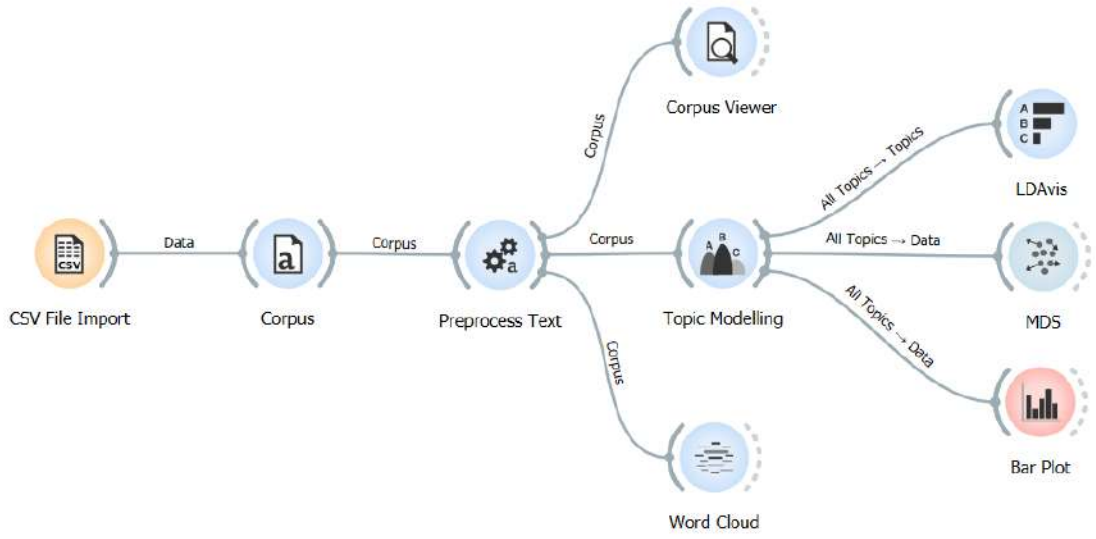

Fig. 1: Project workflow of text mining analysis

Table 4: Preprocessing criteria in the topic modelling

Data	Criteria
Transformation	*Lowercase* = Turning all text to lowercase
	Parse html = Parse out text only and remove html tags
	Remove urls = Remove all urls from text
Tokenization	*Word & Punctuation* = splitting the text by words and keep punctuations symbols
Filtering	*Stopwords* = Removing stopwords from the text and set the language to Indonesian (since the original text / Indonesian was used)
	Numbers = Numbers were not included in the corpus
	Regexp = Splitting the text by providing some separation character

signify an outstanding low-dimensional fit and minimal distortion of inter-topic relationships (Keklik and Şahin, 2022). The resulting Kruskal's stress value was 0.032, indicating excellent low-dimensional representation. Supplementary visual representations, such as word clouds and frequency bar plots categorized by topic, were created to aid in the qualitative analysis of the predominant terms associated within each topic. Topic interpretation was independently reviewed by two researchers to reduce subjectivity, and discrepancies were resolved through discussion. The combined use of LDA, LDAvis, and MDS enabled a robust identification of key behavioural drivers of waste burning and recurring themes in proposed mitigation strategies, grounded directly in respondents' narratives.

RESULTS AND DISCUSSION

Profile of waste burning activity in Indonesia

The provincial-level assessment indicates that waste burning in Indonesia amounts to approximately 26.64 Mt/y, generating a total climate impact of about 23.34 million tons carbon dioxide equivalent ($MtCO_2e$) annually. Of this total, residential waste burning (WB_{Res}) accounts for the dominant share (18.71 Mt/y; ~70 %), while landfill-related fires (WB_{dump}) contribute 7.93 Mt/y (~30 %). This verifies that practices at both the household and neighborhood levels continue to be the main contributors to waste burning across the country, although landfill fires serve as a significant secondary source in certain provinces. It should be noted that these pollutant and climate

impact values were not directly measured in the field. Emissions of CH_4, N_2O, black carbon (BC), particulate matter (PM), CO, NOx, and SO_2 were estimated using established emission factors within an IPCC-based inventory framework. The analysis did not specifically quantify heavy metals that may be associated with the combustion of plastics. The spatial distribution is highly uneven, reflecting strong differences in population density, waste generation, and waste management infrastructure across regions. This study employs a descriptive, inventory-based methodology; consequently, the findings aim to illustrate spatial patterns instead of statistically examining causal factors. Provinces on Java Island overwhelmingly dominate the national waste burning profile. West Java alone contributes more than 5.12 Mt/y, corresponding to a climate impact of 4.49 $MtCO_2e$, making it the single largest contributor nationally. This is followed by East Java (3.41 Mt/y; 3.01 $MtCO_2e$) and Central Java (3.16 Mt/y; 2.78 $MtCO_2e$). Together, these three provinces account for nearly 44 % of Indonesia's total waste burned, underscoring the influence of large populations and high absolute waste generation. Therefore, the prevalence of Java must be understood in the context of demographic size and the intensity of waste generation, rather than merely as a sign of inadequate waste management performance. Banten (1.33 Mt/y) and DKI Jakarta present contrasting profiles: while Jakarta's total waste burned is relatively moderate (1.14 Mt/y), it is overwhelmingly dominated by landfill fires (>99% WB_{dump}), highlighting the role of large, centralized disposal sites rather than household burning in highly urbanized settings. Outside Java, waste burning levels are generally lower in absolute terms but remain environmentally significant. In Sumatra, provinces such as North Sumatra (1.55 Mt/y; 1.33 $MtCO_2e$), South Sumatra (0.89 Mt/y; 0.77 $MtCO_2e$), Lampung (0.89 Mt/y; 0.76 $MtCO_2e$), and Riau (0.79 Mt/y; 0.65 $MtCO_2e$) emerge as regional hotspots. In these provinces, it is clear that residential burning is the dominant practice, although landfill fires also account for substantial contributions, particularly in North Sumatra and Riau. This pattern is consistent with areas where partial collection coverage coexists with continued reliance on informal disposal and household burning (Fig. 2). These associations illustrate the spatial patterns that have been observed and should not be construed as statistically confirmed causal relationships. In Kalimantan, Sulawesi, Bali–Nusa Tenggara, and eastern Indonesia, total waste burned per province is typically below 0.6 Mt/y, yet residential burning remains the principal pathway. Provinces such as South Sulawesi (0.85 Mt/y; 0.73 $MtCO_2e$) and Bali (0.56 Mt/y; 0.50 $MtCO_2e$) stand out due to relatively high tourism- or urban-driven waste generation combined with limited downstream treatment capacity. In contrast, provinces in Papua and Maluku show much lower absolute quantities (generally <0.15 Mt/y per province), with landfill fires playing only a minor role. In summary, the provincial profile indicates that the issue of waste burning in Indonesia is predominantly a residential matter, primarily concentrated in densely populated provinces, whereas landfill fires are particularly critical in major urban and metropolitan regions. This differentiation has important implications for mitigation strategies, indicating that household-level interventions are essential nationwide, while landfill fire prevention should be prioritized in selected high-burden provinces. Fig. 3 demonstrates a distinctly varied spatial pattern of municipal waste combustion across Indonesia, with notable concentrations in regions that are heavily populated and urbanized. The highest waste burning intensities (up to ~117 Mkg/year per administrative unit) are strongly concentrated along Java Island, particularly in metropolitan and peri-urban corridors spanning West Java, Central Java, East Java, and the Greater Jakarta region.

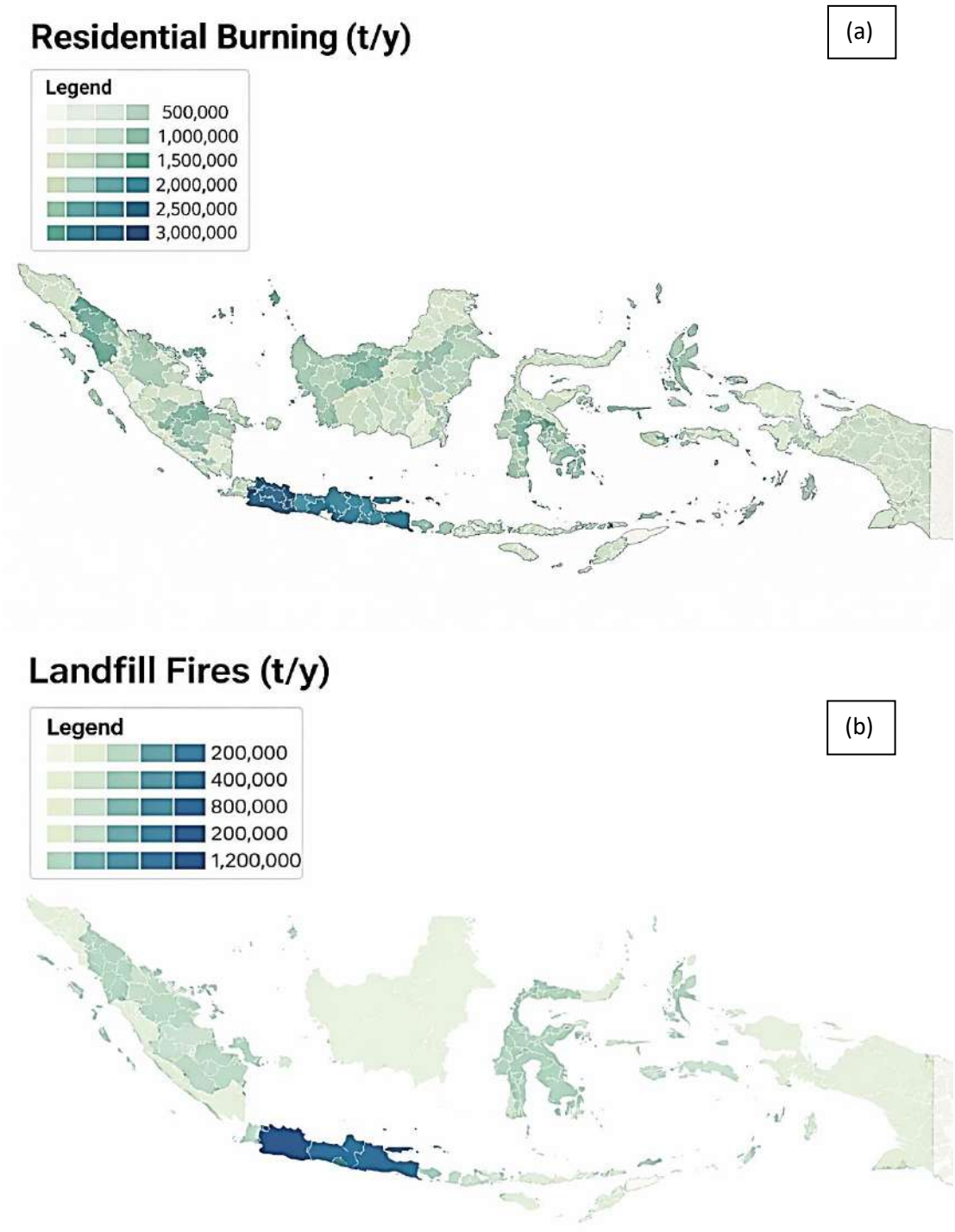

Fig. 2: Estimated (a) residential burning and (b) landfill fires

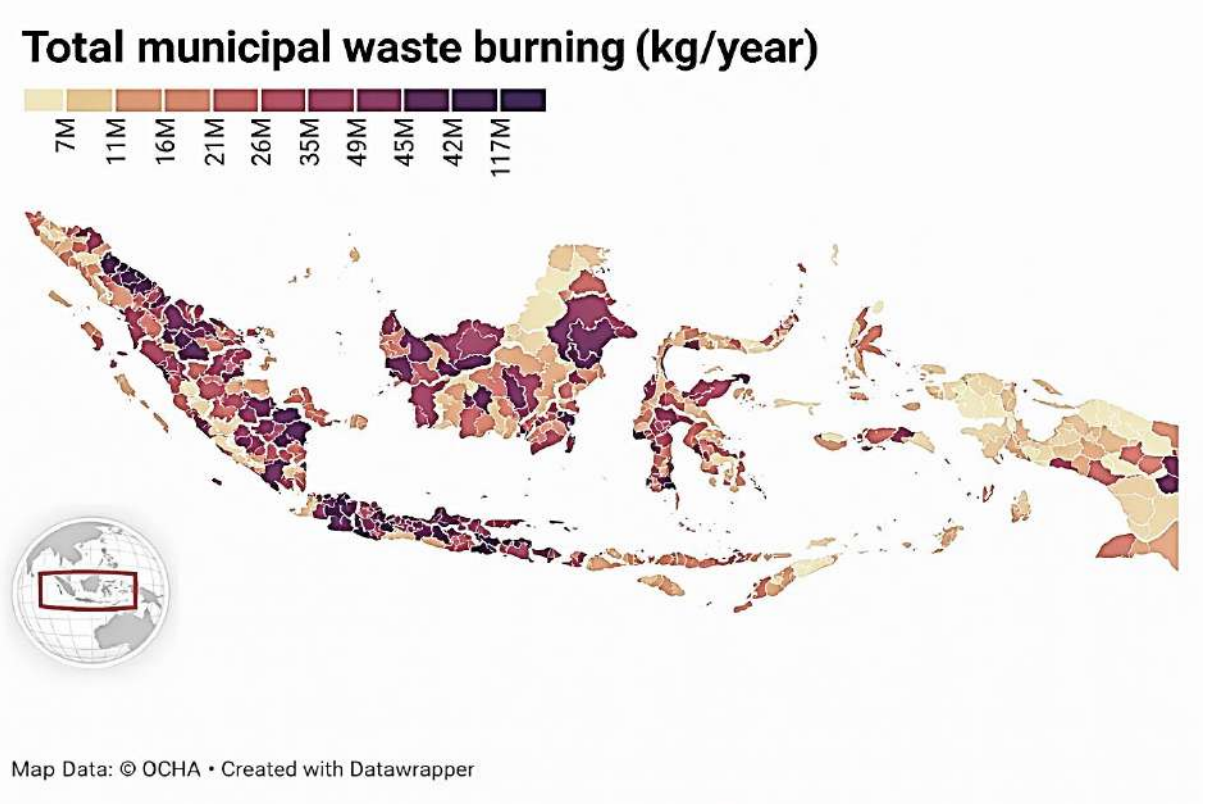

Fig. 3: Total waste burning incidents in Indonesia

This spatial concentration corresponds with regions noted for their high population density, significant municipal solid waste production, and ongoing deficiencies in efficient waste collection and treatment at the neighbourhood level. The continuity of high-intensity classes along Java's urban belt indicates that waste burning is not confined to isolated localities but represents a systemic challenge embedded within broader urban waste management dynamics (Guibrunet *et al.*, 2017). In Sumatra, the practice of burning waste reveals a more disjointed but nonetheless considerable pattern. Several districts in North Sumatra, South Sumatra, Riau, and Lampung fall within medium to high burning categories (approximately 35–77 Mkg/y), reflecting a combination of growing urban centres and semi-urban settlements with partial service coverage. Unlike Java, where high-intensity zones form contiguous clusters, Sumatra shows a patchwork distribution, suggesting localized drivers such as uneven municipal services, differences in settlement density, and variable reliance on informal disposal practices (Ramaswami *et al.*, 2016). The regions of Kalimantan and Sulawesi display mainly moderate to low levels of waste burning intensity, with sporadic hotspots located near provincial capitals and fast-growing urban areas. These localized peaks indicate that waste burning is closely tied to urban growth nodes rather than widespread regional practices (Zaman *et al.*, 2011). In contrast, eastern Indonesia (Maluku and Papua) is dominated by lower intensity classes (generally <21 Mkg/year), consistent with lower population densities and smaller absolute waste generation. Nonetheless, the existence of dispersed moderate-intensity areas indicates that waste burning continues to be significant even in less populated regions, probably influenced by inadequate formal waste

management systems rather than the actual quantity of waste (Salim *et al*., 2023). Overall, the map underscores that municipal waste burning in Indonesia is primarily a population- and urbanization-driven phenomenon, with the most severe burdens occurring in Java and major urban districts nationwide. The fine-scale spatial resolution highlights that mitigation strategies must move beyond provincial averages and instead target district-level hotspots, where interventions such as improved collection coverage, decentralized treatment, and behavioral change programs are likely to yield the greatest emission reductions (Thompson *et al*., 2024). This spatial diversity highlights the importance of implementing place-specific waste management strategies, particularly in fast-developing urban corridors where the rise in waste production continually exceeds the expansion of infrastructure (Midha and Horne, 2024). Open waste burning contributes not only to national greenhouse gas emissions and long-term climate change, but also to immediate local environmental and health risks. Pollutants such as particulate matter (PM), carbon monoxide, and other combustion-related gases can degrade air quality in nearby communities, particularly in densely populated areas where burning occurs close to households. This study focuses on quantifying emissions primarily in relation to their climate impact (expressed in CO_2 equivalents), yet the concentration of high-burning regions implies that the exposure to localized air pollution may be considerable. Therefore, reducing OWB can provide both short-term local air quality benefits and long-term climate mitigation advantages.

Reasons of Household Burning Practices

The survey results (Table 5) indicate that the respondent pool was dominated by female participants, who accounted for 62.88 % (n = 454) of the total valid responses, while male respondents represented 37.12 % (n = 268). This gender distribution indicates that the dataset significantly represents viewpoints from individuals who are frequently engaged in everyday household tasks, such as waste management and disposal choices. As such, the responses provide valuable insight into household-level waste management behaviors and perceptions relevant to residential OWB. Regarding educational qualifications, the participants were predominantly well educated, with the largest proportion holding a Bachelor's degree (42.80 %, n = 309), followed by senior high school or vocational education (39.89 %, n = 288). Smaller shares of respondents reported Diploma-level education (6.09 %) and Master's degree or higher (5.12 %), while respondents with only primary or junior high school education together accounted for less than 6.1 % of the sample. Notably, no respondents reported having no formal education. This educational profile suggests that the survey predominantly included participants who possess adequate literacy and awareness to offer informed feedback regarding waste management practices and perceived drivers of OWB. Regarding household roles and settlement characteristics, only 17.31 % (n = 125) of respondents identified themselves as heads of household, whereas the majority (82.69 %, n = 597) were non-head household members. This indicates that choices concerning waste management and incineration might not be determined exclusively by the heads of households, but are shaped by wider household interactions. Furthermore, most respondents resided in urban areas (78.67 %, n = 568), with 21.33 % (n = 154) living in rural settings. Given the higher representation of urban respondents, the survey results are interpreted as indicative of household experiences and are not used to claim

Table 5: Demographic profile of respondents

Gender	Total	Average
Male	268	37.12%
Female	454	62.88%
Highest level of education	Total	Average
No formal education	0	0.00%
Primary school	11	1.52%
Junior high school	33	4.57%
Senior high school / vocational high school	288	39.89%
Diploma	44	6.09%
Bachelor's degree	309	42.80%
Master's degree or higher	37	5.12%
Head of household	Total	Average
Yes	125	17.31%
No	597	82.69%
Living in urban / rural area	Total	Average
Urban	568	78.67%
Rural	154	21.33%

national prevalence estimates. The robust urban representation corresponds with the spatial analysis that indicates increased waste generation and burning intensity in urban and peri-urban areas, offering a significant demographic foundation for investigating the factors influencing residential OWB practices in Indonesia.

The waste management profile (Table 6) reveals substantial gaps between regulatory awareness, infrastructure availability, and actual household waste disposal practices. Although 41.27% (n = 298) of respondents reported being aware of regulations related to waste burning, a considerable proportion was either reported as not being aware (26.59%) or as not knowing about such regulations (32.13%). This suggests that over fifty percent of the participants do not possess a clear understanding of the current legal limitations regarding waste burning, indicating that regulatory frameworks have not been effectively conveyed or assimilated at the household level (Pathak *et al.*, 2023). Participation in socialization or training activities related to waste management was reported by 57.20 % (n = 413) of respondents, while 42.80% (n = 309) had never participated in any formal waste-related education or outreach. Despite this relatively high level of reported participation, the availability of supporting waste infrastructure remains limited. Only 20.97% (n = 250) of respondents indicated the presence of a waste bank in their neighborhood, while 44.74% reported that no waste bank was available and 20.64% were unsure. Furthermore, MRFs were only available to 18.84% (n = 136) of those surveyed, with nearly half (49.86%) indicating that such facilities were nonexistent in their locality, emphasizing the structural barriers that hinder effective waste diversion strategies. In terms of actual waste disposal practices, open burning remains the most prevalent method, reported by 30.03% (n = 358) of respondents. This exceeds the share of households served by community or private waste collectors (26.85 %) and municipal waste services (15.27%). Alternative disposal methods such as composting (12.25%) and burial (9.90%) were reported less frequently, while environmentally harmful practices such as disposing waste into rivers were reported by a small but notable fraction (2.85%). The minimal percentage of households contributing waste to waste banks (0.50%) highlights the restricted operational scope of material recovery systems (Budihardjo *et al.*, 2022).

Table 6: Waste management profile

Awareness of regulations related to waste burning	Total	Average
Yes	298	41.27%
No	192	26.59%
Do not know	232	32.13%
Socialization / training on waste management	Total	Average
Ever participated	413	57.20%
Never participated	309	42.80%
Availability of a waste bank	Total	Average
Yes	250	20.97%
No	323	44.74%
Do not know	149	20.64%
Availability of material recovery facility	Total	Average
Yes	136	18.84%
No	360	49.86%
Do not know	226	31.30%
Waste disposal method	Total	Average
Collected by community/private waste collectors	320	26.85%
Collected by municipal waste services (Environmental Agency)	182	15.27%
Burned	358	30.03%
Disposed of into the river	34	2.85%
Buried	118	9.90%
Composted	146	12.25%
Disposed of at waste collection site (WCS)	28	2.35%
Collected to waste bank	6	0.50%
Amount of waste generated per day	Total	Average
< 2 L	13	1.80%
5-L waste bin	188	26.07%
10-L waste bin	240	33.29%
15-L waste bin	144	19.97%
20-L waste bin	130	18.03%
More than 20-L waste bin	6	0.83%

Regarding daily waste generation, most households reported moderate waste volumes, with 33.29% (n = 240) generating approximately one 10-liter (L) waste bin per day, followed by 26.07 % (n = 188) using 5-L bins and 19.97% (n = 144) reporting 15-L bins. Only 18.03% generated around 20 L/d, and less than 1% exceeded this amount. This distribution implies that the occurrence of open burning is not chiefly motivated by unusually elevated waste generation, but rather by inadequate access to collection services and treatment infrastructure, highlighting the importance of systemic and institutional factors in shaping residential OWB practices (Ramaswami *et al*., 2016; Velis *et al*., 2021). Fig. 4(a) presents the composition of household waste generated, based on questionnaire responses, while Fig. 4(b) shows the composition of waste found in burned piles, reflecting materials that are preferentially subjected to residential burning. Food waste constitutes the largest portion of the generation profile at 33.68%, succeeded by thin-film plastics at 14.20%, backyard waste such as leaves and garden residues at 10.70%, rigid plastics at 9.85%, and paper and cardboard at 9.61%. Smaller fractions include wood (5.03 %), nappies (2.75 %), textiles, hazardous waste, rubber/leather, metals, and glass, each contributing less than 3 %. This distribution indicates that organic and low-density materials constitute the bulk of household waste streams, consistent with typical municipal waste profiles in Indonesia. Conversely, the structure of charred waste mounds (Fig. 4b) is distinctly different from the generation profile, underscoring selective combustion tendencies.

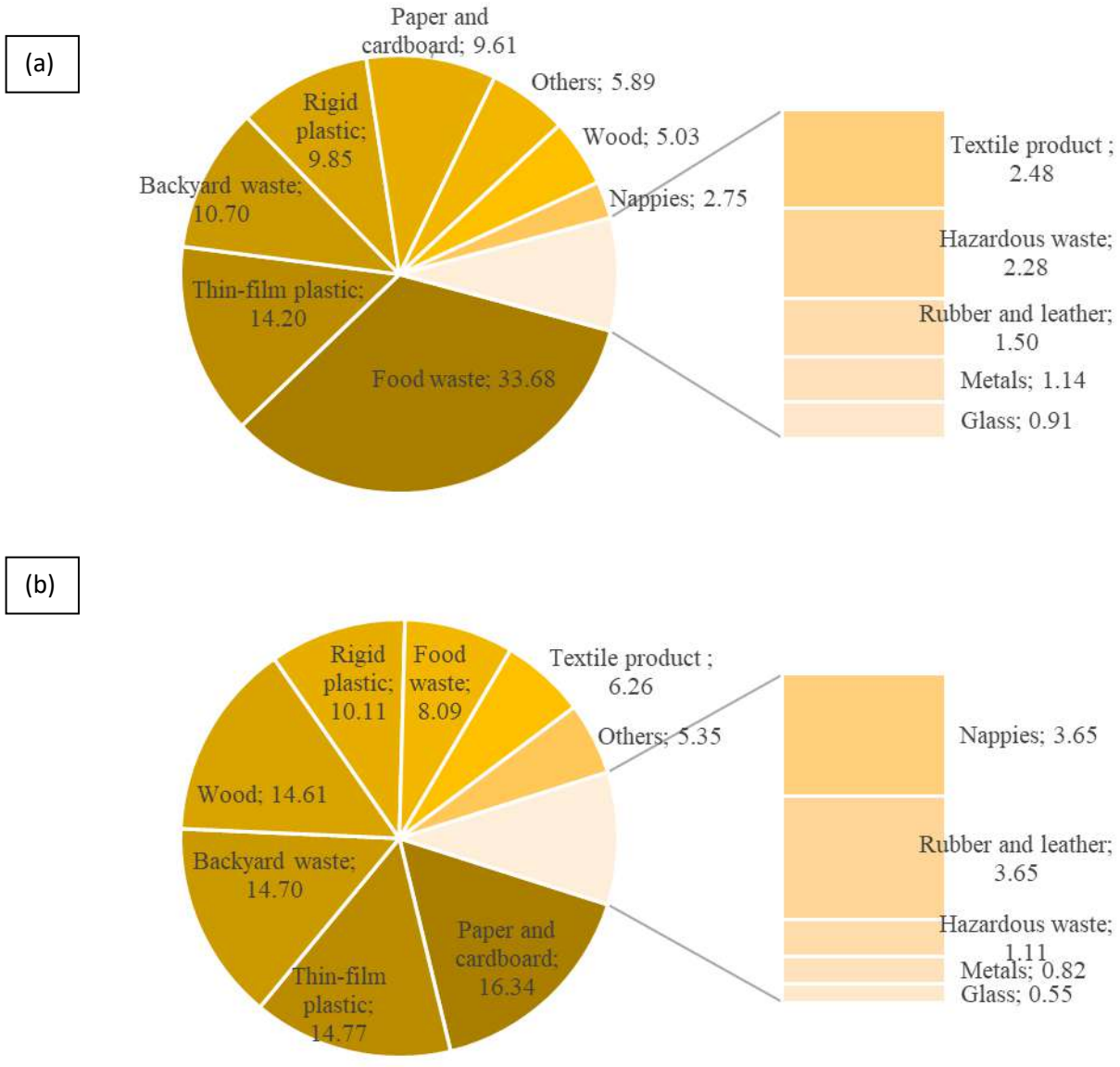

Fig. 4: (a) Percentage of waste generation; (b) percentage of waste found in burned piles based on questionnaire (%)

Paper and cardboard (16.34 %), thin-film plastics (14.77 %), backyard waste (14.70 %), and wood (14.61 %) collectively dominate burned materials, while food waste accounts for only 8.09 %. The diminished occurrence of food waste in incinerated piles indicates that moist organic materials are less prone to combustion, probably because of their elevated moisture levels and reduced combustibility (Chavan *et al.,* 2022). Conversely, dry, combustible materials such as paper, plastics, and wood are disproportionately represented, indicating that households consciously or unconsciously select materials that are easier to ignite and burn efficiently (Ramadan *et al.*, 2022a; Ramadan *et al.*, 2023). The additional data sourced from the SIPSN website further

elucidates these findings within the context of the nation. According to SIPSN, food waste constitutes the largest share of municipal solid waste (40.45 %) in Indonesia, followed by plastics (19.23 %), wood and garden waste (12.43 %), and paper and cardboard (11.16 %). Non-combustible components, including metals (3.57 %) and glass (2.39 %), as well as textiles and rubber/leather, constitute relatively small proportions. The close alignment between the SIPSN composition and the questionnaire-based generation profile supports the representativeness of the survey data, while the divergence between generated and burned waste highlights a critical behavioral dimension of residential OWB (Ramadan *et al*., 2022b). Furthermore, the findings suggest that the characteristics of the waste materials play a more significant role than the total amount of waste in determining the practice of burning residential waste. Although food waste dominates overall waste generation, it contributes far less to burned waste, whereas plastics, paper, and biomass residues are preferentially burned. This finding has important implications for mitigation strategies, suggesting that interventions targeting plastic reduction, paper recovery, and garden waste management may be more effective in reducing residential OWB than approaches focusing solely on organic waste treatment (Sharma *et al*., 2024; Wang *et al*., 2023).

Fig. 5 presents the results of the Latent Dirichlet Allocation analysis applied to open-ended questionnaire responses, revealing four dominant topics that explain the persistence of residential OWB practices. The average topic probability reflects the relative significance of each topic, demonstrating the frequency of the related narrative in the responses provided by participants (Buenano-Fernandez *et al.,* 2020). Topic prevalence reflects the respondent sample and was not weighted to adjust for demographic imbalance; therefore, the identified drivers should be interpreted within the context of the survey profile. The highest-ranked topic (Topic 1) corresponds to insufficient waste collection systems and inadequate infrastructure, emphasizing the structural constraints faced by households. This topic constitutes the most significant portion of responses, suggesting that a considerable number of households engage in waste burning primarily due to the lack, irregularity, or limited accessibility of formal waste collection services, rather than a conscious choice to violate regulations. The second most prominent theme (Topic 3) relates to convenience and ease of waste elimination, where respondents described burning as the fastest and most practical method to remove accumulated waste. This finding suggests that OWB is perceived as a low-effort solution, particularly in contexts where waste separation, storage, or transport to collection points requires additional time or resources. Closely related but less dominant is Topic 2, which highlights the lack of fees, penalties, or enforcement mechanisms associated with burning practices. The comparatively lower status of this subject suggests that economic barriers and regulatory enforcement are of lesser importance when compared to infrastructure and convenience; however, their lack still plays a role in the persistence of OWB. The study did not measure enforcement capacity or penalties directly. However, responses indicate that weak monitoring and limited enforcement reduce the deterrent effect of regulations, especially where waste services are inadequate. The lowest-ranked topic (Topic 4) captures habitual behavior, perceptions, and cultural traditions, indicating that social norms and long-standing practices play a role but are not the primary drivers at the national scale. Despite being considered less significant than structural factors, this issue illustrates that in various communities, open burning is regarded as a habitual and socially accepted practice that has been carried out for

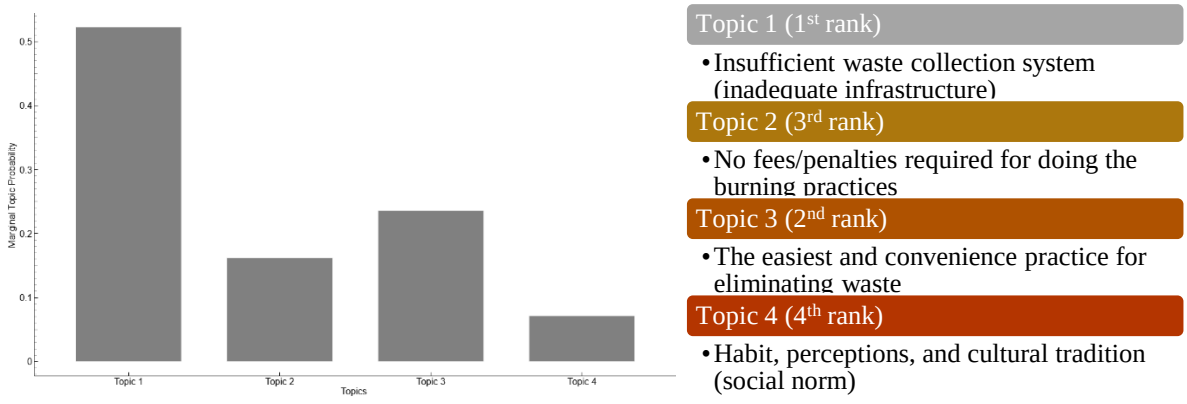

Fig. 5: Reason behind OWB practices

generations, particularly in locations where formal waste management services have historically been unavailable. This suggests that OWB in Indonesia is less a deeply entrenched cultural practice and more a pragmatic response to service gaps and daily household needs. Nevertheless, the persistence of habitual burning behavior indicates that infrastructure improvements alone may not fully eliminate OWB without parallel efforts to shift social norms and everyday household practices. Additional qualitative responses further support this interpretation, citing pest control, low perceived health and environmental risks, and limited awareness as reinforcing factors that sustain burning practices, even among respondents who are aware of alternative waste management options. While the survey lacked a comprehensive health risk perception scale, various responses suggest that the awareness of environmental and health effects is inconsistent. A considerable proportion of respondents reported limited knowledge of regulatory restrictions, and qualitative answers suggest that some households underestimate the health risks associated with smoke exposure. This indicates that insufficient risk awareness may contribute to the persistence of OWB alongside structural constraints. The findings from the LDA indicate that the residential OWB in Indonesia is primarily influenced by structural and practical elements, instead of cultural connections or intentional breaches of regulations. These findings reinforce the need for interventions that prioritize improving waste collection coverage and service reliability, alongside targeted awareness-raising and enforcement measures, to effectively reduce OWB practices at the household level (Etim *et al.*, 2024).

Strategy to reduce OWB practices

Fig. 6 summarizes the dominant strategies for reducing residential OWB as identified through LDA analysis of respondents' open-ended suggestions. The highest-ranked topic (Topic 1) emphasizes the need to improve reliable and affordable waste collection and treatment infrastructure, indicating that respondents perceive structural service improvements as the most effective intervention. This discovery supports previous findings that indicate insufficient collection coverage and restricted access to formal waste management facilities are the main factors contributing to OWB (Chaudhary *et al.*, 2021; Ramaswami *et al.*, 2016). The prominence of this topic suggests that behavioral change alone is insufficient in the absence of accessible and dependable waste services, particularly in densely populated and peri-urban

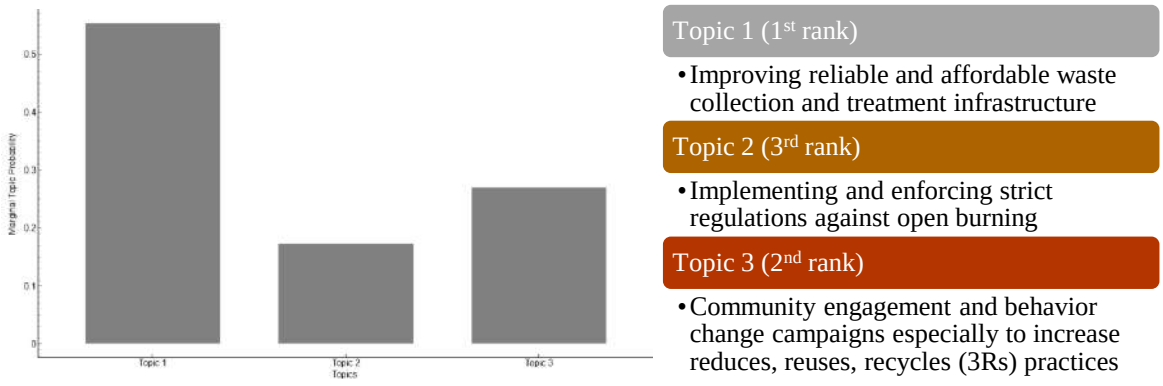

Fig. 6: Strategy to reduce OWB

areas. This outcome also indicates a disparity between the current national waste management regulations and their actual execution at the local level. Although Indonesia has established policy targets to reduce unmanaged waste and improve collection coverage, uneven infrastructure development and limited municipal capacity continue to constrain enforcement and service delivery. Consequently, households may choose open burning not from a lack of regulatory measures, but due to the absence of practical and affordable alternatives. The second most influential theme (Topic 3) highlights the importance of community engagement and behavior change campaigns, with a particular focus on strengthening reduce, reuse, and recycle (3Rs) practices. Participants consistently highlighted the importance of ongoing education, community involvement, and local leadership to promote source separation and waste minimization (Afnan *et al.*, 2025; Alimoradiyan *et al.,* 2024). The relatively high ranking of this topic indicates recognition that infrastructure improvements must be accompanied by social interventions that reshape everyday waste handling practices and perceptions, especially in households that currently rely on burning for convenience. In contrast, Topic 2, which focuses on implementing and enforcing stricter regulations against open burning, was ranked third. This indicates that although regulatory measures are recognized as essential, their effectiveness is viewed as diminished when applied independently (Wonkka *et al.,* 2015). Respondents implicitly recognized that enforcement without viable alternatives may be difficult to sustain and could disproportionately affect households lacking access to waste services. Taken together, the LDA results indicate that an effective OWB reduction strategy in Indonesia requires a sequenced and integrated approach, prioritizing infrastructure provision, reinforced by community engagement, and supported by consistent regulatory enforcement. This indicates that although regulatory measures are recognized as essential, their effectiveness is viewed as diminished when applied independently (Afnan *et al.,* 2025). Several studies and pilot initiatives in Indonesia and other low- and middle-income countries have demonstrated that improved waste collection coverage and community-based waste management programs can significantly reduce open burning practices. For example, community-led waste bank initiatives and expanded door-to-door collection services have been associated with reduced informal disposal and burning in peri-urban settlements (Velis *et al.*, 2021; Afnan *et al.,* 2025). These cases suggest that when reliable collection systems are combined with local engagement and awareness campaigns,

households are more likely to shift away from open burning toward formal disposal pathways. Although this study does not evaluate specific pilot projects quantitatively, existing evidence supports the feasibility of infrastructure and community-driven interventions as effective OWB reduction strategies. To assess the effectiveness of these interventions, it is essential to have clear and measurable indicators. These may include a reduction in the estimated amount of waste burned (Mt per year), lower OWB-related emissions ($MtCO_2e$), increased waste collection coverage (percentage of households served), higher participation in recycling or waste bank programs, and improved awareness of waste regulations. At the community level, a reduction in the reported instances of burning practices and improved waste separation may also signify advancement. Tracking these indicators over time will help evaluate whether the interventions are effective. Reducing open waste burning can also support Indonesia's Nationally Determined Contributions (NDCs). Since OWB produces greenhouse gas emissions, lowering this practice can help reduce national emissions and support the country's climate targets.

CONCLUSION

This study provides a comprehensive national assessment of residential OWB in Indonesia by integrating national datasets, a large-scale household survey, spatial analysis, and machine learning–based text analytics. By combining activity and emission inventory methods with village–city classifications obtained from official statistics, this study enhances prior methodologies and provides a more context-aware assessment of waste burning activities. The refinement introduced in this study specifically lies in the application of official village–city administrative classifications to improve the allocation of uncollected waste fractions and enhance spatial resolution compared with generalized rural–urban assumptions. The results indicate that approximately 26.6 Mt of municipal waste are openly burned annually, resulting in an estimated 23.3 $MtCO_2e$ of climate impact, with residential burning accounting for around 70% of total waste burned, substantially exceeding contributions from landfill fires. Spatial analysis reveals that OWB distributed unevenly, with Java Island accounting for the majority of national totals due to its high population density and significant absolute waste generation. Meanwhile, certain provinces in Sumatra and Sulawesi are identified as secondary hotspots. At finer administrative scales, district-level mapping highlights strong intra-provincial heterogeneity, underscoring the limitations of province-level averages for policy design. The analysis of the composition of waste generation in comparison to that of burned waste illustrates that OWB is a selective process. It shows that and combustible materials such as plastics, paper, wood, and garden waste disproportionately represented in burned piles, despite food waste dominating overall waste generation. The examination of waste generation composition relative to the survey results on burned waste, combined with topic modeling analysis, yields significant understanding of the core drivers of OWB. The dominant reasons for continued burning are structural and practical, particularly insufficient waste collection services and infrastructure, followed by convenience and weak enforcement. Cultural norms and habitual behavior play a secondary role. However, given the descriptive and inventory-based scope of the study and the higher representation of urban respondents in the survey, these findings reflect reported patterns and spatial associations rather than statistically verified causal relationships at the national level. Furthermore, the strategies aimed at reducing OWB focus on bolstering reliable and affordable waste collection and treatment systems, alongside community engagement and initiatives for behavior modification. Regulatory enforcement, on the

other hand, is less impactful without the presence of service provision. These findings highlight that OWB is largely a response to systemic gaps rather than intentional non-compliance. Overall, the study demonstrates that effective reduction of residential OWB in Indonesia requires a hierarchical and integrated policy approach. Priority should be placed on enhancing and stabilizing waste collection coverage, especially in urban and peri-urban hotspots, while also implementing targeted measures for combustible waste fractions. Community-based programs promoting waste reduction and segregation should be strengthened to support infrastructure investments, while enforcement mechanisms should be applied in a supportive and context-aware manner. It is essential to point out that the emission estimates outlined in this study are deterministic central values obtained from existing national datasets and literature-based emission factors. An analysis of uncertainty propagation in a formal context, as well as scenario-based modeling of potential reductions in emissions under better collection coverage were not conducted. Therefore, the reported values should be interpreted as indicative national scale estimates rather than precise measurements with quantified confidence intervals. Future research incorporating uncertainty analysis and mitigation scenario modelling would strengthen the quantitative basis for policy evaluation. By linking household behavior, spatial patterns, and emission impacts, this study provides an evidence-based foundation for designing targeted OWB mitigation strategies and contributes to national efforts to reduce air pollution and climate impacts from unmanaged waste.

AUTHOR CONTRIBUTIONS

B.S. Ramadan Conceptualization, validation, funding acquisition, and writing – original draft; S. Sendari Conceptualization, data curation, writing, review and editing, visualization; B. Ratnawati Visualization, project administration, software; A.D. Sakti Methodology, validation, resources; A.T. Balasbaneh Validation, software, methodology; M.A. Budihardjo formal analysis, project administration; T. Matsumoto Supervision, resources; A.S. Puspita Writing – original draft, validation, resources.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
λ	The proportion of waste at a dumpsite that is burned
δ	The fraction of combustible MSW
<	Less than
3Rs	Reduce, Reuse, Recycle
BC	Black carbon
B_{frac}	Carbon conversion fraction
BPS	Indonesian Statistical Agency
CF_j	The total carbon fractions
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon dioxide
CO_{2T}	Total CO_2 emissions
CSV	Comma-Separated Values
DKI	Daerah Khusus Ibukota
DLH	Dinas Lingkungan Hidup
dm_j	Dry matter
EF	Emission factor
EF_CH₄	Emission factor for methane
FCF_j	The total fossil carbon fraction
$F_{uncollected(rural)}$	Fraction of uncollected waste (rural)
$F_{uncollected(urban)}$	Fraction of uncollected waste (urban)
GRDP	Gross Regional Domestic Product
GWP_X	Global Warming Potential of pollutant x
IPCC	Intergovernmental Panel on Climate Change
kg/d	Kilogram per day
kg/y	Kilogram per year
km^2	Square kilometres
L	Litre
L/d	Litres per day
LDA	Latent Dirichlet Allocation
LDAvis	Latent Dirichlet Allocation Visualization
MDS	Multidimensional Scaling
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSW_p	Municipal Solid Waste generated
Mt	Million tonnes
Mt/y	Million tonnes per year
$MtCO_2e$	Million tonnes of carbon dioxide equivalent
NOx	Nitrogen Oxides (NO dan NO_2)
N_2O	Nitrous Oxide
OWB	Open Waste Burning
$PM_{2.5}$	Particulate Matter ≤2.5 µm
PM_{10}	Particulate Matter ≤10 µm
P_{rural}	Rural population
P_{urban}	Urban population
Rp	Indonesian Rupiah
SIPSN	National Waste Management Information System
SO_2	Sulfur Dioxide
t	Tonne
t/y	Tonnes per year
tCO_2e	Tonne CO_2 equivalent
W_B	Waste burning total
W_{Bdump}	Waste burning at disposal sites
W_{Bres}	Residential waste burning
WCS	Waste Collection Site
WF_j	The fraction of waste type/material of component j in the MSW

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The moderating role of renewable energy in the relationship between economic growth and carbon intensity

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ABSTRACT

BACKGROUND AND OBJECTIVES: Vietnam has experienced rapid economic growth accompanied by increasing energy consumption and environmental pressures, particularly rising carbon intensity. Minimizing carbon intensity is crucial for attaining sustainable development and fulfilling climate obligations. Renewable energy and innovation are expected to contribute to improving energy efficiency and decoupling economic growth from environmental degradation. Nevertheless, empirical data regarding the extent to which renewable energy influences the connection between economic growth and carbon intensity is still scarce. The study objectives were to examine both long-run and short-run relationships among economic growth, renewable energy, innovation, and carbon intensity in Vietnam from 1988 to 2021, while also evaluating the moderating role of renewable energy.

METHODS: This study implements a vector error correction modeling framework to assess long-term equilibrium relationships and short-term adjustment dynamics among the variables. The modeling approach allows identification of cointegration relationships and estimation of both long-run coefficients and short-run adjustment processes using annual time-series data.

FINDINGS: The results confirm a stable long-run equilibrium relationship. Economic growth has a negative and statistically significant effect on carbon intensity, with estimated coefficients of −0.00593 and −0.00503 in the two models, respectively, both statistically significant at the one percent level. In contrast, renewable energy consumption has a positive and statistically significant long-run effect on carbon intensity, with a coefficient of 0.00760. This implies that during the study period, renewable energy has primarily acted as a complement to fossil fuels instead of substituting them the interaction term between renewable energy and economic growth is statistically insignificant, indicating no moderating effect. Innovation also shows no statistically significant impact. In the immediate term, the majority coefficients are not statistically significant, and the movement towards long-run equilibrium takes place gradually.

CONCLUSION: The results reveal that decreasing carbon intensity in Vietnam is a prolonged undertaking that demands significant structural changes and enhanced integration of renewable energy to promote sustainable and low-carbon economic advancement.

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INTRODUCTION

Climate change and environmental degradation have become critical challenges to sustainable development, particularly due to greenhouse gas emissions generated from energy production and consumption. Carbon dioxide emissions (CO_2) are widely recognized as the primary driver of global warming, creating a major policy dilemma for developing economies that must simultaneously reduce emissions and sustain economic growth to achieve broader development objectives. Consequently, the interplay between economic expansion and the quality of the environment has emerged a pivotal subject in environmental and development economics (Grossman and Krueger, 1995; Stern, 2004). Traditionally, economic growth has been associated with increased energy demand, expanded production, and rising emissions, especially in economies heavily dependent on fossil fuels. Nevertheless, contemporary studies imply that the ecological effects of growth are contingent upon the energy framework, technological proficiency, and the comprehensive quality of economic change (OECD, 2011; Bowen and Hepburn, 2014). This perspective has led to the emergence of the green growth concept, which emphasizes the possibility of decoupling economic growth from carbon emissions through structural change and technological progress. Renewable energy has been widely identified as a key pillar of emission reduction strategies and green growth pathways. The expansion of renewable energy sources, including wind, solar, hydropower, and biomass, can reduce fossil fuel dependence and improve the environmental efficiency of economic activity (Sadorsky, 2009; Apergis and Payne, 2014). Nevertheless, empirical evidence indicates that the impact of renewable energy on emissions varies across countries and development stages. In transitional economies, renewable energy frequently serves as a complement to fossil fuels instead of a replacement, thereby constraining its efficacy in lowering emissions. Alongside renewable energy, technological innovation plays a crucial role in enabling economies to sustain growth while reducing environmental pressure. The principle of environmentally focused technological evolution posits that innovation improves energy efficiency and promotes the shift towards more cleaner production frameworks (Rennings, 2000; Popp, 2010). However, innovation does not always lead to environmental improvements, as scale effects may offset efficiency gains, particularly in developing countries (Ahmed *et al.,* 2016; Truong *et al.,* 2024). In this context, carbon intensity (CGI), defined as carbon dioxide emissions per unit of gross domestic product, has become an important indicator for assessing the environmental efficiency of economic growth. Furthermore, CGI serves as a valuable tool for understanding the relationship between economic output and emissions, highlighting the progress made in achieving sustainable growth without compromising environmental integrity (IPCC, 2023; Wang *et al.,* 2022). For Vietnam, this issue is especially urgent. Over the past three decades, Vietnam has experienced rapid economic growth accompanied by industrialization and urbanization, but its fossil fuel–dependent growth model has resulted in increasing emissions and CGI (Nguyen and Kakinaka, 2019; Le and Sarkodie, 2020). In reaction, Vietnam has pledged to attaining net-zero emissions by 2050 at the twenty-sixth United Nations Climate Change Conference held in 2021 and has put into action policies that foster renewable energy and green growth (World Bank, 2022; MOIT, 2024). Despite these efforts, the effectiveness of renewable energy in reducing CGI remains unclear. Existing empirical studies suggest that renewable energy contributes to emission reductions in the long run, while economic growth may increase emissions unless accompanied by structural and technological transformation (Mai *et al.,* 2024). Nonetheless, most studies prioritize direct effects and overlook the potential moderating effect of

renewable energy influences the connection between growth and CGI. To address this gap, this study investigates the moderating role of renewable energy in the relationship between economic growth and CGI in Vietnam, while also considering the role of innovation. Using annual time-series data from 1988 to 2021, this study places CGI at the canter of analysis and employs an interaction approach to assess whether renewable energy contributes to making economic growth more environmentally sustainable.

Theoretical background and analytical framework

This study employs an integrated framework based on three fundamental theoretical perspectives to examine the effects of economic growth, renewable energy, and innovation on CGI in Vietnam. Each theory offers a distinct yet complementary lens, collectively providing a comprehensive explanation of the key drivers and underlying mechanisms of greenhouse gas mitigation within the context of sustainable development. Vietnam, distinguished by its ongoing robust economic growth and a firm dedication to attaining net-zero emissions by 2050, serves as an ideal empirical environment to assess and enhance these theoretical frameworks. Traditional environmental economics posits that economic growth increases energy demand through the expansion of production and consumption activities, thereby leading to higher carbon emissions, particularly in economies heavily dependent on fossil fuels. In the early stages of development, countries often prioritize rapid economic expansion over environmental protection, causing CGI to rise alongside economic growth (Grossman and Krueger, 1995; Stern, 2004). Consequently, economic growth in itself is generally viewed as a factor that exacerbates environmental degradation unless accompanied by technological advancement and structural transformation in the energy sector. Renewable energy is regarded as a crucial tool for decreasing carbon emissions and improving the environmental efficiency of economic growth. Expanding the share of renewable energy in the energy mix gradually substitutes fossil fuels, thereby lowering emissions per unit of gross domestic product (GDP). A multitude of empirical studies reveal that there is a negative correlation between renewable energy usage and CO_2 emissions, particularly in the long run, when clean technologies and energy systems become increasingly stable and efficient (Sadorsky, 2009; Apergis and Payne, 2014). As proposed by green growth theory, economic growth can simultaneously achieve development and environmental protection objectives when supported by energy structure transformation and clean technological innovation. Central to this theory is the possibility of "decoupling" economic growth from environmental pressure, in which renewable energy plays a pivotal role in reducing the CGI of growth (OECD, 2011; Bowen and Hepburn, 2014). This perspective implies that the environmental impact of growth is not fixed but rather depends on the quality and structural composition of the growth process. In the context of the green growth framework, an interaction term involving economic growth and renewable energy is employed to reflect the moderating role of renewable energy on the connection between growth and carbon emissions. Specifically, when the share of renewable energy is low, economic growth tends to increase CGI; conversely, when renewable energy development reaches a higher level, the adverse environmental impact of growth may diminish or even reverse. Consequently, it is generally anticipated that the coefficient of the interaction term will be negative, suggesting that growth becomes more environmentally friendly in the context of energy transition (Zafar *et al.,* 2018; Shahbaz *et al*., 2020). Incorporating the interaction term into the empirical model not only enables the examination of the direct relationships among economic growth, renewable energy, and emissions, but also clarifies the conditions under which economic growth becomes environmentally sustainable. Therefore,

the interaction variable is an essential component in measuring the success of green growth strategies in developing economies. The theory of technological innovation posits that innovation is not solely aimed at enhancing productivity and economic efficiency, but also at mitigating negative environmental impacts. Such advancements include cleaner production technologies, enhancements in energy efficiency, the development of renewable energy sources, and sophisticated environmental management solutions. From this perspective, innovation is regarded as a central driver enabling economies to reduce carbon emissions without compromising economic growth (Rennings, 2000; Kemp and Pearson, 2007). This theoretical framework indicates that innovation leads to a reduction in carbon emissions via three key mechanisms. First, technological advancement enhances energy efficiency, thereby lowering the amount of energy consumed per unit of output. Second, innovation facilitates the transition of the energy structure from fossil fuels to low-carbon or carbon-free energy sources. Third, the role of innovation is to refine environmental management practices and production processes, which results in a reduction of both direct and indirect emissions throughout the value chain. Collectively, these mechanisms contribute to lowering the CGI of the economy in the long run (Popp, 2010; Dechezleprêtre and Sato, 2017). Based on the theories, the analytical framework of the study is illustrated in Fig. 1.

The relationship between economic growth, renewable energy, innovation, and CGI is complex and multidimensional, attracting considerable attention from both international and domestic scholars. Current empirical evidence indicates a lack of absolute agreement; instead, it highlights that the environmental effects of economic growth are significantly influenced by a nation's energy framework, technological capabilities, and institutional-social conditions. At the international level, Sadorsky (2009) finds that economic growth stimulates renewable energy consumption in the long run across emerging Asian economies, implying that economic expansion facilitates investment in clean energy sources. Even though carbon emissions are not directly factored into the model, the research establishes a crucial basis for the claim that renewable energy might aid in lowering the CGI of growth. Building on this line of inquiry, Apergis and Payne (2014), employing panel data and autoregressive distributed lag (ARDL) model approach, demonstrate that renewable energy reduces CO_2 emissions over the long term, whereas economic growth increases emissions. Their findings highlight the decisive role of energy structure in shaping the environmental consequences of growth. From a dynamic perspective, Shahbaz *et al.* (2017) test the Environmental Kuznets Curve (EKC) hypothesis for Asian countries and report that CO_2 emissions increase during the early stages of economic development but decline as countries shift toward cleaner energy sources and more efficient technologies. This evidence indicates the possible "greening" function of renewable energy and technological advancements in alleviating environmental pressures over time. Concurrently, the role of innovation has been emphasized in both theoretical and empirical studies. Popp (2010) demonstrates that technological innovation enhances energy efficiency and reduces carbon emissions in the equilibrium relationship, particularly when supported by appropriate environmental policies. Ahmed *et al.* (2016), employing panel data for Asian countries and applying FMOLS and DOLS estimators, find that technological innovation reduces CGI, whereas economic growth tends to increase emissions in the absence of accompanying innovation. These conclusions bolster the claim that innovation serves as a vital prerequisite for separating economic growth from carbon emissions. Complementing this stream of research, Truong *et al.* (2024), drawing on cross-country data from Asia, provide important and somewhat cautionary evidence. First, it has been established that standard technological

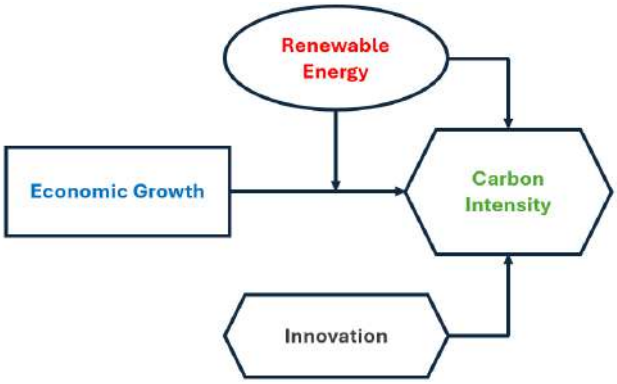

Fig. 1: Analytical framework

advancements, as indicated by the quantity of patents, contributes to a rise in CO_2 emissions, due to the scale effect being more significant than the efficiency effect. Second, renewable energy is identified as the most effective instrument for reducing emissions; however, its share in total energy consumption has been declining, despite an increase in absolute output. Third, the inverted U-shaped relationship between economic growth and emissions suggests that emissions indicates that emissions could persist in increasing without proactive policy measures. Finally, population growth exhibits a strong positive association with CO_2 emissions, whereas forest area contributes to emission reductions only to a modest extent. Based on these findings, the study underscores the necessity of prioritizing innovation in renewable energy, controlling population growth, enhancing energy-saving awareness, and strengthening forest protection policies, rather than relying on the presumed "self-correcting" mechanism of economic growth. In the context of Vietnam, empirical findings are relatively consistent. Nguyen and Kakinaka (2019) and Le and Sarkodie (2020) show that economic growth and fossil fuel consumption increase CO_2 emissions, whereas renewable energy contributes to emission reductions in the long run. Recently, Mai *et al.* (2024) continue to highlight the crucial importance of renewable energy in mitigating the CGI of growth in Vietnam. Specifically, Mai *et al.* (2024) present compelling quantitative data demonstrating the adverse effect of renewable energy on CO_2 emissions. A synthesis of the literature reveals that economic growth is generally associated with rising carbon emissions, whereas renewable energy and innovation, particularly clean energy-oriented innovation, play a crucial role in reducing CGI and promoting sustainable growth. Nevertheless, majority of the current studies, particularly those that focus on Vietnam and the larger Asian context, predominantly analyzes the direct and distinct effects of economic growth or renewable energy on absolute CO_2 emissions, failing to specify the conditions under which economic growth becomes less carbon intensive. In the Vietnamese context, previous research has largely concentrated on the independent roles of renewable energy or technological innovation, while the moderating role of renewable energy in the relationship between economic growth and CGI has not been systematically tested through the inclusion of an interaction term. Furthermore, relying solely on absolute CO_2 emissions fails to completely reflect the environmental efficiency associated with economic growth. In contrast, CGI serves as a more suitable metric for evaluating the decoupling process between growth and emissions. The study aims to underscore the need for an in-depth empirical investigation into the combined and moderating roles of renewable

energy in shaping the CGI of economic growth in Vietnam. This study has been conducted in Vietnam and covers the period 1988-2021.

MATERIALS AND METHODS

Based on the theoretical foundations discussed in the previous section, this analysis examines the relationship among economic growth, renewable energy, and innovation in shaping carbon emission intensity. S In particular, it makes use of time-series data for Vietnam spanning the period 1988 - 2021. CGI serves as the dependent variable, measured as CO_2 emissions per unit of GDP. The variables that explain the phenomenon include economic growth, renewable energy, and innovation, proxied by the number of patent applications. The data are obtained from reputable international sources, such as the World Bank and the International Energy Agency, ensuring reliability and comparability. This dataset facilitates a thorough evaluation of the economic and technological factors influencing emission reduction and green growth. Table 1 presents a detailed description of the variables used in this study.

Variables

The variables employed in this study are classified into dependent, independent, and moderating variables, selected based on their theoretical foundations and empirical relevance to ensure an adequate explanation of the research question. Moreover, all variables are converted into natural logarithms (Ln) to stabilize variance, alleviate potential heteroskedasticity, and diminish the impact of extreme values. The logarithmic transformation not only linearizes potential nonlinear relationships but also enables the estimated coefficients to be interpreted as elasticities, which is consistent with standard practice in empirical studies on economic growth and environmental economics. Carbon intensity (CGI) is defined as the amount of CO_2 emitted per unit of an economic variable such as GDP, energy output, or transport activity. CGI is the dependent variable, measuring the amount of CO_2 emissions per unit of economic value, typically expressed as tons of CO_2 per billion United States Dollar (USD) of GDP. This indicator represents the degree of "dirtiness" or "greenness" associated with economic growth, specifically the amount of emissions produced for each unit of economic output. World Bank (2015) employs this indicator to compare environmental efficiency across countries and growth models. In this study, CGI is measured as tons of CO_2 per billion USD of GDP, following the approach of Wang *et al.* (2022). The representation of economic growth is through GDP at constant 2015 prices, which signifies the total value added created by the economy during a particular year. GDP functions as a primary indicator for evaluating the economic size and performance. As shown by Max (2021), economic growth is defined as “an increase in the output of goods and services that an economy produces over time.” The World Bank (2015) defines GDP as the total value added from all legal productive activities within an economy. In the empirical model, GDP is employed as a proxy for economic growth, following the measurement approach of Ha and Hanh (2024). Renewable energy (RPG) consists of energy obtained sustainably from natural sources that remain inexhaustible. Renewable energy refers to energy generated from naturally replenishable sources, including wind, solar, hydropower, biomass, geothermal, and ocean energy. In this study, RPG is measured as electricity generation from renewable energy sources with billion kilowatt hours (kWh), following the approach of Hoa *et al*. (2023). This variable captures the extent of green energy transition within the economy (IRENA, 2023). Innovation (PAR) characterized as the launch or application of a novel or considerably improved product, organizational approach, or marketing strategy. Innovation is represented by the quantity of resident patent applications, which indicate technological output and the level of

Table 1: Description of variables

Variables	Description	Data Source	Sources
CGI	Carbon intensity of GDP (tons of CO_2 per billion USD of GDP), serving as the dependent variable.	Data for the period 1988-2021 are obtained from the World Development Indicators (WDI) of the World Bank and the International Energy Agency (IEA), collected via TheGlobalEconomy.com (accessed November 12, 2025).	Wang *et al.,* 2022
GDP	Gross Domestic Product, measured in billion USD at constant 2015 prices, representing economic growth.		Ha and Hanh, 2024
RPG	Electricity generation from renewable energy sources (billion kilowatt-hours), representing renewable energy.		Hoa *et al.,* 2023
PAR	Resident patent applications, representing innovation.		Truong *et al.,* 2024

innovative endeavors within the economy (OECD, 2018). The World Intellectual Property Organization (WIPO, 2023) identifies patent counts as the most used indicator to measure innovation at the national level. In the empirical model, PAR serves as the proxy for innovation, following Truong *et al.* (2024).

Gross domestic product × Renewable energy (GDP × RPG)

The interaction term is constructed to capture the moderating role of renewable energy in the relationship between economic growth and CGI. Furthermore, this theory posits that a greater reliance on renewable energy sources will lead to a reduction in the detrimental environmental consequences of economic expansion. Therefore, the coefficient of the interaction term (GDP × RPG) is generally anticipated to be negative (Zafar *et al.,* 2018; Shahbaz *et al.,* 2020). This variable enables the empirical examination of whether economic growth in Vietnam becomes "greener" as the economy transitions toward renewable energy.

Research hypotheses

Drawing upon environmental economics, green growth theory, and the theory of technological innovation, this study formulates a set of testable hypotheses concerning the determinants of carbon intensity. The field of environmental economics underscores the influence of economic growth on environmental results; green growth theory points out the critical role of renewable energy in boosting environmental efficiency, while the theory of technological innovation emphasizes the ability of innovation to reduce emissions through improving energy efficiency and promoting cleaner production processes. Accordingly, the following hypotheses are proposed:

H1: Economic growth exerts a statistically significant long-run effect on carbon intensity.
H2: Renewable energy has a statistically significant impact on carbon intensity.
H3: Innovation significantly influences carbon intensity.
H4: Renewable energy moderates the relationship between economic growth and carbon intensity.

These hypotheses provide the conceptual foundation for the empirical model specification and guide the interpretation of the estimated long-run and short-run coefficients.

Model specification and theoretical foundation

To test the above hypotheses, the following empirical models are specified:

Model 1 is constructed based on the foundational theoretical frameworks in environmental economics and green growth, which posit that economic growth, energy structure, and innovation are key determinants of a country's carbon emissions. Furthermore, traditional environmental economics illustrates that as economic growth occurs, energy demand escalates and production scales up, consequently causing a rise in carbon emissions, especially in economies that are still largely dependent on

fossil fuels (Grossman and Krueger, 1995; Stern, 2004). In contrast, green growth theory emphasizes the role of renewable energy in reducing CGI by substituting polluting energy sources with cleaner technologies (OECD, 2011; Bowen and Hepburn, 2014). Moreover, the theory of environmentally oriented technological change suggests that innovation enhances energy efficiency and accelerates the transition toward low-carbon technologies, thereby contributing to long-term emission reductions (Rennings, 2000; Popp, 2010). On this basis, Model 1 is designed to measure the direct effects of economic growth, renewable energy, and innovation on CGI in Vietnam, in accordance with the empirical strategies employed in prior studies (Sadorsky, 2009; Apergis and Payne, 2014; Nguyen and Kakinaka, 2019):

$$LnCGI_t = \alpha_0 + \alpha_1 LnGDP_t + \alpha_2 LnRPG_t + \alpha_3 LnPAR_t + \varepsilon_t \quad (1)$$

Model 2 extends Model 1 by incorporating an interaction term between economic growth to renewable energy, thereby exploring the moderating influence of renewable energy in the context of economic growth and CGI. This approach is grounded in green growth theory and the "decoupling" framework, which argue that the environmental impact of economic growth is not fixed but depends on the quality and structural composition of the growth process, particularly the energy mix (OECD, 2011; Bowen and Hepburn, 2014). When the share of renewable energy remains low, economic expansion typically results in a rise in CGI; yet, once renewable energy achieves a sufficiently elevated level of development, the detrimental environmental consequences of growth are projected to decrease. Accordingly, the interaction term (GDP × RPG) is incorporated into the model to explicitly capture this moderating mechanism, with the coefficient expected to be negative, indicating that economic growth becomes "greener" in the context of energy transition. The use of an interaction model not only enables the assessment of the individual effects of each variable but also clarifies the conditions under which economic growth in Vietnam can achieve sustainable development objectives and reduce CGI in the equilibrium relationship, using Model 2 (Zafar *et al.,* 2018; Shahbaz *et al.,* 2020):

$$LnCGI_t = \alpha_0 + \alpha_1 LnGDP_t + \alpha_2 LnRPG_t \text{ x } LnGDP_t + \alpha_3 LnPAR_t + \varepsilon_t \quad (2)$$

The selection of the vector error correction model (VECM) in this study is grounded in the robust theoretical foundations of modern time-series econometrics, particularly the theory of cointegration and dynamic modeling. In the context of macroeconomic variables, such as economic growth, renewable energy consumption, innovation, and CGI, which often show non-stationary patterns and develop over time, the use of standard static regression models may result in spurious regression, consequently causing misleading economic interpretations (Granger and Newbold, 1974). Therefore, from a methodological standpoint, it is essential to employ a modeling framework capable of simultaneously addressing the non-stationarity of the data and capturing the long-run equilibrium relationships among the variables. According to Engle and Granger (1987), if non-stationary time series exhibit one or more stationary linear combinations, then the variables are said to be cointegrated and "must be modeled within an error-correction framework to fully capture both short-run dynamics and long-run equilibrium." This assertion offers the theoretical underpinnings for the establishment of the vector error correction model (VECM), in which the error correction term (ECT) denotes the magnitude of departure from long-term equilibrium and functions as an endogenous mechanism that drives the system back toward its equilibrium path. Johansen (1991) extends the Engle and

Granger (1987) approach by developing a cointegration estimation method within a system-of-equations framework, allowing for the determination of the number of cointegrating vectors and the simultaneous estimation of long-run relationships in a multivariate setting. Following Johansen (1995), the VECM is described as "the most natural representation of a system of cointegrated economic variables, in which all variables are treated as endogenous and engages in dynamic interactions over time." This approach is particularly appropriate for the present study, as CGI, economic growth, renewable energy, and innovation do not exhibit a simple unidirectional relationship but instead interact within a complex dynamic system characterized by mutual interdependence. From an economic interpretation perspective, Enders (2015) emphasizes that the VECM highlights that the VECM offers a significant benefit compared to traditional regression models in that it "distinctly separates short-run effects (captured through differenced terms) from long-run effects (captured through the error correction component)," while also delivering insights into the rate at which the system returns to equilibrium. In the present study, the coefficient of the error correction term (ECT) indicates the extent to which CGI in Vietnam adjusts toward its long-run trajectory following shocks arising from economic growth, renewable energy, or innovation. Moreover, Greene (2018) argues that in multivariate dynamic models, assuming exogeneity of certain variables is often unrealistic. System-oriented methods like the VECM are consequently "more aligned with theoretical frameworks, as they permit all variables to be regarded as endogenous and jointly determined." This aspect is especially pertinent to studies concerning the environment and economic progress, where the dynamics among emissions, growth, and technology are characterized by by mutual interactions rather than simple unidirectional causal links. From an empirical standpoint, the use of the VECM in this research is consistent with the methodological practices of numerous international studies examining the nexus between economic growth, energy, and carbon emissions. Research by Sadorsky (2009), Apergis and Payne (2014), Le and Sarkodie (2020), as well as Nguyen and Kakinaka (2019), has employed cointegration-based approaches and VECM/ARDL models to simultaneously analyze short-run dynamics and long-run relationships among environmental and economic variables. This evidence indicates that the VECM is firmly based on robust theoretical principles and demonstrates significant methodological consistency and normative endorsement in empirical studies. First, the study identifies the optimal lag length for the empirical model. The selection of an appropriate lag order in a VECM is crucial to ensure correct model specification and to adequately capture the dynamic interrelationships among economic variables. An optimal lag structure helps balance model fit and model parsimony, while mitigating residual autocorrelation and enhancing the reliability and efficiency of the estimated coefficients. Subsequently, unit root tests are conducted to verify that the variables are integrated of order one. Following this, the Johansen cointegration test is applied to determine the number of cointegrating vectors within the system (Johansen and Juselius, 1990). If at least one cointegrating relationship is identified, the VECM is applied to concurrently estimate both long-run and short-run effects among the variables. In this framework, the error correction term (ECT) captures the speed at which the system adjusts back to its long-run equilibrium after short-run shocks, with the adjustment coefficient expected to be negative and statistically significant (Nkoro and Uko, 2016). Ultimately, to evaluate the sufficiency and dependability of the estimated model, a set of diagnostic tests is performed on the residuals and the overall stability of the system. Specifically, the Normality Test is utilized to determine whether the residuals adhere to a normal distribution, thereby confirming the

reliability of statistical inferences. The Breusch-Godfrey Serial Correlation LM Test is then applied to detect the presence of autocorrelation in the residuals, which could otherwise bias statistical significance tests. In addition, the VEC Residual Heteroskedasticity Test is used to evaluate the stability of residual variance over time, while the CUSUM test is performed to assess the stability of the regression coefficients and to detect potential structural breaks throughout the study period. In conclusion, the utilization of the VECM in this study is well-supported by three scientific arguments: i) from a statistical viewpoint, the VECM effectively resolves the issue of spurious regression when dealing with non-stationary time-series data; ii) from a theoretical perspective, it appropriately reflects the dynamic structure and endogeneity of economic-environmental variables; and iii) from an empirical economics perspective, it facilitates the concurrent estimation of short-run dynamics, long-run relationships, and the adjustment mechanism toward equilibrium, thereby providing a comprehensive analytical framework with significant policy relevance for investigating the nexus between economic growth and CGI in Vietnam.

RESULTS AND DISCUSSION

Regarding the descriptive statistics, CGI has a mean value of 0.711 and ranges from 0.418 to 1.087, indicating substantial variation in CO_2 emissions per unit of GDP in Vietnam over time. GDP exhibits an average value of 148.3 billion USD, with a standard deviation of 90.0, reflecting strong economic growth and significant expansion in economic scale throughout the study period. In a similar vein, both RPG and PAR exhibit notably high standard deviations, indicating significant variations in the development and innovation activities related to renewable energy. Table 2 presents the descriptive statistics and the correlation matrix of the research variables. Table 2 presents the correlation matrix of the variables in their natural logarithmic form, including LnCGI, LnGDP, LnRPG, and LnPAR. The findings suggest that every correlation coefficient is positive, demonstrating a positive linear relationship among the variables in the sample. Specifically, LnCGI exhibits a relatively strong correlation with LnRPG (r = 0.750) and LnPAR (r = 0.672), as well as a moderate-to-high correlation with LnGDP (r = 0.642). These findings suggest that economic growth, renewable power generation, and patent applications generally align with carbon intensity trends throughout the duration of the study. Moreover, the correlations among the independent variables are also relatively high, particularly between LnGDP and LnPAR (r = 0.761), and between LnRPG and LnPAR (r = 0.765). However, these coefficients remain below the conventional threshold of 0.80, indicating no serious multicollinearity concerns based on commonly accepted empirical criteria (Gujarati and Porter, 2009; Hair *et al.,* 2019). Nevertheless, the Variance Inflation Factor (VIF) ought to be performed during the regression phase to guarantee the stability and dependability of the estimated coefficients. Overall, the correlation matrix reveals statistically meaningful linear relationships among the variables, consistent with theoretical expectations and providing a preliminary basis for subsequent econometric modeling. Table 3 reports the results of the optimal lag length selection based on several statistical criteria, including the likelihood ratio (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz criterion (SC), and Hannan–Quinn criterion (HQ).

Table 3 presents the results of the optimal lag length selection for the VAR model based on several statistical criteria, including the Log-likelihood (LogL), Likelihood Ratio (LR), Final prediction error (FPE), Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan–Quinn Criterion (HQ). The results indicate that most information criteria—namely LR, FPE,

Table 2: Descriptive Statistics and Correlation Matrix

Variables	LnCGI	LnGDP	LnRPG	LnPAR
LnCGI	1.00000			
LnGDP	0.642498	1.00000		
LnRPG	0.750245	0.667527	1.00000	
LnPAR	0.671953	0.760638	0.765232	1.00000
Variables	CGI	GDP	RPG	PAR
Mean	0.711097	148.3176	32.44853	261.6765
Std. Dev.	0.186977	90.01107	29.48436	292.2730
Minimum	0.418000	39.90000	1.770000	20.00000
Maximum	1.086600	332.2000	111.7800	1066.000

Table 3: Optimal lag selection

Lag	LogL	LR	FPE	AIC	SC	HQ
0	2.688.045	NA	2.81e-06	-1.430.028	-1.246.811	-1.369.297
1	2.001.766	292.4373*	1.53e-10*	-11.26104*	-10.34495*	-10.95738*
2	2.142.596	2.024.429	1.81e-10	-1.114.123	-9.492.273	-1.059.464

(*) indicates the optimal lag selected according to the corresponding criterion in the lag selection table. Specifically, it marks the lag with the best value, typically the minimum value for information criteria such as the Akaike Information Criterion, Schwarz Criterion, Final Prediction Error, and Hannan–Quinn Criterion.

AIC, SC, and HQ—select a lag length of 1 (lag = 1) as optimal, as denoted by the asterisk (*). Specifically, at lag 1, the AIC (-11.26104), SC (-10.34495), and HQ (-10.95738) attain their minimum values compared to other lag orders, while the LR test is also statistically significant at the 5% level. In accordance with the standard selection principle, the model that corresponds to the lowest values of the information criterion is favored, as it maintains a balance between goodness of fit and model parsimony. The consensus among the criteria in favor of lag = 1 suggests that the dynamic structure of the variable system is not overly complex and that a single lag is sufficient to capture the temporal dependencies among the variables (Lütkepohl, 2005). Therefore, a VAR model with lag length 1 is adopted as the basis for conducting the Johansen cointegration test and estimating the subsequent VECM framework. Overall, the outcomes of the lag selection are coherent and fitting in light of the sample size, thus bolstering the stability and trustworthiness of the time-series estimations. Table 4 reports the results of the Augmented Dickey–Fuller (ADF) unit root tests for the variables LnCGI, LnGDP, LnRPG, LnPAR, and the interaction term LnRPG × LnGDP at both the level and first-difference forms. The results indicate that at the level specification, all variables have p-values greater than 0.05; therefore, the null hypothesis (H_o) of a unit root cannot be rejected. This implies that the series are non-stationary at levels, signifying that they display time-dependent stochastic trends. However, at the first-difference specification, all variables display p-values below 0.05, allowing rejection of H_o at the 5% significance level. Hence, the variables become stationary after first differencing; in other words, all variables are integrated of order one, I(1). The condition that all variables possess the same order of integration, I(1), is essential for carrying out cointegration tests aimed at assessing the existence of a long-run equilibrium relationship among them. These findings therefore provide a solid econometric foundation for applying the VECM framework to analyze both the dynamic and long-run relationships in the subsequent empirical analysis. Overall, Table 4 confirms that the data are suitable for cointegration analysis and do not violate the fundamental requirement regarding

Table 4. ADF stationarity test results

Variable	Level			1st difference		
	Stat.	Prob.	Conclusion	Stat.	Prob.	Conclusion
LnCGI	-0.028006	0.9491	Non-Stationary	-5.664.141	0.000	Stationary
LnGDP	-3.476.471	0.1168	Non-Stationary	-2.681.659	0.001	Stationary
LnRPG	-2.474.729	0.1306	Non-Stationary	-5.369.342	0.001	Stationary
LnPAR	-0.247619	0.9223	Non-Stationary	-5.852.521	0.000	Stationary
LnRPG x LnGDP	0.417116	0.9801	Non-Stationary	-3.591.021	0.012	Stationary

the order of integration of the time-series variables. As suggested by Engle and Granger (1987) and Johansen (1991), when variables are non-stationary at levels but become stationary after first differencing and share the same order of integration, a long-run equilibrium relationship may exist among them. Given these circumstances, utilizing the VECM is both suitable and theoretically well justified.

Table 5 reports the results of the Johansen cointegration test based on both the Trace test and the Maximum Eigenvalue test to determine the number of cointegrating relationships among the variables in the model. For the Trace test, the null hypothesis of no cointegration ("None") is rejected at the 5% significance level (Trace statistic = 51.00355 > Critical value = 47.85613; p = 0.0246). Nevertheless, regarding the hypothesis "At most 1," the test statistic remains below the critical value, and the p-value exceeds 0.05, suggesting that the null hypothesis of having at most one cointegrating relationship cannot be dismissed. This implies the existence of at least one cointegrating relationship within the system. Similarly, the Max-Eigenvalue test rejects the null hypothesis of no cointegration at the 5% level (p = 0.0253), while subsequent hypotheses are not rejected. The consistency between the two tests strengthens the evidence of a unique long-run equilibrium relationship among the variables. The presence of at least one cointegrating vector indicates that, despite the variables being non-stationary at their levels, they are connected in the long term via a stable equilibrium relationship. This finding confirms the appropriateness of employing the VECM framework to analyze both short-run dynamics and long-run relationships in the study. Overall, the Johansen results provide strong econometric evidence of cointegration and justify the estimation of the VECM in the subsequent empirical analysis. The results of the long-run regression analysis concerning the independent variables affecting CGI are displayed in Table 6. In accordance with econometric theory, the statistical significance of a regression coefficient is evaluated using the t-statistic. Under the null hypothesis (H_o), which states that the regression coefficient equals zero, H_o is rejected when the absolute value of the t-statistic surpasses the relevant critical value at the selected significance level. The larger the absolute value of the t-statistic, the lower the probability that the true coefficient is equal to zero, thereby indicating a higher level of confidence in the estimate (Gujarati and Porter, 2009). Wooldridge (2016) further emphasizes that when the absolute value of the t-statistic substantially exceeds commonly used critical thresholds, such as 1.96 at the 5% significance level or 2.58 at the 1% significance level, the rejection of the null hypothesis becomes particularly strong. This provides robust evidence that the relationship between the variables is distinctly recognized and consistently supported by the empirical data. Table 6 reports the long-run estimation results for two models, where Model (1) excludes the interaction term, while Model (2) incorporates the interaction between LnRPG and LnGDP to examine the moderating effect. In Model (1), the coefficient of LnGDP is negative and statistically significant (t = -2.777), indicating that economic growth leads to a decrease in CGI over the long term. Specifically, a 1% increase in GDP is

Table 5: Results of the Johansen cointegration test

Test of trace				
Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob
None *	0.546472	5.100.355	4.785.613	0.0246
At most 1	0.360751	2.570.121	2.979.707	0.1379
At most 2	0.266279	1.138.245	1.549.471	0.1890
At most 3	0.045030	1.474.415	3.841.465	0.2246
Max-Eigenvalue test				
Hypothesized No. of CE(s)	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	Prob
None	0.546472	2.530.233	2.758.434	0.0253
At most 1	0.360751	1.431.877	2.113.162	0.3394
At most 2	0.266279	9.908.033	1.426.460	0.2180
At most 3	0.045030	1.474.415	3.841.465	0.2246

Table 6: Long-run estimation results

Variables	Estimation	Model (1)	Model (2)
		CGI	CGI
LnGDP	Coefficients	-0.197920	-0.267985
	Standard errors	0.16813	0.25857
	t-statistics	-2.77718	-2.93642
LnRPG	Coefficients	0.070065	
	Standard errors	0.09691	
	t-statistics	2.72302	
LnRPG x LnGDP	Coefficients		0.070065
	Standard errors		0.09691
	t-statistics		0.72302
LnPAR	Coefficients	0.156721	0.116380
	Standard errors	0.00445	0.03545
	t-statistics	-0.28251	-0.12410

associated with an approximate 0.198% decline in carbon intensity, suggesting improvements in environmental efficiency as the economy expands. In contrast, LnRPG exhibits a positive and statistically significant coefficient (t = 2.723), implying that renewable power generation is positively associated with CGI during the study period. This observation could suggest a transitional energy system in which renewable energy has not entirely supplanted fossil fuels but rather functions alongside them in the short and medium term. Meanwhile, LnPAR is statistically insignificant, suggesting that patent applications do not exert a clear long-run effect on carbon intensity. In Model (2), after introducing the interaction term LnRPG × LnGDP, the coefficient of LnGDP remains negative and statistically significant (t = -2.936), reinforcing the evidence of the carbon-reducing effect of economic growth. Nevertheless, the interaction term does not exhibit statistical significance (t = 0.723), suggesting a lack of empirical evidence for the moderating effect of renewable energy on the relationship between economic growth and carbon intensity over the long term. The coefficient of LnPAR also remains insignificant. Comparing the two models shows that including the interaction term does not materially alter the sign or significance of LnGDP and does not generate a statistically significant moderating effect. Therefore, the empirical evidence primarily supports the direct impact of economic growth on CGI, while the moderating role of renewable energy is not clearly confirmed in this sample. Overall, the long-run results highlight the importance of economic growth in shaping carbon intensity dynamics, whereas the roles of technological innovation and renewable energy warrant further investigation within the context of the ongoing energy transition. The VECM

estimation outcomes illustrated in Table 7 demonstrate that, in the short term, the adjustment dynamics of CGI are influenced in different manners by the variables in the system, with significant distinctions observed between Model 1 and Model 2 following the incorporation of the interaction term. The coefficient of the error correction term (CointEq1 – ECT) is negative (-0.0534) in both models, which is consistent with the theoretical expectation of adjustment toward long-run equilibrium. However, the coefficient is not statistically significant (t = -0.420), indicating that the speed of adjustment toward long-run equilibrium in the short run is weak and does not provide sufficient evidence of a strong correction mechanism during the study period. Concerning the first-differenced variables, D(LnCGI(-1) does not exhibit statistical significance in either model (t ≈ 1.25), indicating that the short-run endogenous dynamics of CGI are not pronounced. D(LnGDP(-1) carries a positive coefficient but fails to reach statistical significance (t ≈ 1.50–1.59), implying that economic growth does not exert a significant short-run impact on changes in CGI. Similarly, D(LnRPG(-1) and D(LnPAR(-1) are statistically insignificant, indicating that renewable energy and technological innovation do not have a clear short-run effect on carbon intensity. In Model (2), the interaction term D(LnRPG × LnGDP(-1) is also statistically insignificant (t = 0.685), suggesting the absence of a short-run moderating effect of renewable energy on the relationship between economic growth and CGI. An analysis of the two models indicates that the inclusion of the interaction term does not substantially modify the short-run dynamic structure. The VECM findings overall suggest that the connections between the variables predominantly occur in the long term rather than in the short term, whereas the short-term effects are comparatively weak and lack statistical significance. This suggests that the linkage between economic growth, renewable energy, and carbon intensity operates through gradual long-run adjustment rather than immediate short-term fluctuations. The diagnostic tests conducted after estimation, as shown in Table 8, validate that the VECM adheres to the essential econometric assumptions. Specifically, the normality test, Breusch-Godfrey serial correlation test, and heteroskedasticity test all yield p-values greater than 0.05, indicating that the residuals are normally distributed, free from serial correlation, and exhibit constant variance. The Variance Inflation Factor (Table 9) analysis indicates that all cantered VIF values remain below the conventional threshold of 10, suggesting that multicollinearity is not a serious concern in either specification (Gujarati and Porter, 2009; Hair *et al*., 2019). Despite the interaction term displays comparatively elevated VIF values, they are still within permissible boundaries and thus do not compromise the estimation outcomes. Furthermore, the CUSUM test in Fig. 2 confirms the stability of the estimated coefficients over time and the absence of structural breaks, thereby reinforcing the reliability and robustness of the empirical findings.

A synthesis of the VECM results reveals that the relationship among economic growth, renewable energy, innovation, and CGI in Vietnam exhibits a clear divergence between long-run and short-run dynamics, while also reflecting the structural characteristics of a transitioning economy. Over the long term, economic growth demonstrates a negative, stable, and highly statistically significant influence on CGI, suggesting that as the economy achieves higher levels of development, advancements in energy efficiency and structural transformation contribute to reducing emissions per unit of GDP. This result aligns with the green growth framework and empirical evidence from studies such as Shahbaz *et al.* (2017), which argue that the environmental impact of economic growth is not fixed but depends on the quality and composition of growth over the long term. However, in contrast to numerous international and domestic studies that find renewable energy reduces emissions of CGI (Apergis and Payne,

Table 7: Short-run estimation results of the VECM model

Variables	Model (1)	Model (2)
	D(CGI)	D(CGI)
CointEq1 (ECT)	-0.053431 (0.12721) [-0.42002]	-0.053431 (0.12721) [-0.42002]
D(LnCGI(-1))	0.334514 (0.26666) [1.25443]	0.334514 (0.26666) [1.25443]
D(LnGDP(-1))	1.277324 (0.80216) [1.59235]	1.218539 (0.80952) [1.50527]
D(LnRPG(-1))	0.058785 (0.09606) [0.61197]	
D(LnPAR(-1))	-0.002421 (0.04222) [-0.05735]	-0.002421 (0.04222) [-0.05735]
D(LnRPG x LnGDP(-1))		0.056740 (0.09765) [0.68567]

Note: Standard errors in ( ); *t-statistics in* [ ]

Table 8: Post-estimation diagnostic tests

Test	P-Value		Results
	Model (1)	Model (2)	
Normality test	0.54356	0.45345	The residuals follow a normal distribution
Breusch-Godfrey serial correlation LM test	0.76578	0.32098	No autocorrelation
VEC residual heteroskedasticity test	0.89791	0.22345	The residuals of the VECM model exhibit homoskedasticity

Table 9: Variance Inflation Factor (VIF)

Model	Variables	Uncentered VIF	Centered VIF
Model (1)	LnGDP	6.284	2.947
	LnRPG	5.973	2.811
	LnPAR	4.562	2.305
Model (2)	LnGDP	8.742	3.418
	LnRPG × LnGDP	12.416	4.876
	LnPAR	5.231	2.764

2014; Mai *et al.,* 2024), the empirical results of this study demonstrate that renewable energy exerts a positive effect on CGI in the long run. This discovery aligns with theoretical expectations and instead highlights the unique aspects of Vietnam's energy transition throughout the study period. First, the "crowding-out" effect between renewable energy and fossil fuels may not yet have occurred at a sufficient scale. For many years, renewable energy in Vietnam has developed primarily as a complementary source to meet rapidly growing energy demand, rather than directly replacing coal- or gas-based electricity. When renewable energy is predominantly utilized as an enhancement to the total energy supply, there is an increase in overall electricity generation, while the fuel structure largely stays the same, resulting in no corresponding reduction in CGI. Second, this result may reflect the "green paradox" mechanism, whereby the announcement and promotion of renewable energy policies may incentivize increased

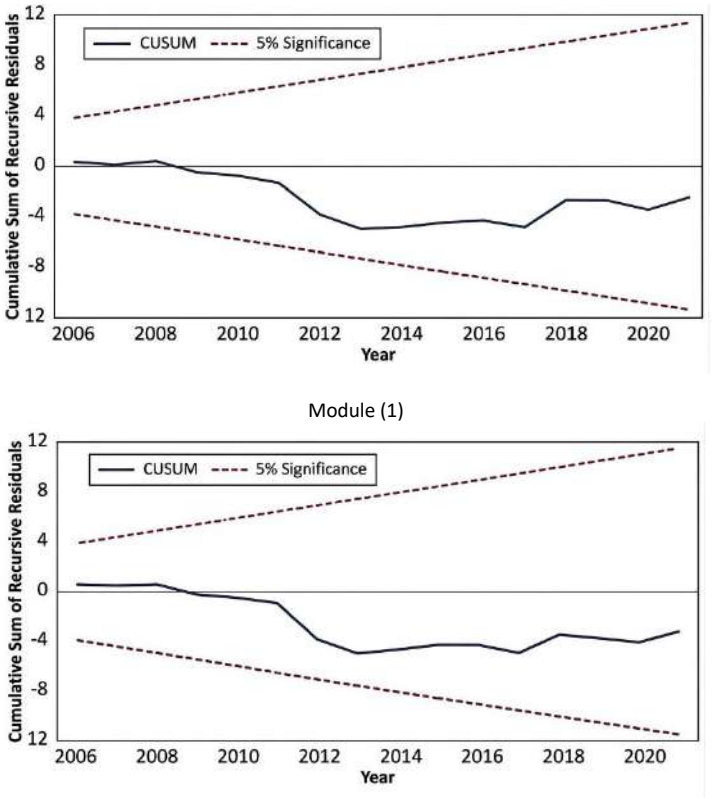

Fig. 2: CUSUM test

extraction and use of fossil fuels in the short and medium term due to expectations of declining future prices. In the context of Vietnam, where coal continues to represent a considerable portion of the energy mix, the concurrent development of both renewable and fossil fuel energy sources may contribute to a rise in total emissions. Third, the process of investing in, constructing, and integrating renewable energy systems, including transmission infrastructure, storage facilities, and imported equipment, may generate considerable indirect emissions. If the emissions throughout the life cycle have not been fully optimized, the overall environmental advantages of renewable energy in the initial phases of implementation may fall short of the anticipated reduction in CGI. Therefore, the positive impact of renewable energy on CGI suggests that the issue does not lie with renewable energy itself, but rather with its limited substitution effect and incomplete integration within the national energy system. This conclusion indicates that for renewable energy to effectively lower CGI, Vietnam should redirect its attention from just expanding capacity to improving substitution efficiency and systematically phasing out high-emission power sources. In addition, the results indicate that innovation and the moderating role of renewable energy, captured through its interaction with economic growth, are not statistically confirmed over the long term. This conclusion aligns with the findings of Truong *et al*. (2024), who assert that the quantity of patents as a measure of innovation does not automatically equate to progress in environmentally conscious technology. In the short run, the explanatory variables do not exert statistically significant

immediate effects on CGI, while the adjustment mechanism toward long-run equilibrium exists but operates at a slow pace. This indicates that the system does not quickly absorb economic and energy-related shocks. These findings are consistent with prior studies employing VECM and ARDL approaches in the Vietnamese context, such as Nguyen and Kakinaka (2019) and Le and Sarkodie (2020). They also imply that reducing CGI is a cumulative and long-term process, requiring sustained, coordinated, and targeted implementation of green growth and energy transition policies, rather than relying on rapid short-run adjustment effects.

Policy Implications

Based on the empirical findings from the VECM and in comparison, with prior research evidence, it can be observed that the process of reducing CGI in Vietnam is driven more by structural and long-term factors than by short-term adjustments. The evidence indicate that economic growth, renewable energy, and innovation do not automatically lead to improvements in environmental efficiency rather, their influence is felt only when they are adequately guided and supported by the right policy frameworks. Therefore, based on the empirical results, the study proposes several key policy implications aimed at promoting the transition toward green growth and reducing CGI in Vietnam over the long term. First, the focus of policy should transition from increasing the magnitude of economic growth to refining its quality. The empirical results show that, in the long run, economic growth contributes to reducing CGI, implying that as the economy reaches higher levels of development, improvements in energy efficiency and structural transformation enhance environmental performance. Therefore, policy initiatives ought to focus on improving productivity enhancement and the development of high value-added and technology-intensive sectors, instead of sustaining a growth model heavily reliant on resource extraction and energy-intensive production. Second, renewable energy policy should be reoriented toward improving depth and effectiveness rather than merely expanding installed capacity. The discovery that renewable energy has a beneficial impact on CGI indicates that, currently, renewable energy in Vietnam mainly functions as a supplementary source instead of effectively substituting fossil fuels. Hence, policy should focus on increasing the effective share of renewable energy in total energy consumption, improving its integration into the national power system, reducing indirect emissions associated with investment and infrastructure development, and accelerating the gradual phase-out of high-carbon energy sources. Third, innovation policy should be reoriented toward promoting "green innovation." The empirical findings indicate that innovation, as measured by patent counts, does not exert a statistically significant impact on reducing CGI. This indicates that not every innovation activity is advantageous for the environment. Therefore, Vietnam should design targeted innovation policies that prioritize energy-efficient technologies, clean production methods, and technologies that support renewable energy development, rather than focusing solely on increasing the overall number of patents. Fourth, policymakers should not expect immediate short-term reductions in CGI but instead adopt consistent and long-term policy frameworks. The lack of notable short-term impacts from economic and energy factors suggests that the reduction of CGI is a gradual process necessitating continuous effort over an extended period. Accordingly, green growth policies should be implemented with a long-term, stable, and coherent strategic vision,

avoiding abrupt policy shifts that could disrupt investment and undermine the effectiveness of the energy transition process. Fifth, the targets for reducing CGI should be incorporated into Vietnam's comprehensive socio-economic development strategy and its commitments to achieving net-zero emissions. As CGI provides a more accurate measure of the environmental efficiency of economic growth than absolute emission levels, it should be adopted as a central indicator for assessing growth quality. Integrating CGI reduction targets into sectoral development planning, national energy strategies, and innovation policies will help ensure that economic growth is aligned in a substantive and sustainable manner with Vietnam's commitment to net-zero emissions. Overall, the proposed policy implications suggest that reducing CGI in Vietnam cannot be achieved through isolated measures or by relying on the self-correcting mechanisms of economic growth. Conversely, it calls for a well-rounded and collaborative strategy that emphasizes the improvement of growth quality, the expansion of renewable energy development, the alignment of innovation with environmentally sustainable technologies, and the preservation of consistent long-term policies. Integrating CGI reduction into socio-economic development strategies and net-zero commitments will ensure that Vietnam's economic growth is not only rapid in scale but also environmentally sustainable, thereby providing a solid foundation for long-term development.

CONCLUSION

This study examines the long-run equilibrium relationship and short-run adjustment dynamics between carbon intensity, economic growth, renewable energy, and innovation in Vietnam over the period 1988-2021 using the vector error correction model framework. The cointegration findings validate the presence of a stable long-term relationship among the variables, suggesting that carbon intensity and its influencing factors progress together over time towards a shared equilibrium trajectory. The long-run estimation reveals that economic growth has a negative and statistically significant effect on carbon intensity across model specifications. This finding suggests that economic development in Vietnam has been associated with improvements in energy efficiency and structural transformation toward less carbon-intensive production activities. With the increase in income levels, the enhancement of technology, the modernization of industrial processes, and the movement towards sectors that add greater value help in lowering emissions per unit of output. These results support the view that sustained economic development can enhance environmental efficiency when accompanied by structural and technological progress. In contrast, renewable energy exhibits a positive and statistically significant long-run effect on carbon intensity in the baseline model. This result indicates that, during the study period, renewable energy expansion may have primarily complemented rather than replaced fossil fuel consumption. The ongoing dependence on fossil fuels, along with transitional inefficiencies and limitations in infrastructure, could have restricted the capacity of renewable energy to reduce carbon intensity. Furthermore, the interaction term between renewable energy and economic growth does not demonstrate a statistically significant moderating effect. This suggests that renewable energy has not yet played a sufficiently strong role in altering the relationship between economic growth and carbon intensity in the long run. These results emphasize that the efficacy of renewable energy in alleviating environmental

stress is contingent not only upon its growth but also on its ability to replace fossil fuels and seamlessly integrate into the energy framework. Innovation does not show a statistically significant effect on carbon intensity in either model. This result suggests that overall patent activity may not adequately capture environmentally oriented technological progress or that innovation has not been sufficiently directed toward clean energy and low-carbon technologies. The advantages for the environment stemming from innovation may necessitate enhanced policy backing, focused investment, and ample time to develop. The short-run results indicate that most explanatory variables do not exert statistically significant immediate effects on carbon intensity, and the error correction mechanism is weak and statistically insignificant. This implies that modifications aimed at reaching long-run equilibrium happen progressively, and that decreases in carbon intensity signify a cumulative and enduring process instead of a result influenced by short-term variations. These findings provide several important policy implications. First, maintaining sustainable economic growth remains essential, as higher levels of development are associated with lower carbon intensity over time. Second, renewable energy policy should prioritize improving substitution efficiency, enhancing grid integration, and reducing structural dependence on fossil fuels, rather than focusing solely on expanding installed capacity. Third, innovation policies ought to prioritize green and energy-efficient technologies to enhance the environmental advantages of technological progress. Fourth, long-term and stable policy frameworks are necessary to support structural transformation and ensure effective decarbonization. Several limitations should be acknowledged. The analysis is based on aggregate national data and may not fully capture sectoral differences or regional heterogeneity. Furthermore, innovation is assessed through patent data, which might not accurately represent the environmental impact of technological advancements. Future research could incorporate sector-specific indicators, energy efficiency measures, and nonlinear modeling approaches to better capture the dynamic relationship between renewable energy, economic growth, innovation, and carbon intensity. A more in-depth examination of threshold effects and structural alterations during the energy transition would also enhance our understanding. Overall, the findings indicate that reducing carbon intensity in Vietnam is fundamentally a long-term structural process that requires sustained economic development, effective renewable energy integration, and targeted technological innovation. Strengthening these factors will be critical to achieving sustainable growth and supporting the transition toward a low-carbon economy.

AUTHOR CONTRIBUTIONS

Khang The Nguyen performed the whole study and confirms as a sole responsibility for the study conception, design, data analysis, interpretation, and manuscript writing.

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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 author.

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ABBREVIATIONS

%	Percent
AC	Autocorrelation
AIC	Akaike Information Criterion
ARDL	Autoregressive Distributed Lag
CE(s)	Cointegrating equations(s)
CGI	Carbon intensity of GDP
CO_2	Carbon dioxide
CUSUM	Cumulative Sum of Recursive Residuals
D	First difference operator
ECT	Error correction term
EKC	Environmental Kuznets Curve
FPE	Final Prediction Error
GDP	Gross domestic product
HQ	Hannan–Quinn criterion
I(0)	Integrated of order zero
I(1)	Integrated of order one
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
LM	Lagrange Multiplier
LR	Likelihood ratio
MOIT	Ministry of Industry and Trade (Vietnam)
OECD	Organisation for Economic Co-operation and Development
PAC	Partial autocorrelation
PAR	Patent applications (resident)
Prob.	Probability value
RPG	Renewable power generation
SC	Schwarz criterion
Std. Dev.	Standard deviation
USD	United States Dollar
VECM	Vector Error Correction Model
WDI	World Development Indicators
WIPO	World Intellectual Property Organization

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ORIGINAL RESEARCH PAPER

Eco-friendly oil-based botanical insecticides for cocoa, efficient in safeguarding non-target species from natural predators of formicidae

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ABSTRACT

BACKGROUND AND OBJECTIVES: Cocoa (*Theobroma cacao* L.) is a major tropical cash crop in Indonesia, but yields are constrained by the cocoa pod borer (*Conopomorpha cramerella*), which can cause 30–50 percent losses. The traditional use of pyrethroids frequently results in resistance and negative impacts on non-target organisms; consequently, there is an urgent need for environmentally friendly alternatives that protect natural enemies. The study objectives were to evaluate oil-based botanical insecticides from *Reutealis trisperma* (candlenut) and *Cerbera manghas* (bintaro) for cocoa pod borer control and for impacts on non-target ants (Formicidae).

METHODS: In South Sulawesi, field trials were performed utilizing a randomized complete block design (eight treatments × four replicates). Treatments included *Reutealis trisperma* and *Cerbera* manghas oil formulations (5 and 10 milliliters), a combined plant extract, lambda-cyhalothrin (1 milliliter), and untreated control. Every 15 days, applications were performed with a knapsack sprayer for a total of six cycles. For each sampled tree, thirty healthy pods were tagged and monitored for infestation, damage severity, and yield loss, which was assessed using a published regression model. Non-target monitoring focused on Formicidae; visual counts were recorded at each sampling and classified using an ordinal scale (+ = 1–10; ++ = 11–20; +++ = 21–30 ants per tree). The analysis of variance and Duncan's Multiple Range Test at $\alpha = 0.05$ were employed to assess infestation, yield, and egg-laying suppression, whereas the Formicidae data were summarized descriptively due to low field densities.

FINDINGS: Botanical oil treatments significantly reduced cocoa pod borer infestation compared with the control ($p < 0.05$), decreasing from 35–72 percent initially to 0–10 percent by the fifth application; lambda-cyhalothrin showed no advantage (39–46 percent). Yield loss remained low in botanical treatments (0.00–0.98 percent) compared with 11.71 percent in the synthetic treatment, and egg-laying suppression reached 90–100 percent. Throughout the different botanical treatments, the abundance of Formicidae stayed within the low (+) category, in contrast to the control, which averaged ++. No significant declines in ant abundance related to the treatments were noted. Phytotoxicity was minor and temporary.

CONCLUSION: *R. trisperma and C. manghas* oil formulations are effective in suppressing cocoa pod borer and in conserving ants' natural enemies under the conditions tested. These botanical insecticides consequently serve as a practical and eco-friendlier aspect of integrated pest management for sustainable cocoa production, with the ability to lessen reliance on long-lasting synthetic pesticides when paired with enhanced formulation and extension support.

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INTRODUCTION

Cocoa (*Theobroma cacao* L.) is a socially and economically important crop in Indonesia, underpinning rural livelihoods and contributing substantially to national export earnings; Indonesia remains one of the world's largest cocoa producers, accounting for roughly 12 percent (%) of global supply (ICCO 2023). Cocoa productivity is, nonetheless, consistently hindered by insect pests and diseases; the most significant of these in Southeast Asia is the cocoa pod borer (CPB), *Conopomorpha cramerella* (Lepidoptera: Gracillariidae), which drills into the pods and can result in considerable yield losses often reported between 30% and 50% when unmanaged (Damalas, 2016; Matthews *et al.,* 2014). The direct economic ramifications of CPB outbreaks surpass yield loss — escalated pest management costs, lower quality, and market effects intensify poverty risks for smallholder producers (Boateng *et al.,* 2023). Economic feasibility is a key consideration for adoption. Damalas (2017) indicated that, on an active-ingredient basis, biopesticides typically incur greater costs than synthetic pesticides, yet they may prove to be economically advantageous in markets where residue-free cocoa is valued more highly. The oils examined in this study can be produced from locally available feedstocks, supporting decentralized production and reducing reliance on imported inputs. Traditionally, CPB and various cocoa pests have been managed through the frequent use of synthetic insecticides, particularly pyrethroids. This method provides rapid knockdown; however, it comes with significant environmental and human health consequences. Botanical formulations contain multiple active compounds, potentially lowering single-site resistance risk compared with pyrethroids; however, adaptation remains possible. Botanical oils should be integrated with pheromone monitoring, sanitation, and rotation within integrated pest management (IPM) programs. However, the rotation within IPM is recommended (Isman, 2020; Pavela and Benelli, 2016). Intensive synthetic pesticide use accelerates the development of insecticide resistance in pest populations and undermines long-term control efficacy (Damalas, 2016; Mishra *et al.,* 2021). At the ecosystem level, many broad-spectrum insecticides are persistent and mobile: residues accumulate in soil and may leach into water bodies, which alter microbial communities, degrades soil quality, and contaminates surrounding aquatic ecosystems (Mubushar *et al.,* 2019). Pesticide drift and contamination have also been linked to reduced pollinator and beneficial-arthropod abundance and to sublethal effects altered reproduction, foraging and development) that diminish the ecosystem services these organisms provide (Desneux *et al.,* 2007; Ndakidemi *et al.,* 2016). Such impacts create a damaging feedback loop in cocoa agroecosystems: loss of natural enemies and pollinators leads to a decrease in biological control and pollination services, which subsequently escalates reliance on chemical control and the risk of secondary pest outbreaks (Bacci *et al.,* 2007; Desneux *et al.,* 2007). Protecting and leveraging natural enemies is therefore central to sustainable CPB management. Natural enemies recorded in cocoa and similar systems include predators (ants, spiders, predatory beetles), parasitoids (various hymenopteran and tachinid species), and entomopathogens; these agents contribute measurable suppression of pest populations and can substantially reduce the need for chemical interventions when conserved (Ndakidemi *et al.,* 2016; Silva *et al.,* 2019). As an illustration, field studies have indicated that effective habitat management and decreased use of insecticides lead to increased numbers of beneficial arthropods, which in turn improves natural biological control (Ochieng *et al.,* 2022). In the present study area, Formicidae (ants) were consistently observed and can act as both predators and deterrents of CPB oviposition, so any effective pest-management strategy must be evaluated for effects on these groups

(Ndakidemi *et al.,* 2016). Given the environmental and socio-economic problems associated with persistent chemical use, there is growing interest in botanical (plant-derived) insecticides as components of environmentally sensitive IPM. Botanical insecticides—such as essential oils, seed oils, and extracts rich in alkaloids or terpenoids—tend to have advantageous environmental characteristics: they are generally rapidly biodegradable, possess low persistence in soil and water, and often display enhanced selectivity, thus reducing non-target impacts in comparison to many synthetic broad-spectrum chemicals (Isman, 2020; Ngegba *et al.,* 2022). Reviews and field reports note that botanical formulations can deliver satisfactory pest suppression while conserving beneficial arthropods and lowering residue loads on crops and in soils (Campos *et al.,* 2019; Fenibo and Matambo, 2025). Significantly, numerous botanicals function through various mechanisms (such as repellence, feeding deterrence, oviposition disruption, and direct toxicity), which may alleviate selection pressure for resistance mechanisms that operate at a single site (Isman, 2020). Nevertheless, botanical products present practical challenges that must be addressed for broad adoption. Plant compounds are often photolabile and volatile, and unformulated extracts may have short residual activity or reduced stability under high temperatures and microbial activity — factors which can lower field persistence and efficacy (Joeniarti *et al.,* 2020; Ayllón-Gutiérrez *et al.,* 2024). Advances in formulation science (e.g., microencapsulation, emulsions, nanoemulsions and ultraviolet (UV) protective adjuvants) can extend residual activity and improve handling, thereby enhancing the operational viability of botanical insecticides while retaining ecological benefits (Ayllón-Gutiérrez *et al.,* 2024). Indigenous plant species exhibiting proven insecticidal characteristics are appealing for farmer-driven, cost-effective measures. Previous laboratory and small-plot studies have reported promising activity for oils and extracts from *Reutealis trisperma* and *Cerbera manghas* against multiple insect pests (Prabowo and Damaiyani 2019; Sholahuddin *et al*. 2018; Purwani *et al*. 2014). Various plants have been employed by researchers as raw materials for botanical insecticides, including garlic (*Allium sativum* L.) (Liliales: Liliaceae) (Ali *et al.,* 2017), lemon (*Citrus limon* (L.) Burm. f.) (Rutales: Rutaceae) (Ali *et al.,* 2017), and tobacco (*Nicotiana tabacum*) (Kanmani *et al.,* 2021), turmeric (*Curcuma longa* L.) (Zingiberales: Zingiberaceae) (Ali *et al.,* 2014), neem (*Azadirachta indica*) (Sapindales: Meliaceae) (Abla and Nyamador, 2019; Adhikari *et al.,* 2020; Castillo-Sánchez *et al.,* 2015), cloves (*Syzygium aromaticum* (L.) Merr. and L.M. Perry) (Myrtales: Myrtaceae) (Ikawati *et al.,* 2020), and Citronella (And*ropogon nardus* L.) Order: Poales: *Poaceae*) (Papulwar *et al.,* 2018). Other plants such as pyrethrum (*Chrysanthemum cinerariaefolium* L.) (Asterales: Asteraceae) (Sun *et al.,* 2020), the crown of gods (*Phaleria macrocarpa* (Scheff.) Boerl.) (Malvales: Thymelaeaceae), jatropha (*Jatropha curcas* L.) (Malpighiales: Euphorbiaceae), black pepper (*Piper nigrum* L.) (Piperales: Piperaceae), Ceylon cinnamon (*Cinnamomum zeylanicum* Bl.) (Magnoliales: Lauraceae) and Chinese cinnamon (*Cinnamomum cassia* (L.) J. Presl) (Laurales: Lauraceae) (Abtew *et al.,* 2015) as well as *Reutealis trisperma* (Blanco) Airy Shaw (Malpighiales: Euphorbiaceae) (Nakayama and Osbrink, 2010) and Bintaro (*Cerbera manghas* L.) (Gentianales: Apocynaceae) (Saxena *et al.,* 2023; Susilo *et al.,* 2020) also have shown potential as botanical insecticides. In addition, concentrations of *R. trisperma* 0.2%, 0.39%, 0.78%, 1.56%, 3.13%, and 6% were tested against *Planococcus minor* Maskell (Hemiptera: Pseudococcidae). When combined with a nanoemulsion, the results showed a 90% mortality rate of *P. minor* within five days. The median lethal concentration-50 (LC_{50}) has been identified as 0.09%, and the median lethal time (LT_{50}) is noted to be 3.7 days, showcasing the formulation's rapid effectiveness against this pest (Prabowo and Damaiyani, 2019). Further research has explored

the effectiveness of Bintaro leaf extract (*Cerbera odollam* Gaertn.) (Gentianales: Apocynaceae) in controlling armyworms (*Spodoptera litura* Fab.) (Lepidoptera: Noctuidae). Concentrations of 0% (control), 0.5%, 1%, 1.5%, 2%, and 2.5% were tested, with results showing that Bintaro leaf extract granules caused 60% mortality at 1.5%, indicating toxicity. The LC_{50} at 48 hours was 1.41% (Sholahuddin *et al.,* 2018). Similarly, a study on Cerbera leaf extract against *Spodoptera littoralis* Boisduval (Lepidoptera: Noctuidae) showed that a 2% concentration led to 75% mortality, weight loss, delayed molting at the second and third instar stages, and disrupted cocoon formation after eight days (Purwani *et al.,* 2014). Considering the mounting concerns about the environmental hazards posed by the heavy use of synthetic pesticides and the developing promise of plant-derived solutions, it is crucial to carry out field-scale assessments of botanical insecticides in genuine production environments to assess their practical effectiveness against the cocoa pod borer (*C. cramerella*), which is recognized as one of the most damaging pests of cocoa. Generating robust field data is essential to support evidence-based policymaking aimed at promoting environmentally sustainable plantation management and reducing dependency on persistent chemical insecticides. The implementation of plant-derived insecticides has the capacity to diminish pesticide residues in soil, water, and harvested cocoa beans, consequently enhancing environmental quality and food safety, while reducing risks to farm laborers and adjacent communities. Building on prior laboratory and small-scale studies, the present field trial evaluates oil-based formulations derived from *Reutealis trisperma* and *Cerbera manghas* for CPB suppression under high natural infestation pressure. In addition to assessing pest control efficacy, the study explicitly examines phytotoxicity, egg-laying suppression, yield impacts, and observable effects on natural-enemy populations, particularly Formicidae (ants), which contribute to biological regulation within cocoa agroecosystems. This study seeks to provide comprehensive evidence for environmentally responsible integrated pest management (IPM) strategies by concurrently assessing agronomic performance and ecological safety. The goal is to minimize the use of synthetic chemical inputs, conserve biodiversity, protect ecosystem services, and enhance the long-term sustainability of cocoa production systems in Indonesia and other tropical regions. The study coincided with a severe outbreak of the cocoa pod borer (*C. cramerella*), ensuring high natural pest pressure under real production conditions. This field experiment was conducted in South Sulawesi, Indonesia, from mid-2023 to the end of 2024.

MATERIALS AND METHODS

Study area

This study took place in South Sulawesi (2°42'16.6"S, 120°14'53.7"E), regions where smallholders cultivate cacao. These sites were selected to evaluate the effectiveness of botanical pesticides in managing CPB on cocoa plants. Field experiments were specifically carried out on cocoa plantations in South Sulawesi.

Botanical pesticides

The raw materials, which include candlenut seeds (*R. trisperma*) and bintaro leaves, fruits, and seeds (*C. manghas*), were collected and processed for spray applications aimed at combating CPB infestations. The process of oil extraction was carried out in West Java.

The extraction of oils for botanical pesticides

The extracted oil is subsequently utilized in the formulation of insecticides. At the outset, the sorting procedure is essential for differentiating viable seeds from those that are either damaged or not fully mature. This stage confirms that only seeds characterized by high oil content and outstanding quality are chosen, consequently increasing the extraction process (Haritha *et al.,* 2021; Rani *et al.,* 2021). Botanical oils were

formulated by emulsifying the neat oil in water with 0.1% Tween-80 as a surfactant. Applications were delivered using a knapsack sprayer at approximately 2000 L at 15-day intervals, for a total of six applications. Each treatment was applied to four cocoa trees (one tree representing one replicate) arranged in a randomized block design. Following the sorting phase, the seeds undergo an extraction process. A widely used method for oil extraction is mechanical pressing, which requires the application of pressure to the seeds to promote the release of oil (Soundararajan *et al.,* 2020). Mechanical pressing is particularly effective for seeds with high oil content, such as Candlenut and Bintaro. Sortation of the seeds and extracted the oils using an artificial pressing machine (no brand name). Typically called an oil press, this machine uses either a screw mechanism or a hydraulic press to exert a force on the seeds. This extraction process facilitates the separation of oil from the seed material while preserving the quality and yield of the extracted oil. Subsequently, this insecticide formulation undergoes field testing. This study was performed on mature, fruit-producing cacao plants found in a farmer's garden. At the time of testing, the farmer had not yet applied any insecticides to the cocoa plants. However, the residues or degradation kinetics of Reutealis or Cerbera oils in soil or water were not measured and thus cannot directly quantify environmental impact. A formal cost-benefit and supply assessment was not conducted. It is essential to evaluate sustainable harvesting, the costs associated with extraction, and the comparison with synthetic insecticides (Balittrasi, 2019; Damalas, 2016).

Experimental design

A randomized block design was implemented to control for variation within the experimental setup eight treatments were arranged in a randomized complete block design, with four replicate trees per treatment and approximately 30 pods per tree. This design, focused on a single site, was chosen for its logistical practicality while ensuring sufficient replication. The experiment comprised eight treatments that encompassed a range of concentrations of Reutealis (Tris), 5 and 10 milliliters per liter (mL/L), Reutealis 2 (KSC) at 5 and 10 mL/L, and Bintaro (Tro at 5 and 10 mL/L) oil-based insecticides, in addition to a synthetic insecticide (lambda-cyhalothrin) and a control treatment. Each treatment was replicated four times, with a spacing of five trees between plots to mitigate the risk of cross-contamination. The insecticides were applied with a knapsack sprayer at a pressure of 4 atm, guaranteeing sufficient coverage of cocoa pods and branches where CPB adults lay their eggs (Matthews *et al.,* 2014). Knapsack spraying suits smallholders; mechanized sprayers would be required for estates, with recalibrated droplet and volume parameters. Spraying was conducted on all sizes of cocoa pods present on the cocoa trees. A total of 30 cocoa pods, each approximately 9 cm in length, were selected from various systematically distributed trees that exhibited no signs of CPB infestation. These pods were identified using colored tape and observed throughout the harvest season. During each spraying event, the nozzle was directed towards the cocoa pods and horizontal branches where adults of CPB lay eggs and rest, as the primary focus of the spraying was the adult stage of the pest. The spraying schedule was conducted six times at intervals of 15 days, whereas the control plot did not receive any pest management measures. The effectiveness of the botanical insecticides evaluated was assessed based on the extent of CPB infestation and the percentage of yield loss observed in the harvested sample pods. These sample pods, which were selected before treatment, were initially free of infestation and measured approximately 9 cm in length. Furthermore, evaluations of CPB infestation were performed every 10 to 15 days subsequent to the application on all pods collected by farmers (excluding those marked with tape). The extent of pod damage was documented and categorized

into classifications of healthy, light, moderate, and severe infestation (Fig. 1). Non-target monitoring — Ant (Formicidae) populations were surveyed on sample trees in each plot during every harvest observation. Counts were visually assessed by scrutinizing marked pods and surrounding branches during a specified observation timeframe, documenting the number of individuals observed per sampled tree. Counts were recorded using an ordinal abundance scale adopted for this study: + = 1–10 ants per tree, ++ = 11–20 ants per tree, and +++ = 21–30 ants per tree. These categorical counts provided a conservative measure of ant abundance across treatments; due to generally low field densities comparisons of ordinal categories is reported rather than formal inferential statistics for ant counts.

The percentage of yield loss was determined using the regression equation, using Eq. 1 (Wardani *et al.,* 2019):

$$Y = -0.0210 + 0.1005X \quad (1)$$

where, the variable Y denotes the percentage of yield loss. The variable X denotes the intensity of infestation. The intensity of infestation (X) is quantified through an index value calculated as the total number of observed pods using Eq. 2 (Wardani *et al.,* 2019):

$$X = (1 \times \text{number of lightly infested pods}) + (3 \times \text{number of moderately infested pods}) + (9 \times \text{number of heavily infested pods}) \quad (2)$$

Statistical analysis

The degrees of CPB infestation and the associated yield loss percentages in the botanical insecticide treatments were contrasted with those noted in the synthetic insecticide and control treatments. The data were analyzed using the SPSS program. The infestation data for cocoa pods were analyzed utilizing Duncan's Multiple Range Test (DMRT), with significant differences established at the 5% level. Furthermore, additional data were obtained regarding the phytotoxicity levels in cocoa plants and the effects of botanical insecticide treatments on the populations of natural enemies. Future trials should assess photosynthesis, flowering, and bean quality.

RESULTS AND DISCUSSION

Observations indicated that botanical insecticides derived from Reutealis and Bintaro oils significantly reduced the infestation rates of CPB when compared to both the synthetic insecticide and control groups. Ongoing assessment of cocoa pods gathered by farmers every two weeks—concentrating on pods that were not previously identified as sample pods—indicated that the infestation rate of CPB during the first harvest ranged from 35.00% and 72.50% (Table 1). Furthermore, Table 1 illustrates a notable reduction in infestation rates beginning from the third harvest, with values decreasing to between 0% and 10% by the fifth harvest. In contrast, the synthetic treatment recorded an infestation rate of 39.29%, while the control group exhibited an infestation rate of 46.13%. Statistical analysis demonstrated that there was no notable difference between the synthetic treatment and the control group.

The analysis of pod damage (infestation rates) showed that botanical insecticides from Reutealis (Tris) and Bintaro (Tro) produced light-to-moderate damage, whereas the synthetic and control treatments exhibited moderate-to-severe damage, underscoring the protective effect of the botanicals. According to Table 2, unmarked pods treated with botanical methods showed light-damage infestations of 7.50% to 36.91% at the first harvest, whereas both the synthetic and

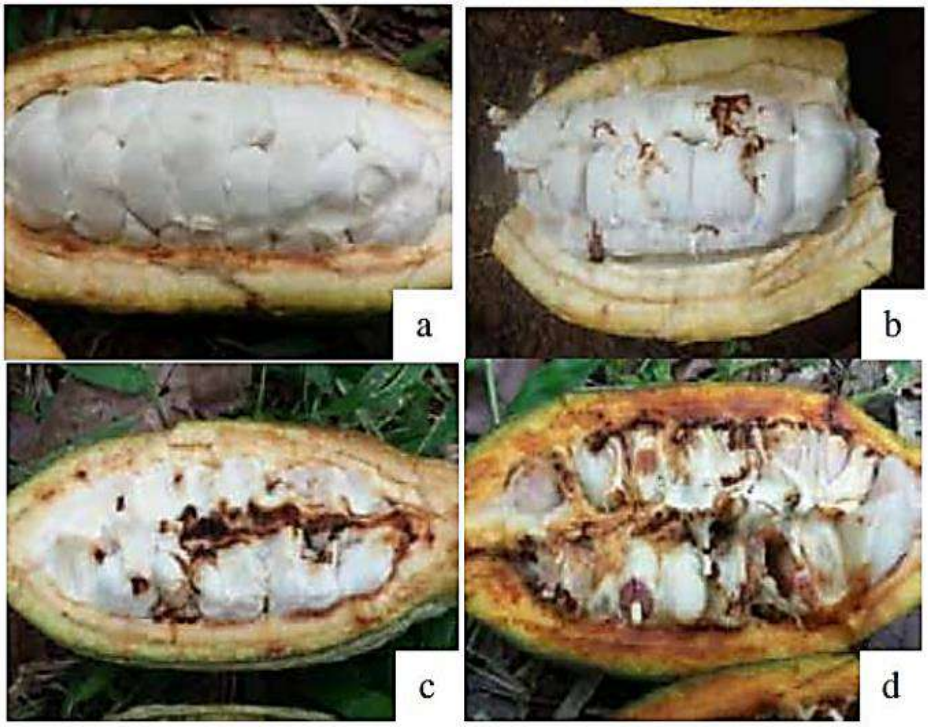

Fig. 1: The classification of pod damage can be categorized into four distinct levels: (a) healthy, (b) light, (c) moderate, and (d) severe

Table 1: The average infestation rates of CPB on unmarked pods subjected to Reutealis and Bintaro

Treatment	Infestation rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	60.6 ± 4.07a	44.2 ± 2.96abc	39.1 ± 2.62b	0.0 ± 0.0b	0.00 ± 0.00b
Tris 10 mL/L	66.7 ± 4.47a	12.5 ± 0.84d	0.0 ± 0.00e	0.0 ± 0.0b	0.00 ± 0.00b
Tro 5 mL/L	72.5 ± 4.86a	35.5 ± 2.38bcd	13.3 ± 0.89cde	4.17 ± 0.28b	5.00 ± 0.33b
Tro 10 mL/L	69.1 ± 4.63a	37.5 ± 2.51bcd	6.25 ± 0.42de	0.0 ± 0.0b	0.00 ± 0.00b
KSC 5 mL/L	65.0 ± 4.36a	25.0 ± 1.67cd	28.7 ± 1.93bc	15.0 ± 1.00b	10.0 ± 0.67b
KSC 10 mL/L	66.4 ± 4.45a	16.7 ± 1.12cd	21.7 ± 1.46bcd	10.4 ± 0.70b	7.74 ± 0.52b
Lambda cyhalothrin 1 mL/L	35.0 ± 2.35b	60.0 ± 4.00ab	61.8 ± 4.30a	59.5 ± 4.20a	39.3 ± 2.62a
Control	66.7 ± 4.47a	62.5 ± 4.18a	75.0 ± 5.00a	60.2 ± 4.26a	46.1 ± 3.12a

Note: *Specially evaluated in unmarked pods. SE = Standard error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

Table 2: The average levels of light damage observed in cocoa pods infested by CPB*

Treatment	Infestation rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	23.3 ± 1.35a	25.8 ± 1.49a	19.3 ± 1.11a	0.00 ± 0.00c	0.00 ± 0.00c
Tris 10 mL/L	26.2 ± 1.52a	12.5 ± 0.72ab	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
Tro 5 mL/L	7.50 ± 0.43b	12.5 ± 0.72ab	13.3 ± 0.77ab	0.00 ± 0.00c	0.00 ± 0.00c
Tro 10 mL/L	36.9 ± 2.13a	15.3 ± 0.88ab	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ±0.00c
KSC 5 mL/L	36.2 ± 2.09a	25.0 ± 1.44a	10.0 ± 0.58b	15.0 ± 0.87a	10.0 ± 0.58b
KSC 10 mL/L	28.9 ± 1.67a	0.00 ± 0.00b	13.4 ± 0.77ab	10.4 ± 0.60b	4.17 ± 0.24bc
Lambda cyhalothrin 1 mL/L	0.00 ± 0.00b	33.6 ± 1.94a	9.17 ± 0.53b	10.7 ± 0.62b	18.6 ± 1.07a
Control	0.00 ± 0.00b	12.5 ± 0.72ab	22.9 ± 1.32a	0.00 ± 0.00c	6.25 ± 0.36bc

Note: *Specially evaluated in unmarked pods. SE = Standard error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

control groups demonstrated a complete absence of light damage. Infestation fluctuated in the second harvest (starting at 12.50%) but declined steadily from the third to the fifth harvest, reaching 0–10% by the fifth harvest; by that time the synthetic treatment had 18.57% infestation and the control 6.25%, with no statistically significant difference between them. The findings of this study suggest that further analysis is needed regarding the residual persistence between sprays. Although overall infestation decreased, average light-damage levels in some Reutealis and Bintaro treatments remained higher than in specific concentration treatments (Tris 5 and 10 mL/L, Tro 5 and 10 mL/L, and KSC 5 and 10 mL/L). Recent literature has been integrated to situate these findings within current advances in botanical insecticide research. The phytochemical characteristics of *Cerbera spp*., which encompasses bioactive substances like cerberin and a range of flavonoids, have been detailed by Saxena *et al*. (2023), supplying mechanistic justification for the documented insecticidal effects. In addition, Ullah *et al.* (2025) highlight the expanding global interest in plant-based insecticides as environmentally compatible alternatives to synthetic chemicals. Within this context, the present study represents, to current knowledge, the first field-based evaluation of these specific botanical oils in cocoa systems, thereby contributing novel applied evidence to literature. In a similar context, the infestation rates of cocoa pods exhibiting moderate damage levels due to the CPB on unmarked pods treated with Reutealis and Bintaro insecticides, as illustrated in Table 3, exhibited a fluctuating trend. Subsequent harvests exhibited variability in the infestation rate, which was noted at 12.50% at the start of the second harvest. Notably, a significant decline in the infestation rate was observed starting from the third harvest, which continued through the fifth harvest, ultimately resulting in infestation rates ranging from 0% to 5% by the conclusion of the fifth harvest. In contrast, the infestation rate linked to the synthetic insecticide treatment was 12.14%, whereas the control group exhibited an infestation rate of 11.91%. Statistically, no significant difference was observed between the synthetic treatment and the control group in this context. Large-scale extraction and formulation processes are now noted as being explored to enhance commercial feasibility, while the potential role of agricultural extension programs in supporting artisanal or smallholder-level preparation of these oils is highlighted to strengthen practical applicability. Simultaneously, the observed reduction in moderate damage levels under the botanical insecticide treatments highlights their efficacy, as these treatments consistently surpassed both the synthetic insecticide and the untreated diminishing in lowering moderate damage rates associated with CPB infestations. In the context of severe damage levels in cocoa pods infested by the CPB, an analysis of unmarked pods treated with Reutealis and Bintaro insecticides (Table 4) indicates that the average infestation rate (%) during the second harvest initially ranged from 0% to 12.50%, demonstrating variability in subsequent harvests. Remarkably, beginning with the third harvest, a considerable decrease in infestation rates was noted across all treatments, a pattern that persisted until the fifth harvest. By the fifth harvest, the infestation rate in the botanical insecticide treatments had decreased to 0%. In contrast, the application of synthetic insecticides resulted in an infestation rate of 8.57% by the fifth harvest, whereas the control group exhibited a markedly higher infestation rate of 27.98%. This finding underscores the superior efficacy of botanical insecticides, which not only surpassed the synthetic treatment but also the control group in minimizing the severe damage associated with CPB infestations. The botanical insecticides exhibited considerable efficacy in mitigating CPB damage over time, especially in the later harvests, where infestation rates were decreased to zero.

Table 3: The average moderate damage levels of cocoa pods infested by the CPB*

Treatment	Infestation rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	0.00 ± 0.00b	0.00 ± 0.00c	19.8 ± 1.14b	0.00 ± 0.00c	0.00 ± 0.00c
Tris 10 mL/L	5.00 ± 0.29b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
Tro 5 mL/L	15.8 ± 0.91a	12.5 ± 0.72b	6.25 ± 0.36c	4.17 ± 0.24c	5.00 ± 0.29b
Tro 10 mL/L	0.00 ± 0.00b	13.9 ± 0.80b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00c
KSC 5 mL/L	6.25 ± 0.36b	12.5 ± 0.72b	18.7 ± 1.08b	0.00 ± 0.00c	0.00 ± 0.00c
KSC 10 mL/L	2.08 ± 0.12b	0.00 ± 0.00c	8.33 ± 0.48c	4.17 ± 0.24c	3.57 ± 0.21b
Lambda cyhalothrin 1 mL/L	5.00 ± 0.29b	0.00 ± 0.00c	44.3 ± 2.56a	42.6 ± 2.46a	12.1 ± 0.70a
Control	16.7 ± 0.96a	25.0 ± 1.44a	20.8 ± 1.20b	24.0 ± 1.39b	11.9 ± 0.69a

Note: *Specially evaluated in unmarked pods. SE = Standard error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

Table 4: Average severe damage levels of cocoa pods infested by CPB*

Treatment	Infestation rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	37.3 ± 2.15ab	18.3 ± 1.06ab	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
Tris 10 mL/L	35.4 ± 2.05ab	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
Tro 5 mL/L	49.2 ± 2.84a	10.0 ± 0.58bc	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
Tro 10 mL/L	32.1 ± 1.86b	8.33 ± 0.48bc	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
KSC 5 mL/L	35.4 ± 2.05ab	4.17 ± 0.24c	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
KSC 10 mL/L	22.5 ± 1.30b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00b	0.00 ± 0.00b
Lambda cyhalothrin 1 mL/L	30.0 ± 1.73b	26.7 ± 1.54a	8.33 ± 0.48b	6.25 ± 0.36b	8.57 ± 0.49b
Control	50.0 ± 2.89a	25.0 ± 1.44a	31.2 ± 1.80a	36.2 ± 2.09a	27.9 ± 1.62a

Note: *Specially evaluated in unmarked pods. SE = Standard Error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

The infestation rates varied among the treatments involving botanical insecticides, synthetic insecticides, and the control group, which subsequently affected the overall levels of yield loss (Table 5). The average yield loss associated with the botanical insecticide treatments decreased from a range of 23.78% to 47.90% during the first harvest to a range of 0.00% to 0.98% by the fifth harvest. Conversely, the yield loss associated with the synthetic insecticide treatment decreased from 27.07% to 11.71%. A statistically significant difference was observed between the botanical insecticide treatments and the synthetic insecticide (control), with both types of insecticides showing significant differences from the control in terms of yield loss attributable to CPB infestation. Among the different botanical insecticides that were examined, no notable differences were detected, implying that the concentrations of the botanical insecticides evaluated exhibited comparable effectiveness. The observed reduction in yield loss associated with the botanical insecticides Reutealis and Bintaro can be attributed to their efficacy in inhibiting female CPB from ovipositing (Table 6). The collected from the final harvest reveals that the inhibition of CPB egg-laying in treatments employing botanical insecticides was markedly more effective, with rates between 90.00% and 100%, in contrastto the synthetic insecticide treatment, which achieved a suppression rate of 60.72%, and the control group, which recorded a rate of 53.87%. However, the findings are explicitly compared with recent literature. For instance, Akhtar *et al*. (2008) found that neem oil resulted in a suppression rate of 70–90% for CPB; the botanical oils assessed in this study reached similar or even higher levels of effectiveness. From a statistical perspective, botanical insecticides exhibited a notable difference when contrasted with both the synthetic insecticide and the control group. The observed conditions of reduced infestation rates, minimal damage categories, decreased yield loss, and enhanced suppression of egg-laying in cocoa pods harvested by farmers are also evident in the marked pods (Table 7).

Table 5: The average yield loss of cocoa pods due to infestation by the CPB*

Treatment	Infestation rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	34.5 ± 2.82bc	17.1 ± 1.47bc	5.82 ± 0.48c	0.00 ± 0.00 c	0.00 ± 0.00 c
Tris 10 mL/L	34.1 ± 2.79bc	0.73 ± 0.13d	0.00 ± 0.00 c	0.00 ± 0.00 c	0.00 ± 0.00 c
Tro 5 mL/L	47.9 ± 3.33ab	11.9 ± 1.09c	1.36 ± 0.11c	0.73 ± 0.06c	0.98 ± 0.08c
Tro 10 mL/L	30.7 ± 2.20c	11.7 ± 1.05c	0.31 ± 0.03c	0.00 ± 0.00 c	0.00 ± 0.00 c
KSC 5 mL/L	23.8 ± 1.88c	0.94 ± 0.17d	4.61 ± 0.37c	1.25 ± 0.10c	0.55 ± 0.05c
KSC 10 mL/L	33.5 ± 2.35bc	6.49 ± 0.70cd	2.28 ± 0.23c	0.48 ± 0.05c	0.00 ± 0.00 c
Lambda cyhalothrin 1 mL/L	27.1 ± 2.11c	25.4 ± 2.25ab	19.7 ± 1.68b	17.5 ± 1.49b	11.7 ± 1.10b
Control	53.2 ± 4.13a	28.6 ± 2.73a	34.7 ± 2.87a	37.9 ± 3.09a	27.2 ± 2.42a

Note: *Specially evaluated in unmarked pods. Standard error (SE). Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

Table 6: The average suppression of egg-laying by the CPB*

Treatment	Infestation Rate (%) ± SE at harvest #				
	1	2	3	4	5
Tris 5 mL/L	39.4 ± 2.10b	55.8 ± 2.80ab	60.9 ± 3.04c	100 ± 0.00a	100 ± 0.00a
Tris 10 mL/L	33.3 ± 1.67b	87.5 ± 4.38a	100 ± 0.00a	100 ± 0.00a	100 ± 0.00a
Tro 5 mL/L	27.5 ± 1.38b	65.0 ± 3.25ab	86.7 ± 4.33ab	95.8 ± 4.79a	95.0 ± 4.75a
Tro 10 mL/L	30.9 ± 1.55b	62.5 ± 3.13ab	93.7 ± 4.69a	100 ± 0.00a	100 ± 0.00a
KSC 5 mL/L	35.0 ± 1.75b	75.0 ± 3.75a	71.2 ± 3.56bc	85.0 ±4.25a	90.0 ± 4.50a
KSC 10 mL/L	33.6 ± 1.68b	83.3 ± 4.17a	78.3 ± 3.91abc	89.6 ± 4.48a	92.7 ± 4.61a
Lambda cyhalothrin 1 mL/L	65.0 ± 3.25a	40.0 ± 2.00b	38.2 ± 1.91d	40.5 ± 2.02b	60.7 ± 3.04b
Control	33.3 ± 1.67b	37.5 ± 1.88b	25.0 ± 1.25d	39.8 ± 1.99b	53.9 ± 2.69b

Note: *Specially evaluated in unmarked pods. SE = Standard error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

Observations of the sampled pods, which initially measured 9 cm and were free from CPB infestation, demonstrated that the use of botanical insecticides successfully protected the pods from harm and yield reduction linked to cocoa pod borer infestation. This result is in opposition to the data gathered from treatments that involved synthetic insecticides and control groups. Table 7 showed the biweekly application of botanical insecticides at varying concentration levels was effective in controlling the CPB and reducing potential yield losses. The difference in the number of pods preserved due to the botanical insecticide treatments, when compared to the yield observed in the control group, ranged from 24.47% to 24.87% (Fig. 2). Consequently, the adverse effect of yield loss on the income derived from cocoa production can be alleviated. The observed reduction in yield loss in marked pods (initial size approximately 9 cm) treated with Reutealis and Bintaro botanical insecticides can be attributed to their effectiveness in inhibiting oviposition by female *C. cramerella*. The suppression of egg-laying by the coffee borer beetle (CPB) in the treatments using botanical insecticides was markedly greater, varying from 91.67% to 97.50%, in contrast to 75.00% with the synthetic insecticide and 48.33% in the control group. Moreover, the percentage of egg-laying suppression in the botanical insecticide treatments demonstrated statistically significant differences when compared to both the synthetic insecticide and the control group (Fig. 3). Formicidae (ants) were the only natural enemies observed, and their abundance remained generally low throughout the trial (Table 8). In botanical-treated plots the modal category was '+' (1–10 ants/tree), while the untreated control averaged '++' (11–20 ants/tree), demonstrated that there were no significant reductions in ant abundance after treatment; the counts in the treated areas were comparable to, or only

Table 7: Infestation rates, damage categories, and yield loss of cocoa pods (marked pods)

Treatments	Infestation rate (%) ± SE	Damage categories (%) ± SE			Yield loss (%) ± SE
		Light	Moderate	Severe	
Tris 5 mL/L	8.34 ± 0.28c	6.67 ± 0.67b	1.67 ± 0.17bc	0.00 ± 0.00c	0.06 ± 0.00b
Tris 10 mL/L	5.84 ± 0.19c	5.84 ± 0.58b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00b
Tro 5 mL/L	8.33 ± 0.28c	5.83 ± 0.58b	2.50 ± 0.25b	0.00 ±0.00 c	0.14 ± 0.01b
Tro 10 mL/L	3.33 ± 0.11c	3.33 ± 0.33b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00b
KSC 5 mL/L	5.84 ± 0.19c	4.17 ± 0.42b	1.67 ± 0.17bc	0.00 ± 0.00c	0.40 ± 0.04b
KSC 10 mL/L	2.50 ± 0.08c	2.50 ± 0.25b	0.00 ± 0.00c	0.00 ± 0.00c	0.00 ± 0.00b
Lambda cyhalothrin 1 mL/L	25.0 ± 0.83b	15.0 ± 1.50a	1.67 ± 0.17bc	8.33 ± 0.83b	7.74 ± 0.77b
Control	51.7 ± 1.72a	18.3 ± 1.83a	8.34 ± 0.83a	25.0 ± 2.50a	24.9 ± 2.50a

Note: SE = Standard error. Values within columns followed by the same letter are not significantly different by DMRT, α = 0.05).

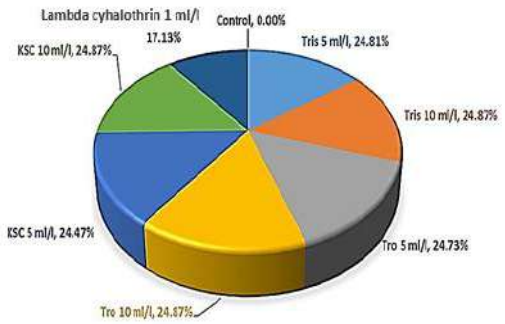

Fig. 2: Yield loss in cocoa pods through the application of Reutealis and Bintaro botanical insecticides

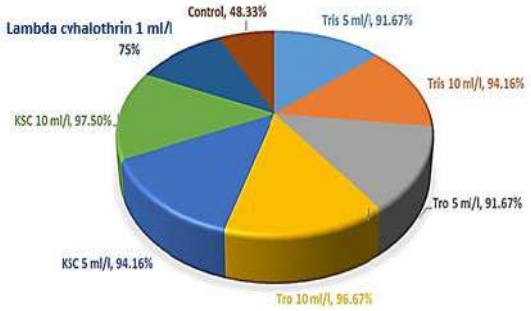

Fig. 3: Egg-laying suppression % of CPB through the application of Reutealis and Bintaro botanical insecticides

Table 8: The average population of Formicidae on cocoa trees subjected to botanical insecticide treatments

Treatment	Formicidae population
Tris 5 mL/L	+
Tris 10 mL/L	+
Tro 5 mL/L	+
Tro 10 mL/L	+
KSC 5 mL/L	+
KSC 10 mL/L	+
Lambda cyhalothrin 1 mL/L	+
Control	++

+: Population of 1–10 individuals; ++: Population of 11–20 individuals; +++: Population of 21–30 individuals; ∞: Population of more than 30 individuals

marginally less than, the control, and no treatment led to a measurable collapse of Formicidae populations. Because overall ant densities were low, differences were described using ordinal categories rather than subjected to high-power inferential tests. Visual counts cannot detect sub-lethal effects. Follow-up assays (foraging trials, brood assessment) are recommended (Desneux *et al.,* 2007). Ants are omnivorous and may contribute to CPB suppression by predation or by interfering with oviposition, so the apparent preservation of Formicidae under botanical treatments supports the ecological safety of these oils in the tested system. It is important to recognize that other non-target groups, such as bees and wasps, need to be evaluated in subsequent research. Botanical insecticides are often more selective (acting, for example, via specific biochemical pathways) (Desneux *et al.,* 2007), but in the study caution that impacts on beneficial insects remain under-investigated. It is acknowledged that species-level identification and biodiversity indices were not conducted, and Ullah *et al.* (2025) is cited to emphasize the need for broader non-target assessments. It is specified that Formicidae were chosen as a key group due to their established role in the suppression of cocoa pests; nevertheless, it is suggested that subsequent research should integrate pollinators and a variety of predator taxa to ensure a more comprehensive ecological evaluation. Relevant literature on the role of ants in cocoa agroecosystems (Ndakidemi, 2016; Akhtar, 2008) is cited to support the importance of ants as biocontrol agents. The botanical insecticides derived from Reutealis (candlenut) and Bintaro demonstrated significant effectiveness in reducing the infestation of CPB, while also minimizing yield losses. These outcomes bolster studies that underscore the potential of botanical insecticides as eco-friendly alternatives to synthetic products (Isman, 2020). The efficacy of Reutealis and Bintaro formulations against CPB—likely due to bioactive fatty acids and alkaloids—aligns with previous reports (Akhtar *et al.,* 2008). Initial variability in control (first harvest infestation 35.00–72.50%) was caused by many mature pods already infested at the time of the first spray (larvae inside pods), which made that application ineffective; however, subsequent sprays with Reutealis and Bintaro significantly reduced infestation, outperforming both the synthetic insecticide and the control in farmer-harvested pods. Notably, the synthetic lambda-cyhalothrin did not diminish CPB infestation when compared to the control, potentially due to insect resistance arising from frequent application or other non-technical influences. Larval development and multi-generation tolerance were not assessed. Future studies should include lethal concentration (LC_{50}), lethal time (LT_{50}) bioassays and lifetable monitoring to detect shifts in susceptibility (Isman, 2020). Botanical treatments exhibited no phytotoxicity towards cocoa and presented diminished risks to non-target organisms, in contrast to the environmental and crop-safety concerns for some synthetics (Desneux *et al.,* 2007). For example, the abundance of Formicidae and Cocoa Pod Borer varies with local humidity and shade cover (ICCO, 2020)—factors that were held constant at the study site. Therefore, the results should be interpreted as specific to this environmental context. Future research should evaluate these botanical treatments across diverse agro-climatic zones. The results that are non-toxic agree with Silva *et al.* (2019), and comparable safety for cajuput and patchouli oils has been reported in rice (Mardiningsih and Rohimatun, 2023). Botanical pesticides are generally highly biodegradable and have limited environmental persistence, which can translate into lower ecological risk compared to many synthetic chemicals (Lengai *et al.,* 2020). As an illustration, a variety of plant-based substances break down swiftly when exposed to field conditions. However, fate depends on compound and context: for instance, the persistence of rotenone

(a botanical insecticide) was shown to vary with soil type and temperature (Ullah *et al.,* 2025; Cavoski *et al.,* 2008). Pereira *et al.* (2025) show that most botanical active compounds are naturally derived and often metabolized by soil microbes. Moreover, plant-oil insecticides generally have short half-lives in soil due to microbial and abiotic degradation (Ayllón-Gutiérrez *et al.,* 2024).

Recent reviews have highlighted key gaps in non-target risk assessment and the environmental fate of botanical pesticides, particularly regarding cinnamaldehyde degradation, emphasizing the need for comprehensive ecological risk analyses (Hashimi *et al.,* 2020; Reyes-Ávila *et al.,* 2022; Ullah *et al.,* 2025). The evidence implies that these botanical oils have a negligible observable influence on non-target ants, aligning with reviews that highlight how plant-based biopesticides generally target specific pests and break down swiftly in the environment. However, unqualified safety is not asserted; com prehensive environmental risk assessments would require further investigation to establish full ecological risk profiles. Plant-based products may also outperform synthetics through combined modes of action—repellence, oviposition deterrence, and direct toxicity (Naeem *et al.,* 2025). The botanical insecticides reduced yield loss substantially: from 23.78%–47.90% in the initial harvests down to 0.00%–0.98% by the fifth harvest, compared with 11.71% for the synthetic treatment. The suppression of egg-laying using botanicals (91.67–97.50%) was more effective than that achieved with synthetic options (75.00%), highlighting the importance ofbotanical insecticides within IPM to maintain crop quality and reduce reliance on persistent synthetic insecticides. In contrast, the synthetic insecticide exhibited a reduction in yield loss from 27.07% to 11.71%. These findings are consistent with the study by Pavela and Benelli (2016), which suggested that botanical insecticides can lead to reduced yield losses over time because of their ability to focus on life stages of pests without adversely affecting the plant. Furthermore, the pronounced suppression of egg-laying by female *C. cramerella* in the botanical insecticide treatments (ranging from 91.67% to 97.50%) compared to the synthetic insecticide (60.72%) and the control group (53.87%) underscores the superior efficacy of these plant-based formulations in disrupting the pest's life cycle. This result reinforces the findings of Naeem *et al*. (2025) about the oviposition deterrent properties of botanical extracts. Similarly, other studies have indicated that botanical pesticides can be highly effective against various pests, offering a viable alternative to synthetic pesticides (Bakar *et al.,* 2021; Manson *et al.,* 2022; Siswanto *et al.,* 2020). For example, botanical insecticides such as α-elaeostearic acid and citronellal were found to be effective against the pod borer (*C. cramerella*) and fruit suckers (*Helopeltis spp*.) when applied every two weeks until harvest. The outcomes revealed that these treatments considerably lowered cocoa pest infestations, as yield losses in all treated plots were kept below 10%, a statistically significant reduction compared to the control group, which experienced a 36.5% yield loss (Siswanto *et al.,* 2020). In another study, the natural biopesticide Glumon was found to be more effective than conventional pesticides in controlling the coffee berry borer (*Hypothenemus hampei* Ferrari) (Coleoptera: Curculionidae), according to interviews with 87% of farmers (Manson *et al.,* 2022). The identified pods assessed in this investigation offer further evidence for the theory that botanical insecticides are remarkably effective in minimizing both the infestation of the CPB and the resultant yield losses. The consistency of the results observed between the marked and unmarked pods highlights the reliability of the Reutealis and Bintaro formulations. These results are consistent with the study carried out by (Isman and Grieneisen, 2014), which indicates that botanical insecticides can offer reliable defense against pests when applied at regular intervals. It is also noted that *Reutealis trisperma* oil is rich in

fatty acids (e.g., oleic and linoleic acids), which have been reported to disrupt insect cuticles and interfere with oviposition processes (Jadid *et al.,* 2021). The significant decrease in egg-laying related to botanical insecticides is especially noteworthy, since the prevention of egg-laying is essential for effective pest population management. In this study, the suppression rates for botanical insecticide treatments varied from 91.67% to 97.50%, which is markedly higher than the 75.00% suppression rate achieved with synthetic insecticide. Essential oils from the Zingiberaceae (e.g., Alpinia galanga, Curcuma longa, Zingiber officinale) have been used against the cocoa pod borer, and A. galanga reduced egg hatchability (Bakar *et al.,* 2021). Cajuput and patchouli oils deterred oviposition—cajuput at 0.002% caused 51.74% deterrence in Nilaparvata lugens fourth instars, while patchouli ranged from 0.002% up to 61.15%, with a maximum deterrence of 83.2% at 0.188% (Mardiningsih and Rohimatun, 2021). Non-target effects were minimal: Formicidae abundance was similar across treatments, suggesting no clear harm to ants, which can aid CPB suppression (Akhtar *et al.,* 2008; Silva *et al.,* 2019). Due to the low densities of ants, abundance was characterized in an ordinal manner instead of being subjected to statistical testing; these descriptive findings are consistent with previous reports indicating reduced non-target effects from botanical products compared to broad-spectrum synthetic chemicals (Desneux *et al.,* 2007; Isman, 2020). Conserving ants and other natural enemies' supports IPM and reduces reliance on persistent synthetics (Ndakidemi *et al.,* 2016; Ochieng *et al.,* 2022). Bintaro (Cerbera odollam) leaf extract caused 60% mortality at 1.5% (LC_{50} = 1.41% at 48 h) and 75% mortality at 2% against Spodoptera littoralis, with additional sublethal effects reported (Sholahuddin *et al.,* 2018; Purwani *et al.,* 2014). Oils from citrus peels and Eugenia reduced lifespan, oviposition, and emergence in Dinoderus porcellus, with Eugenia causing 100% mortality; phenolic components likely enhance activity via oxidative stress (Oni and Ileke, 2008; Farahani and Bandani, 2023). Reutealis and Bintaro oils are promising CPB alternatives, but their persistence and stability in field conditions—susceptible to UV and temperature—require further study (Isman and Grieneisen, 2014).

CONCLUSION

The present field study demonstrates that botanical insecticides derived from *Reutealis trisperma* (candlenut) and *Cerbera (Bintaro)* oils can be effective, practical and safer alternatives to conventional synthetic insecticides for management of the cocoa pod borer (*Conopomorpha cramerella*). During the trials, consistent use of these oil-based formulations at 5–10 mL/L markedly decreased pod infestation, inhibited oviposition, and restricted yield loss, while only causing light to moderate phytotoxic effects; outcomes which together underscore the robust potential of these botanicals for sustainable pest management in smallholder cocoa systems. From an environmental-safety perspective, plant-based oils bring several advantages that address key shortcomings of many synthetic pesticides. Unlike many synthetic active ingredients, botanical oils are generally biodegradable and tend to break down more rapidly in the environment, thereby reducing persistent residues in soil, water and harvested produce. This improves food safety and minimizes the long-term accumulation risks for non-target organisms. In addition, our field results show minimal detectable impacts on ant populations (Formicidae) and no obvious damage to the cocoa plants themselves, consistent with literature showing reduced non-target toxicity for many botanical formulations when properly formulated and applied. Although the data indicate minimal detectable harm to ants, formal ecotoxicological assessments were not conducted. It is identified that the key phytochemicals in Cerbera with potential effects on non-target organisms, are cited to acknowledge possible ecological risks.

Consequently, a thorough risk assessment—which encompasses both toxicity and exposure evaluations—is essential prior to making broad generalization of these findings. Future work will include gas chromatography–mass spectrometry (GC–MS) profiling of the oil constituents to characterize the active compounds more precisely. Cerberin and flavonoids present in C. manghas seeds were identified through GC–MS analysis. Such compounds are known to disrupt insect physiology; for example, cerberin inhibits sodium per potassium adenosine triphosphate (Na^+/K^+)-ATPase activity. These documented modes of action are presently referenced to reinforce the mechanistic and scientific basis of the conclusions. These attributes make botanical oils attractive components of eco-friendly IPM systems where conservation of beneficial insects (natural enemies and pollinators) is a management priority. Nevertheless, botanical insecticides also present formulation and operational challenges that must be managed before wide adoption. Plant oils and extracts are generally more vulnerable to degradation caused by UV light, elevated temperatures, and microbial breakdown compared to numerous synthetic actives; this sensitivity can diminish residual activity in the field and necessitate more frequent application or improved formulation technologies (for example microencapsulation, emulsions or nano-formulations) to extend persistence and maintain field efficacy. Consequently, the research and development of stabilization strategies, including controlled release, UV protectants, or adjuvants, should accompany any scaling program to ensure effectiveness across climatic conditions. From the pest-management perspective, botanical oils may offer multiple modes of action (repellence, oviposition deterrence and direct contact toxicity) that reduce selection pressure for simple target-site resistance compared to single-site synthetic insecticides. The strong oviposition suppression noted (≥ 90% in botanical treatments) is of great value, as it directly interrupts population renewal by decreasing egg laying, which can lead to a reduction in the number of applications needed over a season when combined with good orchard sanitation and monitoring practices. This study covered one production season. To assess long-term consistency and potential adaptation, multi-season trials (≥2 seasons) are mandatory. Such multi-modal action supports integration into IPM packages that combine cultural control, monitoring, timely botanical sprays and use of biological control agents, thereby maximizing long-term pest suppression while conserving beneficial fauna. It is prudent to carry out the following practical actions to facilitate a safe and eco-conscious deployment at scale. steps: 1) adopt standardized, quality-controlled protocols for oil extraction and formulation to ensure consistent concentrations and reduce batch variability; 2) perform local environmental risk assessments and simple non-target toxicity screens (arthropod sentinel assays) before large-scale rollout; 3) explore simple stabilization approaches (for instance., emulsion surfactants or microencapsulation) to improve field persistence in hot tropical climates; 4) integrate botanical applications into an IPM calendar that prioritizes preventive sprays timed to phenology and larval vulnerability; and 5) Involve farmer training and extension regarding the proper handling, dosage, and application intervals to ensure that the products are utilized effectively and safely. Evidence from recent reviews shows the path to commercialization and adoption requires both product standardization and regulatory clarity so farmers can trust and deploy botanicals reliably. *Reutealis* and *Bintaro* oil-based insecticides are promising eco-friendly tools for cocoa pod borer management: they reduce infestation and yield loss, minimize detectable impacts on at least some beneficial fauna, and align well with IPM and residue-reduction goals in cocoa production. In

order to transform this promise into a standard practice, additional efforts are required regarding formulation stability, dose optimization across various agroclimatic zones, cost–benefit analyses for smallholders, and formal environmental risk assessments. However, temperature, UV, and rainfall accelerate degradation and wash-off, likely influencing persistence under field conditions. By utilizing these supporting data and farmer-focused delivery systems, which include local processing, clear labeling, and training, botanical insecticides can significantly enhance the safety and sustainability. This study provides field-scale evidence that these botanical oils can suppress CPB under high pest pressure. To inform regionally applicable recommendations across Indonesia and other tropical regions, multi-site, multi-season trials and supporting ecological and economic assessments are required.

AUTHOR CONTRIBUTIONS

I.M. Trisawa contributed by conceptualizing the study, coordinating research activities, and drafting the initial manuscript. Wiratno contributed by designing the experimental procedures, conducting the study, and finalizing the manuscript. Siswanto contributed by managing research activities, conducting the study, and reviewing the manuscript. Samsudin contributed by conducting the study, analyzing the data, and assisting in drafting the initial manuscript. T.L. Mardiningsih contributed by collecting the data, performing preliminary analysis, and assisting in manuscript preparation. G. Indriati contributed by analyzing the data and supporting the writing of the manuscript. P. Maris contributed by contributing to data validation and finalizing the manuscript. Rohimatun contributed by supporting the literature review and initial manuscript editing. M. Rizal contributed by assisting in data interpretation and manuscript revision. A. Meilin contributed by preparing data visualizations and assisting in manuscript drafting. R.F. Sunet contributed by reviewing and revising the manuscript critically for important intellectual content. A. Kardinan contributed by collecting the data, validating the data.

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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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The author(s) declared that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
+ / ++ / +++	Population levels of f*ormicidae*: + = 1–10, ++ = 11–20, +++ = 21–30 individuals
α	Alpha (significance level, usually 0.05)
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
C. cramerella	*Conopomorpha cramerella* (Cocoa Pod Borer)
C. manghas	Cerbera manghas (Bintaro)
CPB	Cocoa pod borer
DMRT	Duncan's Multiple Range Test
Fig.	Figure
GC–MS	Gas chromatography–mass spectrometry
ICCO	International Cocoa Organization
IPM	Integrated pest management
K	Potassium
KSC	*Reutealis trisperma* oil formulation 2 (coded treatment)
LC_{50}	Median Lethal Concentration (causing 50% mortality)
LT_{50}	Median Lethal Time (time to 50% mortality)
mL/L	Milliliter per liter
Na	Sodium
P. minor	Planococcus minor
R. trisperma	*Reutealis trisperma* (Candlenut)
SE	Standard error
SPSS	Statistical package for the social sciences
Tris	*Reutealis trisperma* oil-based insecticide (coded treatment)
Tro	Cerbera manghas (Bintaro) oil-based insecticide (coded treatment)
UV	Ultraviolet

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ORIGINAL RESEARCH PAPER

Runoff and sediment dynamics modeling for erosion risk reduction and sustainable watershed management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sedimentation threatens the long-term storage capacity and operational safety of Mosul Dam, one of Iraq's largest strategic reservoirs. The inflow of sediment from tributary valleys progressively diminishes the effective volume of the reservoir and heightens hydrological risks in the context of fluctuating rainfall patterns. This study aimed to quantify long-term runoff and sediment yield from three major tributaries draining into Mosul Dam and to establish a predictive runoff–sediment relationship to support spatial erosion management.

METHODS: The soil and water assessment tool was applied using climatic, land use, soil, and topographic datasets covering 1985–2024. A gradual manual calibration technique was performed based on the observed runoff and sediment data from Fayda Valley, the only sub-basin in the watershed that has been subject to monitoring. Model performance was evaluated using the Nash–sutcliffe efficiency as the principal objective function, supported by the coefficient of determination (R^2), the index of agreement, the root mean square error and the mean absolute error and parameter sensitivity analysis was performed to identify dominant hydrological and sediment controls.

FINDINGS: The calibrated model achieved good performance (Nash–sutcliffe efficiency up to 0.94 for runoff and 0.91 for sediment load). Mean annual precipitation was 362 millimeter, characteristic of semi-arid conditions. In the largest sub-watershed, simulated runoff depths reached 91 millimeters, reflecting a notable generation of runoff in relation to the total rainfall amounts in the region. The combined average sediment contribution from the three valleys was approximately 3.8×10^3 tons per year, with Sweedy Valley accounting for 84 present of total sediment inflow, identifying it as the dominant erosion hotspot. Power-law relationships between annual runoff and sediment yield produced R^2 values between 0.77 and 0.82, indicating moderate statistical association and confirming nonlinear sediment response to hydrological variability.

CONCLUSION: The findings indicate that the sediment transport to Mosul Dam is highly localized and primarily determined by the intensity of runoff. Prioritizing erosion control in Sweedy Valley can substantially reduce sediment inflow and help safeguard reservoir storage capacity. By promoting focused watershed management and minimizing sediment risks, the results directly aid in the protection of water resources as outlined in sustainable development goal 6, as well as enhance climate-adaptive watershed resilience in accordance with sustainable development goal 13.

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INTRODUCTION

Water resources systems in semi-arid and arid regions are increasingly exposed to hydrological instability driven by climatic variability, land degradation, and intensifying anthropogenic pressures (El-Mahroug *et al.,* 2025; Hroub *et al.,* 2025; Hadadin *et al.,* 2022). In these environments, the generation of surface runoff and the transport of sediment are vital processes that they significantly affect watershed resilience, reservoir sustainability, and long-term water security (Abu-Afifeh *et al.,* 2023; Al-Afeshat *et al.,* 2025). Runoff–sediment interactions are inherently nonlinear, as sediment detachment, transport capacity, and delivery ratios increase disproportionately with runoff magnitude, particularly during high-intensity rainfall events and flash floods (Gupta *et al.,* 2021; Chadalawada *et al.,* 2020). Responses influenced by thresholds are especially marked in watersheds defined by steep gradients, soils that are low in permeability, and sparse vegetation, where erosive energy swiftly mobilizes and transports sediment to downstream hydraulic structures (Al-Hussein *et al.,* 2024; Hamid and Mohammed, 2023). Sediment accumulation in reservoirs progressively reduces effective storage capacity, alters flood routing efficiency, and increases operational and structural risks (Milanović *et al.,* 2019; Buchner *et al.,* 2018). Beyond volumetric losses, sediment-laden inflows can damage hydraulic components, obstruct intakes, and modify internal pressure distributions within dam systems. These effects underscore the importance of strong sediment assessment frameworks at the watershed scale, which are essential for quantifying sediment sources and pinpointing key erosion hotspots (Assaf *et al.,* 2025). Physically based hydrological models have become essential tools for simulating runoff and sediment processes under spatially distributed watershed conditions. Among these, the soil and water assessment tool (SWAT), developed by the United States Department of Agriculture (USDA), has been widely applied for long-term hydrological and sediment yield simulations at basin scales (Muhammed and Akmırza, 2025; Darwish and Talozi, 2024). The integration of SWAT within geographic information system (GIS) environments enables detailed watershed delineation, hydrological response units (HRUs) definition, and spatially distributed parameterization, making it particularly suitable for multi-decadal sediment assessments in large catchments (Mohammadzadeh-Habili *et al.,* 2021; Farzanmehr and Mohammadzadeh-Habili, 2024). Mosul Dam, situated on the Tigris River in northern Iraq and in operation since 1986, is considered one of the most strategically significant hydraulic structures in the region. However, sedimentation has emerged as a persistent operational challenge. Previous investigations reported significant storage capacity losses due to sediment deposition (Al-Ansari *et al.,* 2013a; Issa *et al.,* 2013; Issa *et al.,* 2015; Adamo *et al.,* 2021), while other studies applied SWAT and related approaches to evaluate sediment inflows from selected sub-catchments (Al-Ansari *et al.,* 2013b). Structural safety assessments have also identified seepage, foundation instability, and sediment-related hydraulic pressures as contributing factors to long-term vulnerability (Wakeley *et al.,* 2007; Annunziato *et al.,* 2016; Al-Ansari *et al.,* 2021). Notwithstanding these endeavors, current studies have predominantly concentrated on individual sub-catchments, brief monitoring durations, or structural evaluations, failing to deliver a comprehensive, long-term assessment of spatial sediment contributions throughout significant tributary valleys and their predictive runoff-sediment interactions. Recent studies have also highlighted the importance of sustainable and decentralized water management approaches in addressing water resource challenges and improving environmental sustainability (Obeidat *et al.,* 2025a). The Sweedy, Crnold, and Alsalam valleys represent dominant left-bank tributaries contributing substantial sediment inflow to Mosul

Dam. However, a comprehensive multi-decadal assessment (1985–2024) integrating climatic variability, land use, soil characteristics, and topographic controls to quantify their relative sediment contributions and parameter sensitivities remains limited. Furthermore, while severe hydrological events affect sediment delivery, the long-term sediment budget and dominant controlling parameters under historical climatic conditions have not been comprehensively assessed. In addition, studies examining decentralized water treatment and management systems emphasize the growing need for sustainable strategies that integrate environmental and social dimensions of water resource management (Obeidat *et al.,* 2025b). This study consequently intends to offer a long-term, spatially distributed analysis of runoff and sediment dynamics within the Mosul Dam watershed, based on historical climatic conditions, acting as a baseline framework for prospective climate or land-use scenario developments. Specifically, the objectives are to: 1) Simulate surface runoff and sediment yield using the SWAT model through integration of climatic, land use, soil, and topographic datasets. 2) Quantify and compare sediment contributions from the Sweedy, Crnold, and Alsalam valleys to identify priority erosion sub-watersheds. 3) Assess the responsiveness of essential hydrological and sediment-related parameters, including Manning's roughness coefficient, soil saturated hydraulic conductivity, channel hydraulic conductivity, curve number (CN), and sediment transport coefficients. 4) Develop a predictive relationship based on empirical data that links runoff magnitude to sediment yield, aimed at enhancing erosion mitigation planning and informing watershed management decisions. This study has been carried out in the Mosul Dam watershed in northern Iraq, in which the performance period extended from 1985 to 2024.

MATERIALS AND METHODS

Study area and watersheds characteristics

The Tigris and Euphrates Rivers, located in Iraq within the Middle East, define the historical region of Mesopotamia (Fig. 1). Mosul Reservoir, situated on the Tigris River in northern Iraq approximately 60 km northwest of Mosul city at 36°37'44" North (N) latitude and 42°49'23" East (E) longitude, represents Iraq's largest and most strategically significant hydraulic structure and is ranked as the fourth-largest dam in the Middle East (Issa *et al.,* 2015). The reservoir covers a surface area of about 380 square kilometers (km²). At its maximum operational level (330 meter (m) above mean sea level), the dam's total storage capacity reaches 11.11 billion cubic meters (m³), comprising 8.16 billion m³ of live storage and 2.95 billion m³ of dead storage (Issa *et al.,* 2015). The Mosul Dam is an earth-fill embankment structure that stands 113 meters tall and spans roughly 3.4 kilometers (km) in length, incorporating a clay-core design and a crest width of 10 m. The dam includes a service spillway situated on its eastern side, controlled by five radial gates, with a maximum discharge capacity of 12,400 m³ per second at peak reservoir levels. The Tigris River itself serves as the main source of inflow for the reservoir (Sissakian *et al.,* 2014). The selected study area for this research focuses specifically on three tributary valleys, Sweedy, Crnold, and Alsalam, that contribute significantly to the reservoir's inflow from the northwest (right bank). These valleys were chosen to assess their roles in sediment transport resulting from erosion processes driven by rainfall and runoff. The combined area of the three valleys examined in this study is roughly 568.03 km². The Sweedy Valley watershed comprises the largest portion of the study area, covering about 447.5 km², equivalent to approximately 79 percent (%) of the total area. The Crnold Valley ranks second with an area of 75.27 km², representing approximately

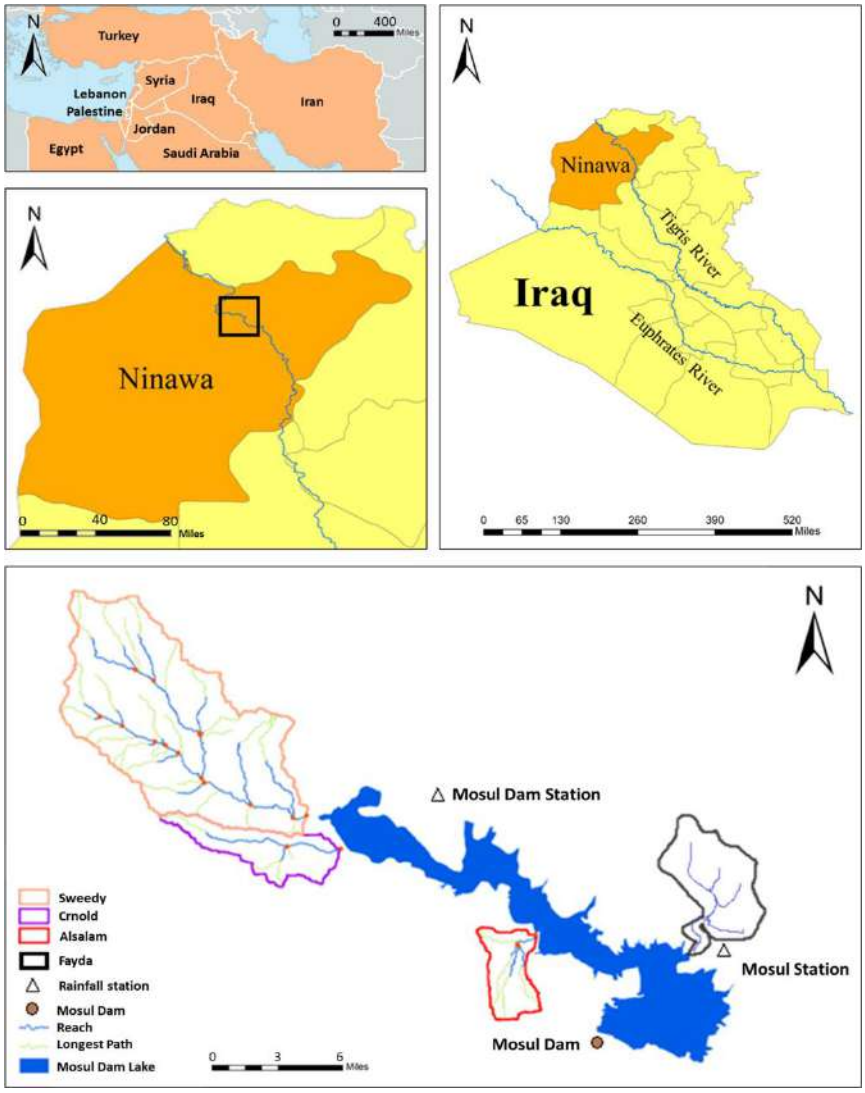

Fig. 1: Geographical location and streams network of the study area at Mosul Dam in Ninawa, Iraq

13% of the study area, while the Alsalam Valley is the smallest, encompassing 45.26 km² or about 8% of the total watershed area. The classification of land cover in the study area identified clear dominant land uses throughout the three valleys. Pasture emerged as the most prevalent land use category, occupying approximately 38.81% and 48.44% of Sweedy and Crnold valleys, respectively. In contrast, the Alsalam valley is predominantly covered by Range-Grasses, constituting about 57.7% of its total area. Regarding soil characteristics, the predominant soil type in the Sweedy valley is clay, comprising around 78.5% of the valley area. On the other hand, clay loam soil dominates the Crnold and Alsalam valleys, covering approximately 81.5% and 100% of their areas, respectively. The characteristics of land cover and soil types have a substantial impact on the processes of runoff generation and sediment transport processes within each valley. The slope category ranging from 5% to 10% is the dominant terrain feature in all studied valleys. Specifically, this slope interval accounts for approximately 42.1% of Sweedy

Valley's total area, 42.3% of the Crnold Valley's area, and 41.2% of the Alsalam Valley's area. The occurrence of moderate slopes has a considerable impact on the dynamics of surface runoff and sediment yield within these watersheds. The spatial locations and main characteristics of these valleys are detailed in Table 1.

The SWAT model setup and calibration

The SWAT model, that integrated into GIS, serves as a highly effective tool for analyzing water resources by simulating hydrological processes such as surface runoff, sediment transport, and watershed response to varying climatic conditions. Watershed delineation was conducted utilizing a digital elevation model (DEM) with a spatial resolution of 30 m, which is generally regarded as sufficient for hydrological modeling at the watershed scale in semi-arid regions. The DEM was used to define flow direction, flow accumulation, stream networks, and sub-basin boundaries within the SWAT–GIS environment. Elevation within the study area ranges from 311 m to 779 m above sea level, reflecting moderate topographic variability that influences runoff concentration and sediment transport processes. The chosen DEM resolution was considered adequate to represent terrain variability at the watershed scale while ensuring computational efficiency. The HRUs were delineated by overlaying land use, soil, and slope datasets within the SWAT–GIS framework. A digital land use map and a soil map of northern Iraq, harmonized to the DEM projection and spatial resolution, were used to define HRUs. Slope was classified into five categories, and HRU thresholds were maintained within 10–20% to preserve dominant land–soil–slope combinations while reducing excessive spatial fragmentation. Climatic inputs on a daily basis, such as precipitation, minimum and maximum temperatures, relative humidity, solar radiation, and wind speed, were collected from Mosul Station and the Mosul Dam Weather Station for the time frame of 1985–2024 (Fig. 1). The datasets were quality-checked for completeness and consistency before being formatted for continuous daily simulations. While spatial interpolation between two stations may introduce minor climatic uncertainty, their proximity to the study area ensures representative hydro-climatic characterization. Despite the fact that SWAT incorporates temperature-driven snowmelt processes, the occurrence of snowfall in the study area is infrequent and episodic. Due to the predominantly rainfall-driven hydrology of the watershed, snowmelt contribution to annual runoff and sediment yield is considered negligible for this assessment. The Fayda Valley (black-contour basin shown in (Fig. 1), located northwest of Mosul and draining into the left side of the Mosul Dam reservoir at coordinates 36°43'35" N latitude and 42°55'10" E longitude, was selected as the calibration watershed due to the availability of observed runoff and sediment data. Fayda encompasses an area of roughly 106.3 km² and exhibits similar climatic conditions, geological structures, soil properties, and hydrological patterns as the targeted tributary valleys. Within the Mosul Dam catchment, Fayda represents the only sub-basin with consistent observed hydrological and sediment records. Given the absence of monitored runoff and sediment data in the three study valleys, calibrated parameter values were transferred under the assumption of regional hydro-geomorphic similarity. This method of transferability is frequently utilized in watersheds with limited data, yet it brings about intrinsic uncertainty. Therefore, a stepwise manual calibration approach was adopted. Model performance was primarily evaluated using the Nash–Sutcliffe Efficiency (NSE) as the principal objective function, supported by the coefficient of determination (R^2), the index of agreement (IOA), the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) to ensure balanced agreement between simulated and observed runoff and sediment values (Moriasi *et al.,* 2007). In this study, model performance was interpreted

Table 1: Main valleys characteristics from SWAT model (Kassem *et al.,* 2025)

Characteristic		Valleys		
		Sweedy	Crnold	Alsalam
Outlet coordinates	Latitude	36º 49’ 58’’	36º 48’ 52’’	36º 43’ 53’’
	Longitude	41º 50’ 12’’	42º 29’ 11’’	42º 44’ 2’’
Area (km²)		447.5	75.27	45.26
Main Stream Length (km)		37.6	20.8	8.3
Dominant land use		Pasture (38.81%)	Pasture (48.44%)	Range-Grasses (57.7%)
Secondary land use		Grassland/ shrubs	Grassland	Minimal variation
Dominant soil type		Clay (78.5%)	Clay Loam (81.5%)	Clay Loam (100%)
Dominant slope		5-10 %	5-10 %	5-10 %
Terrain / slope characteristics		Mixed slopes with steep sections contributing to high runoff velocity	Moderate slopes	Gentle to moderate slopes
Implications for runoff and sediment		High sediment potential due to erodible clay soils and steep slopes	Moderate sediment yield	Lower sediment detachment, dominated by clay-loam soils

using commonly applied criteria for long-term watershed simulations, where NSE ≥ 0.50 indicates satisfactory performance, NSE ≥ 0.65 indicates good performance, and NSE ≥ 0.75 indicates very good performance; similarly, R^2 ≥ 0.60 was considered satisfactory for reproducing observed variability (Moriasi *et al.,* 2007). IOA values that are close to 1.0 reflect a greater degree of agreement, whereas RMSE and MAE function as supplementary error indicators, with lower values denoting enhanced model performance. Thses parameters are expressed mathematically, using Eqs. 1, 2, 3, 4 and 5 (Moriasi *et al.,* 2007):

$$IOA = 1 - \frac{\sum_{i=1}^{n}(X_r - X_s)^2}{\sum_{i=1}^{n}\left(|X_r - \bar{X}_r| + |X_s - \bar{X}_r|\right)^2} \quad (1)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(X_r - \bar{X}_r)\times(X_s - \bar{X}_s)}{\sqrt{\sum_{i=1}^{n}(X_r - \bar{X}_r)^2 \times \sum_{i=1}^{n}(X_s - \bar{X}_s)^2}}\right]^2 \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_s - X_r)^2} \quad (3)$$

$$MEA = \frac{1}{n}\sum_{i=1}^{n}|X_s - X_r| \quad (4)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_r - X_s)^2}{\sum_{i=1}^{n}\left(|X_r - \bar{X}_r|\right)^2} \quad (5)$$

where: X_r is the measured data value, $\bar{X}_r$ is the average measured data values, X_s is the value of the results obtained from the model, $\bar{X}_s$ is the average values of the results obtained from the model and n: The number of data points.

A total of six critical parameters were identified for calibration, based on their recognized effects on runoff and sediment dynamics in semi-arid watersheds. The CN was varied within ±15% of its initial HRU-based value; soil saturated hydraulic conductivity (SOL_K) was adjusted within −20% to +20%; Manning’s roughness coefficient (n) within ±15%; channel hydraulic conductivity (CH_K) within −20% to +20%; and linear sediment routing parameters (SPCON) and the exponential sediment transport coefficient (SPEXP) were varied within ±20% of default SWAT values. Calibration was executed step by step by altering a single parameter at a time, ensuring that the other parameters remained unchanged, to ascertain its specific sensitivity. After determining optimal values for each parameter, a combined calibration run was performed using all adjusted parameters simultaneously. This step allowed evaluation of interaction effects and reduced potential equifinality by verifying that simultaneous parameter adjustments improved model performance consistently across NSE, R^2, RMSE, and MAE metrics. Parameter sets that yielded inconsistent or conflicting performance enhancements were dismissed, thereby guaranteeing calibration results that are both physically consistent and statistically robust.

Parameter sensitivity and model uncertainty

A one-at-a-time (OAT) sensitivity analysis was conducted to quantify the influence of key hydrological and sediment-related parameters on simulated runoff and sediment yield. The six calibrated parameters (CN, SOL_K, n, CH_K, SPCON, and SPEXP) were systematically varied within their defined calibration ranges while holding other parameters constant. Sensitivity was assessed by examining the relative variations in NSE, R^2, and the response of sediment load. This approach allowed identification of dominant runoff- and sediment-controlling parameters under semi-arid watershed conditions. Model outputs may exhibit uncertainty due to variability in climatic inputs, the resolution of DEM, the accuracy of soil and land use classifications, and the transfer of parameters from the calibration watershed. These uncertainties are inherent in data-scarce environments and were minimized through consistent data preprocessing, HRU threshold optimization, and multi-metric performance evaluation. Nevertheless, structural and input-related uncertainties remain and are acknowledged as limitations of the modeling framework.

Surface runoff estimation methods

The SWAT model provides two primary approaches for estimating surface runoff: the Green–Ampt infiltration method and the soil conservation service–curve number (SCS-CN) method (Al-Ghobari *et al.,* 2020). The Green–Ampt method (Green and Ampt, 1911) calculates infiltration explicitly based on soil hydraulic properties and rainfall intensity, with excess precipitation contributing to surface runoff. Nevertheless, this method necessitates comprehensive soil hydraulic parameters and high-resolution rainfall intensity data, which are not accessible from the meteorological stations within the study area. Therefore, the SCS-CN method was adopted within the SWAT framework. The SCS-CN approach estimates runoff as a function of soil type, land use, slope, and antecedent moisture conditions, making it well suited for semi-arid watersheds where only daily climatic data are available. In this study, CN values were derived from HRU-based land use and soil classifications. The method was opted owing to its alignment with the existing data and its recognized reliability in hydrological simulations conducted at the watershed scale.

Sediment yield and transport processes

Sediment yield was simulated using the modified universal soil loss equation (MUSLE) embedded within SWAT (Williams, 1995). In contrast to the original universal soil loss equation (USLE), the Modified Universal Soil Loss Equation (MUSLE) substitutes the rainfall energy factor with a runoff energy term, facilitating event-based sediment estimation that is influenced by simulated discharge and peak flow. In this study, MUSLE parameters were derived from HRU-specific soil erodibility, slope length and steepness, land cover, and conservation practice factors. The method enables spatially distributed estimation of sediment generation and routing toward the reservoir, consistent with watershed-scale sediment assessment objectives. When modeling sediment transport, SWAT makes a distinction between erosion occurring on the landscape and sediment routing that takes place in channels. Landscape erosion represents sediment detachment and delivery from HRUs to the stream network, whereas in-channel processes simulate sediment transport, deposition, and potential re-entrainment within reaches. The movement of sediment in channels is determined through a stream power-based technique that evaluates sediment carrying capacity as influenced by discharge and hydraulic conditions. Watershed delineation resulted in multiple sub-basins representing the complete drainage network contributing to Mosul Dam. Channel geometry and hydraulic characteristics for each reach were internally derived within SWAT based on DEM-based topography, drainage area, and simulated discharge. Consequently,

reach length, slope, and hydraulic properties characteristics differ spatially across sub-basins based on their physiographic features. All delineated sub-basins, including smaller upstream catchments, were included in the simulation framework to ensure comprehensive representation of sediment contributions at the valley scale (Hamid and Mohammed, 2025). The equation for stream power, known as the Bagnold equation, is utilized to estimate the maximum quantity of sediment that water is capable of transporting, as illustrated in Eq. 6 (Lu and Chiang, 2019):

$$Sed_{out} = Sed_{ch} \times \frac{V_{out}}{V_{ch}} \quad (6)$$

where, Sed_{out} is the sediment transported out of the reach in tons, Sed_{ch} is the suspended sediment in the reach in tons, V_{out} is the outflow volume during the time step in m³ of water and V_{ch} is the water's volume in the reach in m³ of water.

RESULTS AND DISCUSSION

Surface runoff simulation

Model performance statistics are summarized in Table 2. The calibrated model achieved NSE values of 0.94 for runoff depth, 0.61 for sediment concentration, and 0.91 for sediment load. Corresponding R^2 values ranged from 0.89 to 0.98, while IOA values exceeded 0.93 for all variables. The relatively low RMSE and MAE values further indicate acceptable predictive accuracy. These results illustrate an acceptable to commendable performance for long-term hydrological and sediment simulations. Following performance evaluation, calibrated parameter values were finalized. The CN values were determined as 91 for Sweedy Valley, 80 for Crnold Valley, and 77 for Alsalam Valley, with a calibration adjustment of +10%. The sediment routing parameter SPEXP was optimized at 1.6. These parameter values have been maintained for upcoming simulations and assessments. Although CN and SPEXP were identified as sensitive parameters, their uncertainty was constrained within defined calibration ranges through sensitivity analysis, and potential variability should be considered when applying the results to mitigation planning.

Hydrological and sediment model validation

The evaluation of the hydrological and sediment transport model was conducted by comparing measured and estimated values of runoff depth, sediment concentration, and sediment yield across several storm events. These parameters are essential indicators of watershed hydrological response and erosion dynamics. The validation results presented in Fig. 2, Fig. 3 and Fig. 4 demonstrate the model's capability to simulate runoff generation and sediment transport processes under varying hydrological conditions. The comparison between observed and simulated values provides insight into the reliability of the model in representing rainfall–runoff relationships and sediment mobilization within the study watershed.

Runoff depth validation

Fig. 2 presents the comparison between measured and estimated runoff depths, illustrating the model's performance in representing rainfall–runoff dynamics. The observed runoff values range from approximately 6 mm to 30 mm, while the estimated values vary between about 8 mm and 28 mm, indicating a generally close agreement between the two datasets. In most cases, the deviation between measured and estimated runoff remains within 2–3 mm, suggesting that the model effectively reproduces the magnitude and variability of runoff events. However, slight discrepancies are observed across different runoff magnitudes. The model tends to underestimate moderate runoff events, while slight overestimation occurs during

Table 2: Values of the statistical parameters for model calibration

Variable	R^2	IOA	NSE	RMSE	MAE
Runoff depth	0.98	0.997	0.94	3.98	2.59
Sediment concentration	0.89	0.93	0.61	0.08	0.08
Sediment load	0.95	0.98	0.91	365	228

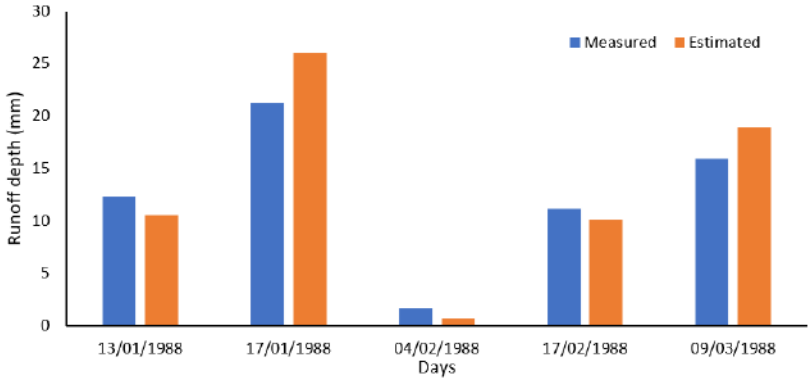

Fig. 2: Measured and estimated results for runoff depth

higher runoff conditions. These differences may be attributed to factors such as variations in antecedent soil moisture, infiltration capacity, rainfall intensity distribution, and spatial heterogeneity in land surface conditions, which may not be fully represented within the model structure. Despite these minor deviations, the overall alignment between measured and simulated runoff values indicates that the model adequately captures the hydrological processes governing runoff generation within the watershed. Consequently, the runoff simulation results provide a reliable basis for evaluating sediment transport processes.

Sediment concentration simulation

Fig. 3 illustrates the comparison between measured and estimated sediment concentrations, providing insight into the model's ability to simulate suspended sediment dynamics. The sediment concentration values range from approximately 0.05 mg/L to 0.55 mg/L, reflecting variability in sediment mobilization associated with different runoff conditions. The estimated concentrations closely follow the measured data, indicating that the model successfully reproduces the general magnitude and temporal variability of sediment concentration. A particularly strong agreement is observed during the peak sediment concentration event, where the measured concentration of 0.53 mg/L corresponds closely with the estimated value of 0.52 mg/L, demonstrating high precision in representing sediment mobilization under intense runoff conditions. Minor deviations occur at moderate concentration levels, where the model slightly underestimates or overestimates sediment values. These variations likely reflect the influence of additional environmental factors such as soil texture, vegetation cover, rainfall erosivity, land management practices, and antecedent soil moisture conditions. Such factors play a significant role in controlling sediment detachment and transport processes but may not be fully represented in the simplified modeling framework. Nevertheless, the close correspondence between measured and simulated sediment concentrations confirms that

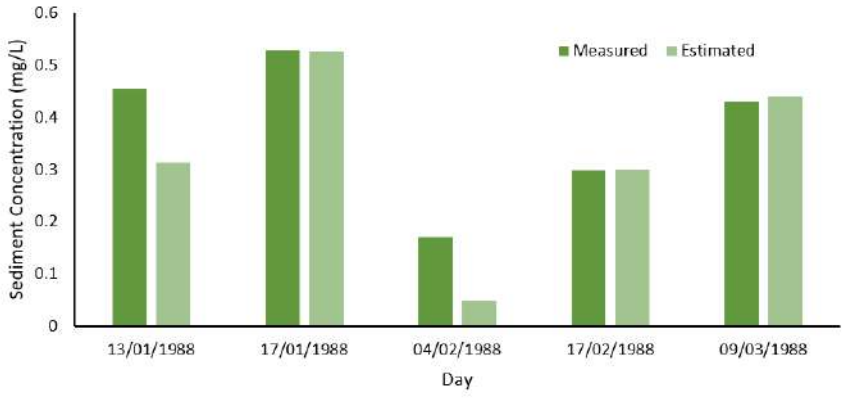

Fig. 3: Measured and estimated results for sediment concentration

the model effectively represents the sediment transport mechanisms operating within the watershed.

Sediment yield estimation

Fig. 4 presents the comparison between measured and estimated sediment amounts, providing a cumulative assessment of the model's performance in simulating sediment yield during runoff events. The measured sediment loads range from approximately 30 tons to 1200 tons, while the estimated values vary between about 5 tons and 1450 tons, indicating that the model captures the overall magnitude and variability of sediment transport. For instance, a measured sediment load of 600 tons corresponds to an estimated value of 350 tons, indicating moderate underestimation. In contrast, a major runoff event recorded a measured sediment load of 1200 tons and an estimated value of 1450 tons, reflecting the model's sensitivity to high-intensity hydrological events. Other events show closer correspondence between observed and estimated values, including 355 tons measured versus 325 tons estimated, and 745 tons measured versus 885 tons estimated. The results suggest that the model tends to slightly overestimate sediment loads during extreme runoff conditions, while moderate sediment events may be underestimated. These discrepancies are likely influenced by watershed characteristics such as slope gradient, soil erodibility, vegetation cover, rainfall intensity, and land management practices, all of which affect sediment detachment and transport processes. Despite these variations, the overall agreement between measured and simulated sediment loads confirms that the model reliably represents sediment yield dynamics within the watershed.

The results obtained in this study demonstrate improved agreement between measured and estimated hydrological and sediment parameters compared with previous modeling studies conducted in the region. Fadhil (2013) applied the Water Erosion Prediction Project (WEPP) model to estimate sediment loads entering the Mosul Dam reservoir during the period 1994–2012, while Ezz-Aldeen *et al.* (2012) used the SWAT model to estimate sediment transport for the period 1988–2008. In contrast, the present study covers a longer simulation period (1985–2024) and utilizes Fayda Valley as the calibration site instead of the Al-Khoser River, which was used in the previous studies. The extended temporal coverage and localized calibration contribute to the improved correspondence observed between measured and estimated runoff depth, sediment concentration, and sediment yield in Fig. 2, Fig. 3 and Fig. 4.

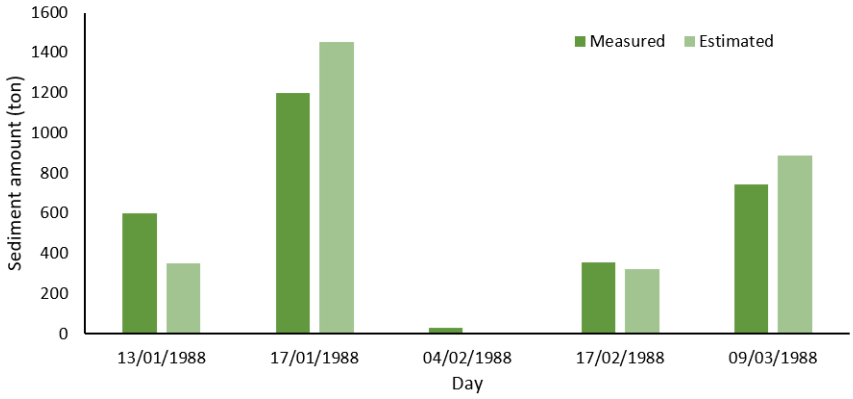

Fig. 4: Measured and estimated results for sediment amount

This alignment indicates that the Fayda Valley calibration effectively represents local hydrological characteristics, including hydraulic conductivity, rainfall erosivity, and soil erosion dynamics. Overall, the comparison of hydrological and sediment parameters demonstrates that the model performs satisfactorily in simulating watershed processes. The runoff depth results show strong agreement within the range of 6–30 mm, while sediment concentration values between 0.05 mg/L and 0.55 mg/L are accurately reproduced by the model. Similarly, sediment yield values ranging from 30 tons to 1200 tons are simulated with reasonable accuracy, although slight overestimation occurs during extreme events. The minor discrepancies observed between measured and estimated values can be attributed to natural variability in watershed characteristics, including soil erodibility, slope conditions, vegetation cover, rainfall intensity, and antecedent moisture levels. Despite these uncertainties, the overall agreement confirms that the model effectively captures the key processes controlling runoff generation and sediment transport. Therefore, the calibrated model can be considered sufficiently reliable for long-term hydrological and sediment simulations within the study watershed. The satisfactory agreement between measured and estimated runoff depth, sediment concentration, and sediment yield presented in Fig. 2, Fig. 3 and Fig. 4 confirms the reliability of the calibrated model for representing hydrological and sediment transport processes within the watershed. Based on this validated performance, the model outputs were further utilized to investigate the long-term relationship between surface runoff and sediment yield across the sub-basins. This analysis provides insight into runoff-driven sediment dynamics and enables the development of empirical relationships for predicting sediment yield under varying hydrological conditions, as illustrated in Fig. 7, Fig. 8 and Fig. 9 for the Sweedy, Crnold, and Alsalam valleys.

Precipitation and Surface Runoff Characteristics from SWAT Simulation (1985–2024)

Fig. 5 shows that the SWAT simulation results indicated an average annual precipitation of approximately 362.66 mm for the 39-year study period (1985–2024). This result closely matched the observed average annual precipitation at Mosul (362.37 mm) and Mosul Dam (352.81 mm) meteorological stations. During the simulation, the maximum monthly precipitation reached 68.97 mm in December, while the peak annual

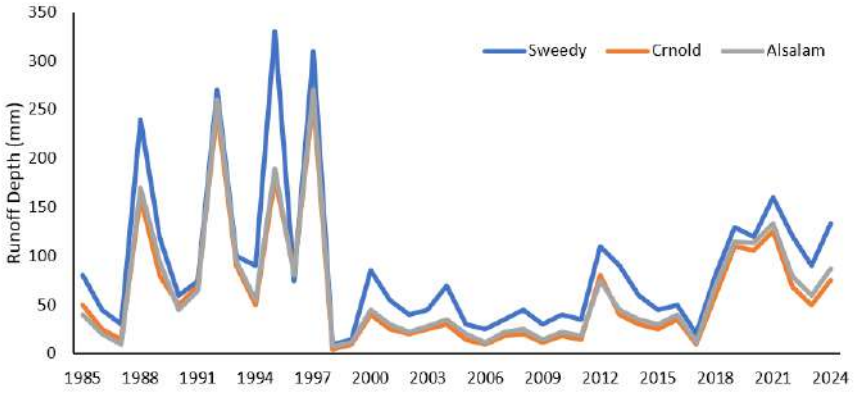

Fig. 5: The average annual surface runoff depth for all valleys (1985-2024)

precipitation of 797 mm was noted in 1996. Surface runoff depths averaged over the 39-year simulation period were approximately 91.2 mm/year for Sweedy Valley, 61.5 mm/year for Crnold Valley, and 60.3 mm/year for Alsalam Valley. Correspondingly, the average annual runoff volumes were estimated at 40.8, 4.6, and 2.7 million cubic meters per year (MCM/y) for Sweedy, Crnold, and Alsalam valleys, respectively. In February, the maximum monthly surface runoff depths were consistently observed, attaining values of 18.07 mm, 11.9 mm, and 12.86 mm for the respective valleys. On an annual basis, maximum runoff depths recorded were 329 mm in 1996 for Sweedy Valley, 270 mm in 1993 for Crnold Valley, and 261.6 mm in 1998 for Alsalam Valley. Inter-annual variability in runoff and sediment yield demonstrates that maximum sediment export does not necessarily coincide with the highest rainfall year. While Fadhil (2013) reported peak runoff in 1996 for Sweedy Valley and in 1994 for Crnold and Alsalam Valleys, and Ezz-Aldeen *et al.* (2012) identified 1993 as the dominant runoff year across valleys, the present study confirms that peak sediment export occurred in 1998, despite 1996 representing one of the highest rainfall years. This observed temporal disconnection between the intensity of rainfall and sediment yield demonstrates the nonlinear and threshold-dependent characteristics of sediment transport processes in semi-arid watersheds. The 1996 high-rainfall year likely triggered extensive hillslope erosion; however, a substantial portion of detached sediment was temporarily stored within hillslopes, ephemeral channels, and floodplain deposits rather than being immediately delivered to the reservoir. Intermediate storage zones of this nature are prevalent in semi-arid drainage systems, which are defined by intermittent flow and variable channel connectivity. In subsequent years, particularly 1998, hydrological conditions may have enhanced channel connectivity and transport efficiency, mobilizing previously stored sediment and producing a larger annual sediment export despite lower rainfall totals. This conduct corresponds with the sediment delivery ratio (SDR) concept, wherein merely a portion of the eroded sediment arrives at the basin outlet within the same hydrological event. The SDR is strongly influenced by watershed connectivity, storage capacity, and runoff intensity rather than rainfall volume alone. Episodic remobilization patterns are commonly observed in semi-arid basins, where sediment accumulated during intense rainfall events is progressively discharged during

later flow periods. Such storage–remobilization dynamics introduce lag times between peak rainfall and peak sediment yield and explain why sediment maxima may follow rather than coincide with precipitation extremes. Seasonal variability further contributes to sediment dynamics. In semi-arid regions, intense winter storms generate rapid surface runoff under conditions of limited vegetation cover, increasing detachment and transport efficiency. Nevertheless, the moisture conditions that exist beforehand and the sequence of storm events are vital in ascertaining if sediment is either transported away or temporarily retained. Successive moderate rainfall events may gradually mobilize previously deposited material, amplifying sediment yield during years that do not necessarily record the highest precipitation totals. These findings highlight the importance of internal watershed storage mechanisms in regulating sediment export to Mosul Dam. Rather than attributing inter-annual differences solely to rainfall variability or land-use change, the present results emphasize hydrological connectivity and sediment storage–release cycles as dominant controls. This interpretation bolsters confidence in the 1998 sediment peak by situating it within recognized sediment transport theory instead of regarding it as an unusual result. Overall, analysis of inter-annual runoff and sediment variability demonstrates that sediment export in the Mosul Dam watershed is governed by nonlinear hydrological thresholds, storage capacity, and episodic remobilization processes. Such dynamics are particularly relevant for reservoir sediment management, as they suggest that single extreme rainfall years may not immediately translate into maximum reservoir sedimentation, but instead contribute to cumulative sediment pulses over subsequent hydrological cycles (Asres *et al.,* 2025).

Sediment yield simulation

The simulation further provided the cumulative sediment load and volume entering the dam reservoir over the 39-year period. Results revealed sediment loads totaling 111.4×10^3 tons for Sweedy Valley, 14.24×10^3 tons for Crnold Valley, and 7.34×10^3 tons for Alsalam Valley. Corresponding sediment volumes were 42.04×10^3, 5.37×10^3, and 2.77×10^3 m^3/year, respectively. The cumulative sediment yields were calculated as 443.85 tons/ha for Sweedy Valley, 176.47 tons/ha for Crnold Valley, and 124.12 tons/ha for Alsalam Valley. Peak sediment production was consistently observed in February, with maximum monthly sediment yields recorded as 1.17×10^3, 1.86×10^2, and 1.08×10^2 tons for Sweedy, Crnold, and Alsalam valleys, respectively. Additionally, the year 1998 marked the highest annual sediment yield for all valleys, with recorded sediment yields of 102.04, 53.15, and 57.29 tons/ha for Sweedy, Crnold, and Alsalam valleys, respectively. The average annual sediment loads for each valley are demonstrated in Fig. 6. Table 3 provides a comparative summary of the results from the current study and to prior studies carried out within the same watershed. The comparison reveals variations in study duration, modeling frameworks, runoff volumes, and sediment load estimates, while simultaneously confirming consistent spatial sediment patterns across the basin.

Comparison with Previous Hydrological and Sediment Modeling Studies

To conduct a substantial comparison studies, one must carefully consider the variations in temporal coverage, model structure, spatial discretization, and calibration strategies. One of the most significant distinctions lies in the simulation period. The present study spans 1985–2024, providing the longest temporal coverage relative to Khaleel and Mahmood (2018)

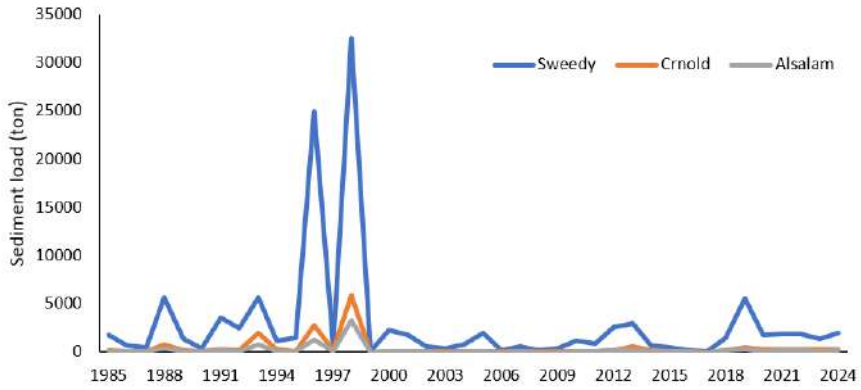

Fig. **6**: The average annual sediment load for all valleys (1985-2024)

Table 3: Summarized results of this study compared with previous studies

Parameter		Current study	Khaleel and Mahmood (2018)	Fadhil (2013)	Ezz-Aldeen *et al.* (2012)
Study period		1985-2024	1988-2016	1994-2012	1988-2008
The used software		SWAT	SWAT-MATLAB	WEPP	SWAT
Average annual runoff Volume $\times 10^3$ (m^3/year)	Sweedy	40.8	13.6	19.2	20.6
	Crnold	4.6	1.37	3.4	3.1
	Alsalam	2.7	1.08	1.1	0.8
Annual average load $\times 10^3$ tons/year	Sweedy	111.4	792.21	330.5	747.5
	Crnold	14.24	31.45	29.2	104.3
	Alsalam	7.34	34	20.5	45.9

(1988–2016); Fadhil (2013) (1994–2012), and Ezz-Aldeen *et al.* (2012) (1988–2008). Prolonged simulation periods naturally encompass various hydrological which include both wet extremes and extended dry phases, consequently mitigating the effect of isolated years with high-magnitude erosion. In contrast, shorter simulation periods may be disproportionately influenced by individual sediment-producing events, particularly in semi-arid systems where interannual variability is high. Differences in modeling frameworks further contribute to discrepancies. While the present study and Ezz-Aldeen *et al.* (2012) applied SWAT, Khaleel and Mahmood (2018) integrated SWAT with MATLAB processing, and Fadhil (2013) utilized the WEPP model. The fundamental differences among these models lie in how they represent erosion, partition runoff, and implement sediment routing algorithms. Continuous watershed-scale simulation, as implemented in SWAT, accounts for cumulative storage, channel deposition, and remobilization processes, whereas event-based frameworks may emphasize peak-event erosion. Even within SWAT applications, differences in DEM resolution, HRU threshold definitions, parameterization strategies, and calibration targets can significantly influence sediment magnitude estimates. Runoff comparisons illustrate these structural differences. The present study estimates annual runoff of 40.8 × 10^3 m^3 for Sweedy Valley, compared to 13.6 × 10^3 m^3 (Khaleel and Mahmood, 2018), 19.2 × 10^3 m^3 (Fadhil, 2013), and 20.6 × 10^3 m^3 (Ezz-Aldeen *et al.*, 2012). The differences in climatic datasets, watershed discretization, and parameter calibration are reflected in this variation. For instance, HRU threshold selection influences runoff

concentration by altering slope–soil–land use combinations, while DEM resolution affects flow path length and slope gradients, both of which directly impact runoff energy. Discrepancies are more pronounced in sediment load estimates. For Sweedy Valley, reported annual sediment loads range from 792.21 × 10^3 tons (Khaleel and Mahmood, 2018) to 111.4 × 10^3 tons in the present study. This almost seven-fold disparity does not inherently suggest inconsistency; instead, it indicates a sensitivity to parameterization and routing assumptions. Sediment routing parameters such as SPCON and SPEXP exert nonlinear control on channel transport capacity; small adjustments in sediment exponents can lead to exponential amplification of predicted annual loads. Furthermore, sediment yield is highly responsive to peak runoff intensity, slope representation, and channel erosion assumptions. Studies utilizing coarser DEM resolution might lead to an overestimation of slope length factors, whereas variations in HRU discretization can either intensify or diminish erosive energy throughout the watershed. The extended simulation period in the present study likely contributes to more conservative long-term sediment averages. Semi-arid systems frequently exhibit episodic sediment pulses driven by extreme rainfall years. A condensed calibration period characterized by high-intensity occurrences can artificially elevate the average annual sediment yield (Mohammadzadeh-Habili and Khalili, 2020). By integrating almost forty years of hydrological variability, this study tempers these episodic surges and effectively captures the dynamics of cumulative storage and remobilization. This may partly explain why estimated sediment magnitudes are lower than those reported in shorter-term studies. Despite differences in absolute magnitude, all studies consistently identify Sweedy Valley as the dominant sediment contributor. In the present analysis, Sweedy accounts for approximately 84% of the total sediment load generated by the three valleys, compared with substantially smaller contributions from Crnold and Alsalam. This persistent spatial superiority observed in separate studies enhances trust in the pattern of sediment contributions, even when the absolute values vary. The high sediment yield from Sweedy Valley reflects interacting geomorphological and hydrological controls, including steeper slopes, erodible soil textures, limited vegetative cover, and efficient runoff concentration. These characteristics enhance sediment detachment and delivery efficiency beyond what drainage area alone would predict. Temporal discrepancies in peak sediment years also warrant analytical interpretation. Fadhil (2013) identified 2006 as the peak year for Sweedy and Crnold, whereas Ezz-Aldeen *et al.* (2012) reported 1988 as the highest sediment year. The present study identifies 1998 as the dominant sediment year across valleys. Differences in peak-year identification are influenced by variation in study periods and rainfall distribution patterns. Furthermore, the process of sediment generation may include mechanisms of delayed storage and remobilization, where eroded materials are temporarily held in channels or floodplains prior to being mobilized during later high-flow events. Such processes can decouple sediment peaks from rainfall peaks and contribute to temporal variability among modeling studies. The sensitivity analysis results indicating strong influence of CN, SPCON and SPEXP are consistent with established SWAT literature rather than representing a novel finding. Numerous watershed-scale applications have demonstrated that CN governs runoff generation magnitude, while sediment transport coefficients regulate channel carrying capacity. In semi-arid systems characterized by infiltration-excess runoff, CN exerts dominant control over flow energy, which in turn drives sediment

detachment and transport. The current study affirms the recognized behavior in the context of the Mosul Dam watershed and highlights its importance for spatial sediment prioritization, instead of proposing a novel theoretical contribution. Comparable international investigations reinforce the broader relevance of these findings. Zago *et al.* (2024) demonstrated that excessive sediment deposition in the Disueri reservoir significantly reduced storage capacity and disrupted downstream sediment balance, affecting water availability and agricultural sustainability. Similarly, Yıldırımer and Özalp (2024) showed that anthropogenic interventions altered flow regimes and sediment dynamics in Turkish catchments, highlighting the importance of careful model calibration under human-influenced conditions. These studies correspond with the current analysis, stressing the critical need for long-term datasets, systematic assessment of parameters, and comprehensive watershed evaluation to optimize sediment management and reservoir sustainability. Overall, although numerical values vary across different studies, the essential hydrological behavior and the prevailing patterns of spatial sediment dominance remain unchanged. The extended study period, structured sensitivity analysis, and refined parameter calibration applied in the present research enhance confidence in runoff and sediment simulations. The comparison underscores that reliable watershed-scale sediment modeling requires not only appropriate modeling tools but also transparent calibration procedures and comprehensive temporal coverage to support sustainable reservoir management and erosion mitigation planning.

Runoff and sediment yield relationship

Power-law relationships were identified between annual runoff and annual sediment yield for each studied valley. The fitted equations yielded R^2 values of 0.80, 0.77, and 0.82 for the Sweedy, Crnold, and Alsalam valleys, respectively, indicating a strong statistical association between runoff magnitude and sediment production. These relationships do not suggest causation; instead, they serve as empirical predictive tools for assessing sediment yield in relation to runoff variability at the sub-basin level. Separate equations were developed to reflect valley-specific geomorphological and hydrological characteristics, allowing improved representation of spatial heterogeneity in sediment response within the watershed, using Eqs. 7, 8 and 9 (Hadadin and Al-Adwan, 2020):

The Sweedy valley Eq.:

$$ASY = 49.7 \times Q_{surf}^{1.14} \quad (7)$$

The Crnold valley Eq.:

$$ASY = 26 \times Q_{surf}^{1.02} \quad (8)$$

The Alsalam valley Eq.:

$$ASY = 25.4 \times Q_{surf}^{1.32} \quad (9)$$

where: ASY represents the calculated annual sediment yield (ton/ha). These results are aligned with those estimated by Hadadin and Al-Adwan (2020) for Wadi Al-Arab Dam and Al-Weshah *et al.* (2025) for Wadi Shu'eib Dam in Jordan. Fig. 7, Fig. 8 and Fig. 9 illustrate the Surface Runoff-Sediment Yield Relationship for each valley respectively. The runoff–sediment relationships were derived from long-term simulated outputs calibrated against the available dataset in the Fayda catchment. Consequently, the unavailability of ongoing monitoring of runoff and sediment data in the target valleys restricts the ability to independently validate the derived relationship.

Therefore, the predictive relationship should be interpreted as a long-term theoretical estimation framework rather than a site-specific operational forecasting tool.

Surface runoff-sediment yield relationship for Sweedy valley

As shown in Fig. 7, the empirical data demonstrates a strong positive correlation between surface runoff and sediment yield, characterized by an R^2 value of 0.80. At lower runoff levels below 50 mm, sediment yield remains relatively low, generally staying under 10 ton/ha. However, as runoff intensity increases to 114 mm and 120 mm, sediment yields rise to 18.5 ton/ha and 20 ton/ha, respectively. Further observations indicate yields of 19 ton/ha at 150 mm, 25 ton/ha at 210 mm, and 24 ton/ha at 250 mm. The upper threshold of the data shows that a runoff of 280 mm generates a sediment yield of 34 ton/ha, while the relationship peaks at a maximum yield of 42 ton/ha for a runoff of 330 mm. The power law relationship, defined by a scaling constant of 49.7 and a power exponent of 1.14, suggests that sediment mobilization increases at a slightly higher rate than runoff volume. This trend implies that higher runoff velocities provide the critical shear stress necessary to disproportionately detach and transport larger quantities of soil particles from the land surface.

Surface runoff-sediment yield relationship for Crnold valley

As shown in Fig. 8, the empirical data demonstrates a strong positive correlation between surface runoff and sediment yield, characterized by an R^2 value of 0.77. At lower runoff levels below 50 mm, sediment yield remains relatively low, generally staying under 5 ton/ha. However, as runoff intensity increases to 150 mm and 200 mm, sediment yields rise significantly to 19 ton/ha and 18.2 ton/ha, respectively. Further observations indicate yields of 25 ton/ha at 210 mm, 24 ton/ha at 250 mm, and 17 ton/ha at 270 mm. The upper threshold of the data reveals that a runoff of 280 mm generates a sediment yield of 34 ton/ha, with the highest observed yield reaching 42 ton/ha for a runoff of 330 mm. The power law relationship, defined by a scaling constant of 26 and a power exponent of 1.02, suggests a nearly linear but slightly accelerating rate of sediment mobilization as runoff volume increases. This trend implies that higher runoff volumes provide the necessary energy to detach and transport significant quantities of soil particles, though the scatter in the data at higher runoff levels suggests that secondary factors such as rainfall intensity or soil moisture also influence the final yield.

Surface runoff-sediment yield relationship for Alsalam valley

As shown in Fig. 9, the empirical data demonstrates a strong positive correlation between surface runoff and sediment yield, characterized by an R2 value of 0.82. At lower runoff levels below 100 mm, sediment yield remains relatively low, generally staying under 10 ton/ha. However, as runoff intensity increases to 150 mm and 180 mm, sediment yields rise significantly to approximately 19 ton/ha and 14 ton/ha, respectively. Further observations indicate yields of 25 ton/ha at 210 mm and a notable spread at 250 mm with values reaching 16 ton/ha and 24 ton/ha. The upper threshold of the data shows that a runoff of 280 mm generates a sediment yield of 34 ton/ha, while the maximum yield reaches 42 ton/ha for a runoff of 330 mm. The power law relationship, defined by a scaling constant of 25.4 and a power exponent of 1.32, suggests that sediment mobilization increases at a significantly higher rate than runoff volume. This trend implies that higher runoff velocities provide

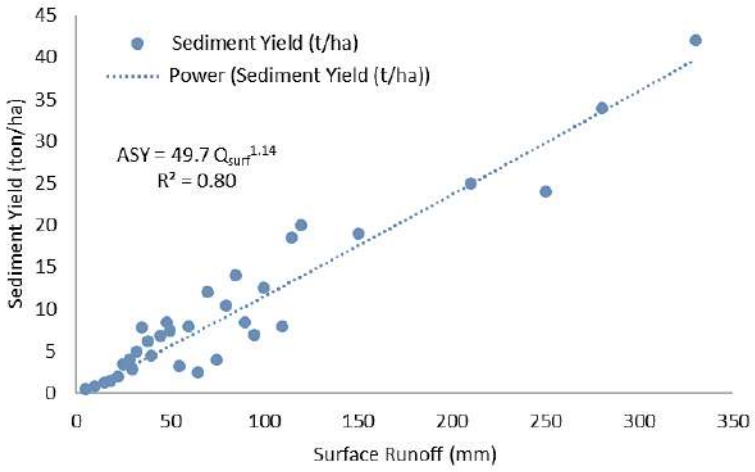

Fig. 7: Surface runoff-sediment yield relationship for Sweedy valley

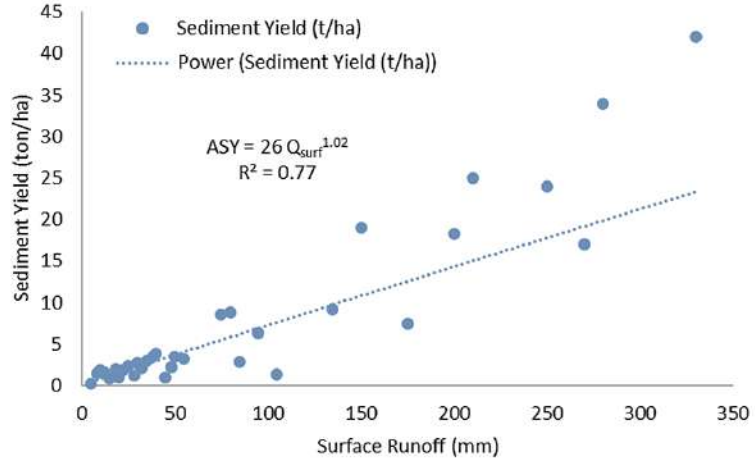

Fig. 8: Surface runoff-sediment yield relationship for Crnold valley

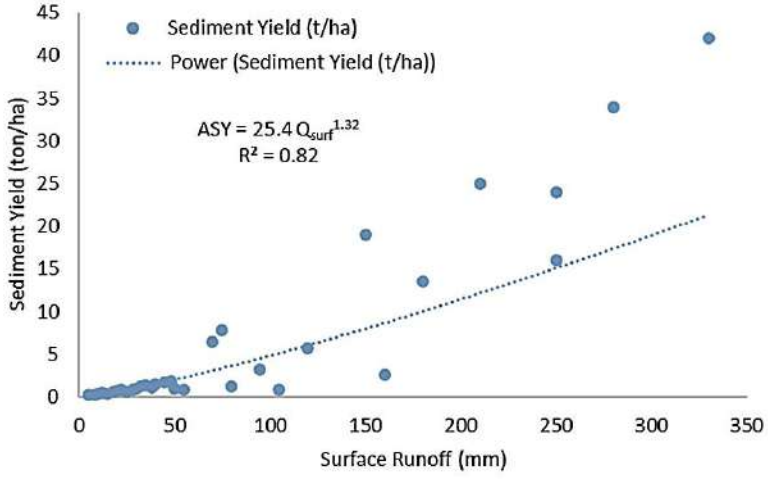

Fig. 9: Surface runoff-sediment yield relationship for Alsalam valley

the critical shear stress necessary to disproportionately detach and transport larger quantities of soil particles from the land surface. The derived runoff–sediment yield relationships demonstrate that sediment production in the studied valleys responds strongly to variations in surface runoff, confirming the critical role of hydrological processes in controlling soil erosion dynamics within the watershed. The power-law relationships indicate that sediment yield increases nonlinearly with runoff, particularly in the Sweedy and Alsalam valleys where the exponents exceed unity. This suggests that intense runoff events can significantly accelerate soil detachment and transport processes, thereby increasing erosion risk. From a watershed management perspective, these modeling results provide an important predictive framework for identifying runoff thresholds that trigger substantial sediment mobilization. The higher exponent observed in Alsalam valley (1.32) indicates greater sensitivity to runoff fluctuations, suggesting that this sub-basin may require prioritized soil conservation and erosion control interventions. In contrast, the near-linear relationship in Crnold valley (exponent 1.02) indicates relatively stable sediment response under increasing runoff conditions. Overall, the runoff–sediment dynamics modeling highlights the importance of implementing integrated watershed management strategies, including vegetation restoration, slope stabilization, and runoff control structures, to reduce erosion risk and sediment transport. By linking hydrological processes with sediment yield responses, the developed relationships support sustainable watershed management by enabling better planning of soil conservation measures and improving the understanding of long-term erosion dynamics in data-limited catchments.

CONCLUSION

This study provides a long-term assessment of runoff and sediment dynamics within the Mosul Dam watershed using the SWAT model over a multi-decadal simulation period. The model achieved satisfactory to good performance for both runoff and sediment variables, thereby affirming the reliability of the simulated watershed response. A moderate nonlinear relationship between annual runoff and sediment yield was identified, confirming that sediment export increases disproportionately in high-flow scenarios and is chiefly determined by hydrological variability. Clear spatial heterogeneity in sediment contribution was observed. Sweedy Valley has been recognized as the primary source of sediment, accounting for roughly 84% of the overall sediment load supplied by the three main tributaries. This dominance illustrates the collective impact of steeper slopes, erodible soils, limited vegetation cover, and efficient runoff concentration rather than solely the drainage area. The identification of this priority sub-watershed provides a direct basis for spatially targeted erosion control measures. Sensitivity analysis has established that the response of sediment in the basin is predominantly influenced by the CN and sediment transport coefficients, whereas the impact of other hydraulic parameters is comparatively limited. This finding aligns with established SWAT applications in semi-arid systems and reinforces the importance of carefully constraining runoff generation and sediment routing parameters during calibration. While the study did not explicitly measure the long-term loss of reservoir storage or the degradation of water quality, the extent and geographical distribution of sediment inflow suggest an ongoing threat to both reservoir capacity and operational sustainability. The results therefore provide essential input for evaluating sediment management strategies aimed at reducing future storage decline. From a management perspective, erosion mitigation should be prioritized in Sweedy Valley, where targeted vegetation enhancement, hillslope stabilization, and riparian buffering are expected

to yield the greatest reduction in sediment delivery. Structural interventions like small retention or check dams can additionally decrease peak sediment transport during high-flow events. These recommendations are directly derived from the spatial hotspot analysis rather than generalized watershed practices. Overall, this study provides a comprehensive sediment budget framework at the basin scale, which incorporates long-term hydrological simulations, the identification of spatial hotspots, and an analysis of the linkage between runoff and sediment to facilitate. By identifying dominant sediment sources and key controlling parameters, the findings provide a decision-support foundation for protecting Mosul Dam's storage capacity under ongoing hydroclimatic variability. The outcomes directly contribute to sustainable development goal (SDG) 6 through improved water resource protection and reservoir sustainability, and to SDG 13 by strengthening adaptive watershed management under climate-related hydrological extremes.

AUTHOR CONTRIBUTIONS

W.Th. Aness performed the conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing, original draft preparation, visualization and supervision. N.A. Hadadin contributed to conceptualization and methodology development, performed formal analysis, provided resources, supervised the research process, and assisted in project administration and manuscript drafting. M.M. Zoubi contributed to conceptualization, methodology design, software implementation, validation, formal analysis, investigation, and data curation, and participated in drafting and supervising the manuscript. Q.Y. Abu-Afifeh contributed to conceptualization, methodology development, software implementation, resource provision, data curation, manuscript drafting, and supervision. A. Al-Afeshat and H. Al-Jawaldeh contributed to software implementation, validation, data curation, and manuscript review and editing. T.A. Qutishat assisted in investigation, data curation, manuscript review and editing, and visualization. M.R. AlHalaigah contributed to formal analysis, data curation, and manuscript review and editing. N.H. Alnizami provided resources, assisted in validation, and contributed to manuscript review and editing. A. Aljarrah provided resources and contributed to manuscript review and editing. Y.A. Alta'any contributed to methodology development, software implementation, preparation of the original draft, and manuscript review and editing. A.J. Alzubaidi contributed to methodology development, software implementation, and manuscript review and 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
ASY	Annual sediment yield
CH_K	Channel effective hydraulic conductivity
CN	Curve number
DEM	Digital elevation model
E	East
EUCPM	European union civil protection mechanism
GIS	Geographic information system
ha	Hectare
HRUs	Hydrological response units
IOA	Index of agreement
km	Kilometer
km²	Square kilometers
km³	Cubic kilometers
m	Meter
m³	Cubic meters
MAE	Mean absolute error
MCM/y	Million cubic meters per year
mm	Millimeter
MUSLE	Modified universal soil loss equation
N	North
n	Manning's roughness coefficient
n (statistical)	Number of data points
OAT	One-at-a-time
Q_{surf}	Surface runoff
RMSE	Root mean square error
S	Retention coefficient
SCS-CN	Soil conservation service-curve number
Sed_{ch}	Suspended sediment in the reach
Sed_{out}	Sediment transported out of the reach
SOL_K	Saturated hydraulic conductivity of soil
SPCON	Linear sediment transport coefficient
SPEXP	Exponential sediment transport coefficient
SWAT	Soil and water assessment tool
UN	United nations
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USLE	Universal soil loss equation
V_{ch}	Water volume in the reach
V_{out}	Outflow volume during time step
X_r	Measured data value
$\bar{X}_r$	Average measured data values
X_s	Model-simulated value
$\bar{X}_s$	Average simulated values

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ORIGINAL RESEARCH PAPER

Conservation of fragile karst forests through rhizosphere microbiome of endangered species and ecological restoration of *Hopea celebica*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Hopea celebica is an endangered dipterocarp endemic to Sulawesi, restricted to fragile karst forests with shallow nutrient- poor soils. Furthermore, the conservation value is high, yet the threats to its habitat are on the rise, and ecological knowledge, especially concerning its belowground microbial relationships, is still quite restricted. The rhizosphere microbiome plays an important role in plant nutrition and stress tolerance, yet the microbial community associated with H. celebica remains undocumented. The objective of this study was to record the diversity of bacteria and to identify the ecologically and functionally significant dominant taxa in the rhizosphere of H. celebica in the Maros-Pangkep Karst region.

METHODS: Rhizosphere soil samples were collected from four natural populations of H. celebica within the Maros Karst region, South Sulawesi, Indonesia. Total community deoxyribonucleic acid was extracted, and the composition of the bacterial community was analyzed using 16S ribosomal ribonucleic acid gene amplicon sequencing targeting the Variable regions 3 and 4 region on the deoxyribonucleic acid nanoball sequencing-G400 platform. Sequence data were processed using the quantitative Insights Into microbial ecology 2 pipeline, including quality filtering, amplicon sequence variant inference, and taxonomic classification against the systematic interactive labeled viewer of alignments 138.1 reference database. Alpha diversity indices were applied to evaluate bacterial richness and evenness among sampling sites.

FINDINGS: A total of 89,862 high-quality sequence reads were obtained, representing 12 bacterial phyla, 103 orders, 155 families, 204 genera, and 720 species. Proteobacteria were the most abundant and diverse phylum, forming two major phylogenetic clusters dominated by families such as Geminicoccaceae, Methyloligellaceae, and Rhizobiales incertae sedis. The family Gaiellaceae, especially the Gaiella genus, consistently exhibited dominance across every sampling sites. The analysis of alpha diversity revealed that the composite sample derived from rhizosphere soils linked to mature trees at the Leang-Leang site exhibited the highest bacterial richness and community evenness when compared to the other samples tested..

CONCLUSION: As an initial exploratory baseline, this study reveals that Hopea celebica is associated with a structured rhizosphere microbiome functionally equipped for extreme environments. The prominence of particular taxa implies possible essential functional roles, including the solubilization of rock phosphates, the promotion of nitrogen cycling, and the enhancement of stress tolerance, which collectively aid in the survival of plants in nutrient-scarce karst soils.

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INTRODUCTION

Hopea celebica (family Dipterocarpaceae) is a tropical hardwood tree that can constitute a significant portion of primary forests in Sulawesi. Members of Dipterocarpaceae often dominate the canopies of Asian tropical forests. Since 1998, *H. celebica* has been listed as Endangered on the International Union for Conservation of Nature (IUCN) Red List due to severe population decline. This tree, commonly called "kerih" in the local context, is essential for sustaining forest structure and offering ecosystem services in its indigenous area of South Sulawesi. Its population has plummeted by an estimated 75 percent (%) in recent decades (Arsyad *et al.,* 2022). *H. celebica* grows slowly and regenerates naturally only via seeds (Sudarmonowati *et al.,* 2020). It is valued for its dense wood (often yielding resin, oil, and camphor) and is found in a few primary forest locations on Sulawesi (Luwu, Maros in South Sulawesi, and Nuha in Southeast Sulawesi), typically at elevations of around 500 meters (m) above sea level (asl). In particular, the Maros provenance prospers within the primary forests found in karst landscapes (Michely, 2021). Past research on Dipterocarpaceae has traditionally focused on breeding (Indrioko *et al.,* 2006), conservation, and genetic diversity (Cheng *et al.,* 2014). Recent studies highlight the critical role of *rhizosphere* microbiomes in supporting the survival and nutrient acquisition of Dipterocarpaceae species, particularly in nutrient-poor tropical soils (Essene et al., 2017; Li *et al.,* 2024). Nonetheless, a considerable knowledge gap persists concerning the microbial symbionts of *H. celebica,* especially the variety of of microbes in its *rhizosphere* within the karst forests of Maros. Furthermore, tropical karst ecosystems present unique edaphic challenges—such as shallow soils, low nutrient availability, and specific hydrological dynamics—that strongly shape the taxonomy and metabolic potential of soil microbial communities (Jiang and Zeng, 2023). Due to the fact that disruptions in these ecosystems greatly impact delicate microbial networks (Sniegocki *et al.,* 2022), conservation strategies are transitioning from conventional reforestation to the restoration of belowground microbial communities in order to maintain nutrient cycling (Daniel, 2005; Juliawaty *et al.,* 2009). To achieve this, understanding the *rhizosphere*—where plants selectively enrich specific microbes via root exudates to buffer against environmental stress—is critical (Hakim *et al.,* 2021). Next-generation sequencing (NGS) provides a powerful, culture-independent metagenomic strategy to define these essential symbiotic networks and their possible ecological roles (Riesenfeld *et al.,* 2004; Edge *et al.,* 2020). Recent studies in karst regions of China have highlighted distinctive soil microbial communities in such environments (Chen *et al.,* 2022; Zhang *et al.,* 2022). Unlike studies in Chinese karst areas, documentation of the *rhizosphere* microbiome of *H. celebica* in tropical karst has never been conducted. While 16S ribosomal ribonucleic acid (rRNA) sequencing is commonly employed to characterize *rhizosphere* communities in both agricultural and model plants, the precise microbial relationships that facilitate the adaptation of endemic species like *H. celebica* to adapt to the extreme edaphic stress of tropical karst ecosystems are still largely uncharted. In fact, the thin and nutrient-poor karst soil conditions require plants to selectively recruit specific microbes to support nutrient uptake and stress tolerance. Consequently, this research not only addresses a deficiency in the documentation of bacteria study that thrive in oligotrophic conditions but also seeks to extend beyond a mere community description by offering detailed ecological insights into plant-microbe resilience in extreme environments. This triggers a paradigm shift in conservation, moving from traditional methods that focus on planting seedlings to a holistic ecological restoration approach (holobiont) that integrates the restoration of underground microbiome communities to save this endangered species. The objectives of the study include 1) catalog the diversity of bacteria present in the *rhizosphere* of *H. celebica* growing

in karst forests, and 2) Determine the leading microbial taxa along with their possible microbially-mediated ecological strategies that could play a crucial role in the host's survival. This study was conducted in the Maros-Pangkep Karst region in 2025.

MATERIALS AND METHODS

The locations for the study were determined following an initial survey that outlined the distribution of *H. celebica* in karst forests (Fig. 1). It should be noted that *H. celebica* was found only at these specific locations in Maros-Pangkep karst area. At each location, soil from the *rhizosphere* (soil attached to and surrounding the roots) of *H. celebica* was collected from a depth of 20–30 centimeters (cm). Sampling was differentiated between seedlings and mature trees (Table 1). At every sampling location, *rhizosphere* soil was gathered from a single representative individual of Hopea celebica, as the species is found infrequently and only one accessible plant at each site fulfilled the sampling requirements. In total, four natural populations samples were obtained, including two from seedlings (H1 and H2) and two from mature trees (H3 and H4). For each plant, approximately 500 g of *rhizosphere* soil was collected as a composite sample, formed by combining several subsamples taken from different points around the root zone (20–30 cm depth). This composite depicts the *rhizosphere* of a specific individual plant, and no composite samples across multiple plants or different locations were assembled. The *rhizosphere* soil was placed in sterile plastic containers, and stored on ice during transport. In the laboratory, samples were stored at –20 degrees Celsius (°C) prior to deoxyribonucleic acid (DNA) extraction to maintain microbial DNA integrity.

DNA extraction and PCR amplification

Microbial DNA was extracted from *rhizosphere* soil samples using the Presto™ Soil DNA Extraction Kit (GeneAid, Taiwan) following the manufacturer's protocol. Genomic DNA quality was first assessed using agarose gel electrophoresis (2% gel) to confirm high-molecular-weight DNA and by spectrophotometric quantification. The isolated DNA served as a template for the amplification of the rRNA gene through polymerase chain reaction (PCR). The hypervariable V3–V4 region of the 16S rRNA gene was targeted using universal bacterial primers. Each PCR reaction contained the necessary controls and were performed under conditions refined for the primer set. PCR reactions were performed using *KAPA HiFi Hot Start Ready Mix* (KAPA Biosystems), with the following thermal cycling conditions: initial denaturation at 95 °C for 3 min; 25 cycles of 95 °C for 30 s (denaturation), 55 °C for 30 s (annealing), and 72 °C for 30 s (extension); followed by a final extension at 72 °C for 5 min. The PCR products were assessed by electrophoresis on a 2% agarose gel (stained with sybio research (SYBR) Green) to verify successful amplification. A DNA band of ~400–450 base pairs (bp) corresponding to the Variable regions 3 and 4 (V3–V4) amplicon was expected. Only samples that produced a distinct, singular band of the appropriate size were chosen for subsequent processing. These target amplicons were then excised and purified from the gel using the Qiagen gel extraction kit (Qiagen, Germany) to remove any nonspecific products or primer dimers (NRCS *et al.,* 1999).

Library preparation and sequencing

Quantification of purified PCR amplicons from each sample was performed, and they were subsequently pooled in equimolar concentrations for library preparation. Indexed sequencing libraries were constructed according to standard protocols. Paired-end sequencing (2 × 250 bp) was performed on the mission genomics initiative (MGI) DNA nanoball sequencing (DNBSEQ) -G400 platform (MGI Tech Co., Shenzhen, China), which is similar to Illumina technology. This platform was selected due to its exceptional throughput and



Fig. 1 : Geographical location of the study area along with the rhizosphere soil sampling of *Hopea celebica* in Maros Karst, in Indonesia

Table 1: *Rhizosphere* soil sampling sites for *H. celebica* in Maros Karst. Each location is identified by a sample code and categorized by host plant age class, and elevation (meters above sea level, m asl) is provided

Sample Name	Location	Category	Latitude (m) (asl)
Hopea 1 (H1)	Karaenta	Seedling	338
Hopea 2 (H2)	Pattunuang	Seedling	108
Hopea 3 (H3)	Bantimurung	Tree	55
Hopea 4 (H4)	Leang-Leang	Tree	39

accuracy in amplicon sequencing. The sequencing run followed the protocol outlined by (Bolyen *et al.,* 2019) for microbiome analysis, ensuring sufficient depth to capture the diversity of bacteria in each sample.

Sequence processing and diversity analysis

Raw sequencing reads underwent processing with the QIIME2 pipeline (version 2021.4) for quality control and taxonomic analysis (Bolyen *et al.,* 2019). Cutadapt was employed to trim the adapter and primer sequences. Denoising, error correction, paired-end merging, and chimera removal were performed using the DADA2 algorithm (Callahan *et al.,* 2016), resulting in high-resolution amplicon sequence variants (ASVs). Phred quality scores that fell below Q20 were disregarded, and low-quality bases were removed prior to downstream analysis. Following quality filtering, 89,862 high-quality reads were retained from the four *rhizosphere* samples. Taxonomic assignment utilized the SILVA database (version 138.1) with a 99% similarity threshold for bacterial 16S rRNA gene sequences. To standardize sequencing effort, the ASV table was rarefied to equal sequencing depth before diversity analysis. Rarefaction curves approached saturation, and Good's coverage values approached 1, suggesting

that the sequencing depth was adequate to encompass the majority of microbial diversity, including rare taxa within each sample. To evaluate within-sample diversity, indices of alpha diversity such as Observed ASVs, Shannon, Simpson, and Inverse Simpson were calculated. The vegan package in R (version 4.2.3) was utilized for these computations. Visualization of community composition was illustrated through relative abundance plots and heatmaps. Predictive functional profiling was conducted with PICRUSt2. Beta diversity was assessed using Bray–Curtis dissimilarity and visualized with principal coordinate analysis (PCoA) implemented through the phyloseq and vegan packages in R. Considering the restricted sample size and absence of biological replication, inferential statistical tests (such as Kruskal–Wallis for alpha diversity or PERMANOVA for beta diversity) were not performed to avoid pseudoreplication. The distinctions between locations were analyzed descriptively, with a clear acknowledgment that the variations observed could be attributed to sampling variation or localized microsite heterogeneity rather than definitive site-level differences. Consequently, all diversity metrics, including alpha and beta, are articulated in a descriptive manner, while visualizations serve to highlight patterns within community composition. The raw sequencing data were deposited in the National Center for Biotechnology Information (NCBI) sequence read archive (SRA).

RESULTS AND DISCUSSION

Sequencing depth and relative abundance across locations

In total, 89,862 high-quality bacterial sequence reads (ASVs) were obtained from the *rhizosphere* of *H. celebica* across the four sampled locations (H1–H4). It is imperative to point out that the sequence read counts indicated here reflect relative sequence abundance and the technical depth of sequencing, rather than the true size of microbial population. The abundance of sequences varied notably by site (Table 2 and Fig. 2). The highest number of sequence reads was obtained from location H1 (Karaenta, seedling *rhizosphere*) with 24,657 sequences, representing 27.43% of the total reads. In contrast, location H2 (Pattunuang, seedling) had the lowest abundance at 19,655 sequences (21.87% of total). Locations H3 (Bantimurung, mature tree) and H4 (Leang-Leang, mature tree) yielded 24,002 and 21,548 sequences, respectively. It is essential to understand that the differences in total sequence reads are indicative of variations in technical sequencing depth and potential PCR amplification biases, rather than reflecting the absolute abundance of bacteria or microbial biomass present in the soil. Therefore, subsequent analyses focus strictly on the relative compositional abundance of specific taxonomic groups. This indicates that H1 and H3 (which included one seedling and one mature tree site) had relatively higher sequencing depth than H2 and H4. Furthermore, while the total sequence reads may vary due to differences in technical sequencing depth among samples, the following analyses emphasize the relative abundance of particular taxonomic groups within these libraries to elucidate community composition. According to Song *et al*. (2025), the sampling location and lithology can significantly impact microbial population sizes in the *rhizosphere*. H1 (the richest sample) might have more favorable microhabitat conditions or root exudate profiles that support a larger microbial load. In contrast, H2's lower count could be due to less hospitable soil conditions or lower root activity. Yang *et al.* (2023) similarly noted that karst forest soils have heterogeneous patches; certain microsites can impose limitations on microbial proliferation due to differences in soil chemistry and parent rock. For instance, fluctuations in soil pH, moisture levels, and nutrient availability influenced by the presence of limestone or dolomite can determine the dimensions of microbial communities.

Table 2: Total sequence reads and relative sequence abundance of *rhizosphere* bacteria from *H. celebica* at four Maros karst locations

Location	Total	Percentages (%)
H1	24.657	27,43
H2	19.655	21,87
H3	24.002	26,70
H4	21.548	23,97
Total	89.862	100

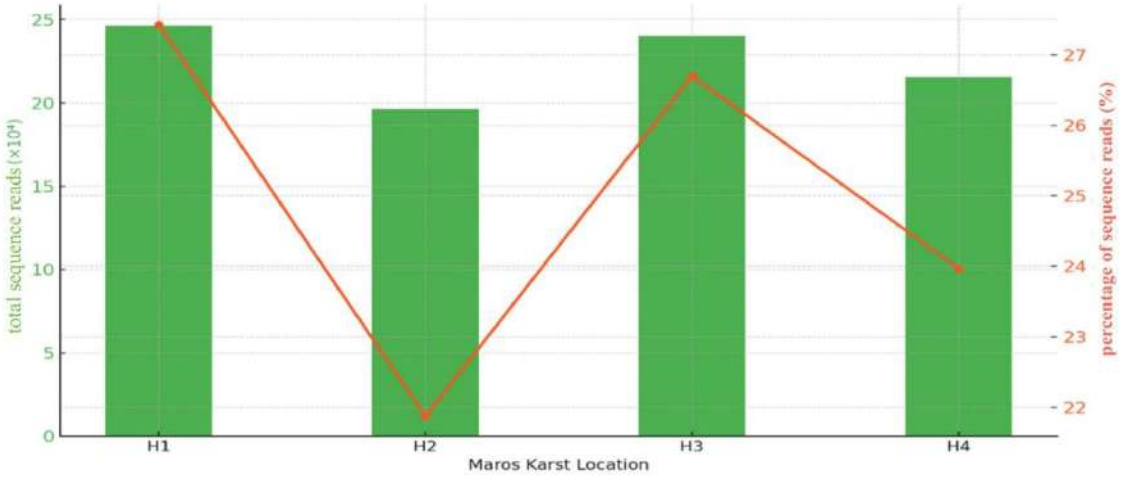
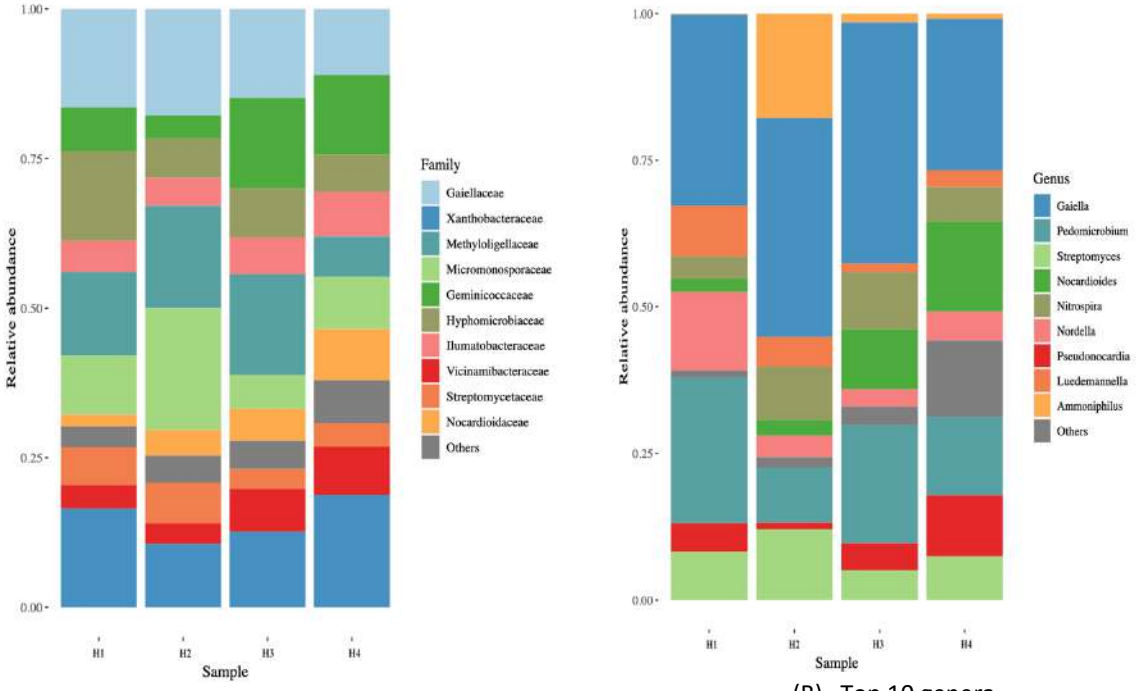


Fig. 2 : Total squence reads and relative sequence abundance of rhizosphare bacteria From *H. celebica* at Four maros karst location (H1: Karaenta seedling; H2: Pattunuang seedling; H3: Bantimurung mature tree; H4: Leang-Leang mature tree)

Lithology thus plays a crucial role in determining soil properties that ultimately influence the abundance of soil microbes. Even though this baseline study did not involve direct measurement of specific environmental and soil parameters, the findings are derived from well-established lithological traits and edaphic conditions found in typical karst ecosystems (Li *et al*., 2021; Ran *et al*., 2023), with the assumption that comparable baseline characteristics pertain to the Maros karst region.

Taxonomic composition of the rhizosphere microbiome

Rich taxonomic diversity was observed across all samples, with 12 bacterial phyla identified, comprising 103 orders, 155 families, 204 genera, and 720 species-level taxa. The prominent groups were examined for a clearer comprehension. (Fig. 3A) shows the top 10 families by relative abundance in the combined dataset. The most abundant family was *Gaiellaceae*, comprising about 16% of all sequences. Members of *Gaiellaceae* were detected in all four locations, with the highest representation in H1. The *Gaiellaceae*, specifically the genus *Gaiella*, consists of oligotrophic organisms that are capable of thriving in nutrient-scarce conditions, which likely contributes to their dominance in the karst *rhizosphere*. Indeed, *Gaiella* was identified as the most common genus overall, representing 36% of all sequences (Fig. 3B). The dominance of *Gaiella* and related *Gaiellaceae* in both family- and genus-level analyses suggests they are well adapted to the *rhizosphere* environment of *H. celebica*, perhaps by efficiently utilizing sparse resources or root exudates. In spite of the environmental differences observed among the sampled locations, the data suggest the existence of a potential core microbiome for *H. celebica*. Several key bacterial taxa, notably the family *Gaiellaceae* and genus *Gaiella*, were consistently detected



(A) Top 10 families (B) Top 10 genera.

Fig. 3: Relative abundance of major bacterial taxa across the four *rhizosphere* samples: (A) Top 10 families, (B) Top 10 genera. Each bar represents the percentage of sequences attributed to that taxon in each location (H1: Karaenta seedling; H2: Pattunuang seedling; H3: Bantimurung mature tree; H4: Leang-Leang mature tree). *Gaiella*ceae and the genus *Gaiella* are consistently dominant in all samples

across all locations. The persistence of these core microbes suggests they may provide essential, non-redundant functions for the host, such as foundational nutrient acquisition or basal stress tolerance in these challenging habitats. Recognizing this fundamental microbiome holds considerable practical significance for conservation initiatives. These consistent, host-adapted bacteria could be isolated and developed into specific bioinoculants. Applying such bioinoculants to *H. celebica* seedlings in nurseries could enhance their resilience and survival rates before outplanting, thereby improving the success of reforestation and conservation programs in degraded landscapes. Other prominent families included Geminicoccaceae, Micromonosporaceae, Streptomycetaceae, and Xiphinematobacteraceae, each forming notable clusters in the phylogenetic analysis (discussed below). Nocardioidaceae was identified as the least abundant family among the top families, with a representation of about 5.2%. The members of Nocardioidaceae might be less competitive in the H. celebica *rhizosphere*, possibly due to their dependence on soil nitrogen and carbon sources that are restricted. Intense competition for scarce nutrients could be suppressing the abundance of Nocardioidaceae (Zhang *et al.,* 2022; Chen *et al.,* 2022). At the genus level, the second-most common genus after *Gaiella* was Pedomicrobium (~19% of sequences). Pedomicrobium spp. are aerobic, frequently phototrophic, typically located in nutrient-dense aquatic habitats. Their presence in smaller proportions in the *H. celebica rhizosphere* might indicate micro-niches where nutrients (perhaps root exudates) accumulate, allowing these bacteria to survive despite generally oligotrophic

soil conditions (Lauber *et al.,* 2008). In summary, bacterial community structure across the different sites was largely characterized by a small group of oligotrophic taxa, including *Gaiellaceae*/*Gaiella*, that prosper in the low-nutrient conditions of the karst soil, along with a long tail of less common taxa. Because our sampling was exclusive to *H. celebica*, it remains to be experimentally determined if these dominant bacteria are strictly host-specific. While many detected soil bacteria are cosmopolitan, the extreme edaphic conditions of karst ecosystems—characterized by high alkalinity, severe drought, and nutrient scarcity—uniquely enrich specific extremophilic and stress-tolerant taxa. Due to their extensive presence in oligotrophic environments and significant dominance in these areas, taxa like *Gaiellaceae* are highly likely to signify a signature karst-adapted microbiome. This is further supported by the detection of extremophilic genera like *Ammoniphilus*, which illustrate a unique microbial assemblage tailored to this fragile landscape. *H. celebica* likely recruits and selectively enriches these stress-tolerant microbes in its *rhizosphere* to buffer against the harsh edaphic conditions, rather than forming exclusive symbiotic associations. These results emphasize the way in which the difficult karst soil conditions preferentially support specific microbial groups that are adapted to stress, whereas other groups continue to exist in reduced quantities.

Alpha diversity and richness

Alpha diversity was evaluated to understand within-sample (within-location) microbial diversity (Table 3). Location H4 (Leang-Leang, mature trees) showed the highest richness, with Observed ASVs = 1023, slightly more unique taxa than the other sites (H1 had 977, H2 had 898, H3 had 970 observed taxa). The Shannon diversity index, which accounts for both abundance and evenness of species, was also at its peak in H4 (Shannon ≈ 6.22). This suggests that the community in H4 is not only diverse in species but also relatively balanced, with no single taxon excessively dominating. In comparison, H1, H2, and H3 had Shannon indices around 5.9, suggesting. slightly lower diversity than H4. The Simpson index (1 – D, where D is dominance) was very high (>0.99) for all samples, reflecting that each community has a broad distribution of taxa with no extreme single-taxon dominance. H4's Simpson index (≈0.996) was marginally higher than others, consistent with its greater evenness. The inverse Simpson index (which can be thought of as the "effective number of species") was markedly highest for H4 (InvSimpson ≈ 254), whereas H1 and H2 had values around 137–140, and H3 around 107. The data indicates that the sample collected from Location H4 contains the most significant bacterial diversity compared to the other sampled sites, yet this cannot be statistically substantiated in the absence of replicates. The rarefaction analysis (Fig. 4) supports these diversity results: the rarefaction curve for H4 rises the highest, indicating more OTUs/ASVs were detected at H4 for a given sequencing depth compared to the other locations. The H4 curve had not been fully stabilized, yet its incline was getting close to the asymptote, implying that a significant portion of the diversity had been recorded by the sequencing depth. H1, H2, and H3 rarefaction curves leveled off slightly lower, aligning with their slightly lower observed richness. The greater diversity at H4 could be attributed to ecological differences at that site. H4 is a conservation plot with numerous large and mature *H. celebica* trees in a well-established stand. These fully grown trees have intricate root systems and gather larger quantities of organic matter throughout their extended growth, in addition to sophisticated soil weathering that liberates minerals and forms microhabitats rich in resources. This idea is supported by Van Elsas *et al.* (2019), who noted that soil weathering enhances nutrient availability, thereby supporting more diverse microbial communities. It is conceivable that the soil in H4 exhibits marginally superior moisture retention or nutrient quality (for instance, areas

Table 3: Alpha diversity indices for *H. celebica rhizosphere* bacteria at each location. (Observed = number of ASVs observed; Shannon = Shannon diversity index; Simpson = Simpson's diversity index (1 – dominance); InvSimpson = Inverse Simpson index)

Location	Observed	Shannon	Simpson	InvSimpson
H1	977	5.98	0.9928	139.55
H2	898	5.87	0.9927	136.55
H3	970	5.88	0.9906	106.69
H4	1023	6.22	0.9961	254.38

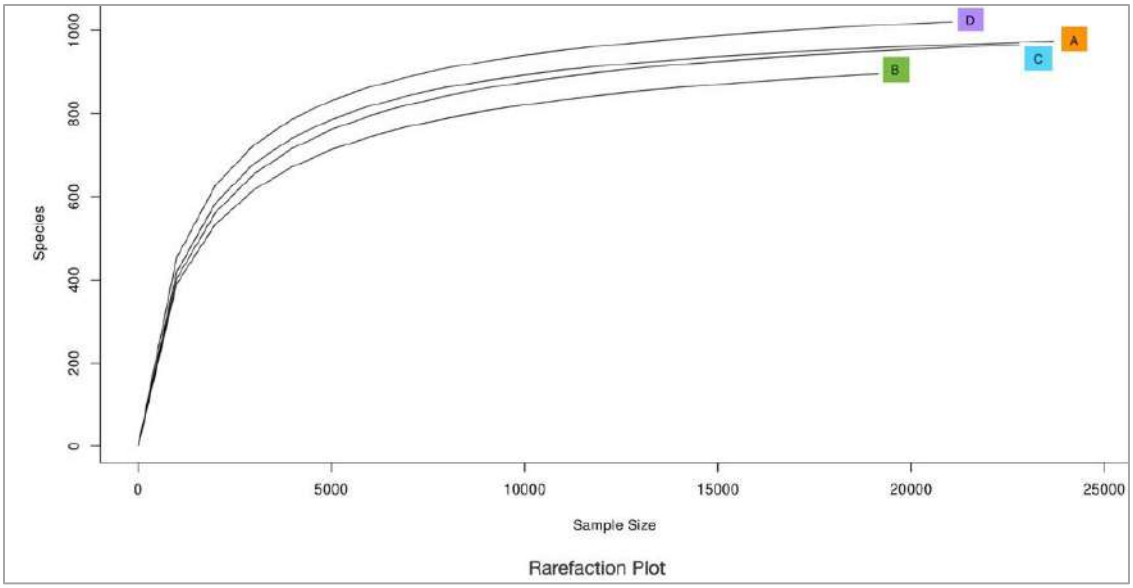


Fig. 4: Rarefaction curves for each location's 16S libraries, and diversity indices. H4 (green line) reaches the highest plateau, indicating greater richness. The curves suggest sufficient sequencing depth, as they begin to approach saturation.

with elevated phosphorus or organic carbon from litter) compared to the other locations, thereby facilitating the coexistence of a greater number of taxa. While the study provides a valuable baseline, the *H. celebica rhizosphere* microbiome likely fluctuates seasonally and across plant developmental stages. For instance, fast-growing bacteria may dominate during wet seasons or during early development to acquire nutrients rapidly, whereas stress-tolerant taxa (such as Actinomycota) likely prevail in mature stands or during dry periods to mitigate drought. These time-related alterations are vital for alleviating environmental stress and supporting nutrient cycling. Therefore, future longitudinal studies examining these dynamics are essential to inform comprehensive conservation strategies.

Community structure and beta diversity

To qualitatively describe and compare community profiles among various locations, the relative abundance of bacteria was examined at broader taxonomic levels. At the phylum level, all four locations shared the same dominant phyla, but with differing proportions. Proteobacteria were the most abundant phylum in every sample, followed by Actinobacteriota, Verrucomicrobiota, Acidobacteriota, Gemmatimonadota, Firmicutes, and Nitrospirota (in various orders of abundance). However, the proportional dominance of certain groups varied by site. For instance, the family Geminicoccaceae (within Proteobacteria) showed a notable jump in relative abundance from H2 to H3, indicating a shift in community composition between those sites. Similarly, the

Methyloligellaceae (another Proteobacteria family) had lower relative abundance at H4 than at H1–H3. Conversely, Nocardioidaceae, belonging to Actinobacteriota, was found to be most prevalent at H4, while its abundance was considerably lower at H1 and H2. It was also observed that Ammoniphilus (a genus in the family Paenibacillaceae, phylum Firmicutes) became significantly more abundant at H2 than elsewhere, and Pseudonocardia (family Pseudonocardiaceae, Actinobacteria) was less abundant in H2 compared to H1 and H3. Collectively, H4 exhibited demonstrated the greatest overall diversity along with a more balanced distribution of taxa, in contrast to H2's whose community was affected by a few taxa that were either on the rise or decline. These descriptive differences suggest a potential influence of environmental factors on shaping the *rhizosphere* microbiome, although without biological replication, we acknowledge these variations might also be driven by fine-scale spatial patchiness or sampling variation. Specifically, the severe edaphic stress of the karst environment—characterized by shallow topsoil, high alkalinity, and nutrient scarcity—acts as a strict environmental filter. It influences the composition and abundance of microbes by significantly enhancing stress-tolerant oligotrophs (for instance, *Gaiellaceae*) while inhibiting nutrient-demanding taxa; it induces spatial variations in diversity depending on the capacity of localized micro-niches to mitigate these stresses; and it selects for potential ecological functions strictly centered on vital nutrient scavenging, such as phosphate solubilization and nitrogen cycling, which are indispensable for host survival in this oligotrophic landscape. Even though all sites are within the same general karst forest, micro-environmental variations (such as soil depth, moisture microclimate, presence of other vegetation, or human disturbance) can alter the competitive balance among microbial taxa. The differences in family/genus dominance patterns among H1–H4 highlight that each location's community is unique, molded by its specific conditions. This aligns with findings by Lu *et al.* (2014) and Alam *et al.* (2021) that spatial heterogeneity in forests (like variation in soil chemistry, pH, and organic matter) leads to site-specific microbial communities. Forest soils frequently display uneven nutrient distribution and microsites, with each *H. celebica* tree potentially affecting its surrounding soil environment in distinct ways (for instance, through variations in root exudate quantity and quality), consequently promoting different microbial communities at each site.

Phylogenetic clustering of dominant taxa

To further interpret the community structure, a phylogenetic tree of dominant ASVs was constructed, and how they clustered based on taxonomy was analyzed (Fig. 5). The phylogenetic analysis revealed eight major clusters corresponding largely to high-level taxonomic groups:

a. Cluster 1: Phylum Actinobacteriota, containing six families – *Gaiellaceae*, Micromonosporaceae, Streptomycetaceae, Nocardioidaceae, Ilumatobacteraceae, and Rubrobacteriaceae. These families of actinobacteria are recognized for their contributions to the breakdown of soil organic matter in soil and typically generate spores to withstand severe environments, which might clarify their existence in karst soils.
b. Cluster 2: Phylum Verrucomicrobiota, represented primarily by the family Xiphinematobacteraceae. *Candidatus Xiphinematobacter*, found in this cluster, is notable as an endosymbiont of certain plant-parasitic nematodes (genus Xiphinema). Its detection in the *rhizosphere* suggests these bacteria (possibly living inside nematodes or free-living relatives) are part of the soil food web around *H. celebica* roots.
c. Cluster 3: Phylum Proteobacteria, represented by family Geminicoccaceae. This cluster emphasizes a specific segment of the

Proteobacteria present, associated with the Geminicoccaceae, which are often oligotrophic bacteria discovered in diverse soil types.

d. Cluster 4: Phylum Gemmatimonadota, including the family Gemmatimonadaceae. Members of this relatively less-understood phylum are common in soils and are thought to be involved in nitrogen and phosphorus cycling.
e. Cluster 5: Phylum Acidobacteriota, including Vicinamibacteraceae. Two distinct lineages within Vicinamibacteraceae were identified, suggesting the presence of various Acidobacteria taxa thriving in the *rhizosphere*. Acidobacteria are typically acidophilic and abundant in many soils, playing roles in degrading complex substrates. Phyla such as Acidobacteriota and Actinobacteriota are also known to degrade recalcitrant organic matter and solubilize minerals, such as phosphate. The activities they engage in release nutrients that are stored in soil organic matter and the parent rock, thus effectively providing sustenance to the host plant (Lu *et al.,* 2020).
f. Cluster 6 represents the phylum Proteobacteria (second cluster) and consists of six families, namely KF-JG30-B3 (which is an uncultured lineage often found in soils), Methyloligellaceae, Rhizobiales incertae sedis (which represents an as yet unclassified Rhizobiales group), Hyphomicrobiaceae, Xanthobacteraceae, and Dongiaceae are further represented in this cluster. This cluster therefore very clearly highlights the broad diversity within Proteobacteria. For instance, both the families Xanthobacteraceae and Hyphomicrobiaceae are well known Alphaproteobacteria and are also recognized for their roles in nitrogen fixation as well as plant association, which may consequently indicate the presence of potential plant-growth-promoting bacteria in the H. celebica rhizosphere.
g. Cluster 7: Phylum Firmicutes, represented by the family Paenibacillaceae. Within this cluster, sequences of Ammoniphilus, a genus of Paenibacillaceae, were identified. Ammoniphilus species are noteworthy for tolerating extreme conditions (pH, temperature, salinity) (Lu *et al.,* 2014). The presence of these organisms suggests that certain microbes in the *rhizosphere* are capable of withstanding the challenges posed by the karst environment (for instance, variations in moisture levels or nutrient surges).
h. Cluster 8: Phylum Nitrospirota, represented by the family Nitrospiraceae. Nitrospiraceae includes nitrite-oxidizing bacteria (such as Nitrospira), playing a role in the nitrification process. Their presence indicates that active nitrogen cycling, particularly nitrification, occurs in the *rhizosphere*, which may play a crucial role in making nitrogen accessible to plants.

Candidatus Xiphinematobacter is typically an endosymbiotic bacterium of Xiphinema nematodes. Its detection could indicate interactions between soil nematodes and the bacterial community in the *H. celebica rhizosphere*, revealing an additional layer of complexity (a plant-root–nematode–bacterium interaction network). Meanwhile, Ammoniphilus (Paenibacillaceae) is recognized for its ability to withstand extreme environmental conditions, including a wide pH range, temperature extremes, high salinity, drought, and low humidity (Abbey *et al.,* 2025; Ran et al., 2023). The presence of Ammoniphilus suggests the existence of sporadic niches in the soil where these hardy bacteria can persist, possibly in microsites with fluctuating conditions inhospitable to more sensitive microbes. Collectively, the microbiome's taxonomic profile suggests three vital ecological functions enabling *H. celebica* to survive in nutrient-poor karst soils. First, it aids nutrient acquisition: Rhizobiales and nitrospiraceae drive nitrogen cycling, while Actinobacteriota solubilize rock phosphates (Singh *et al.,* 2024). Second, it improves stress resilience: extremophiles like

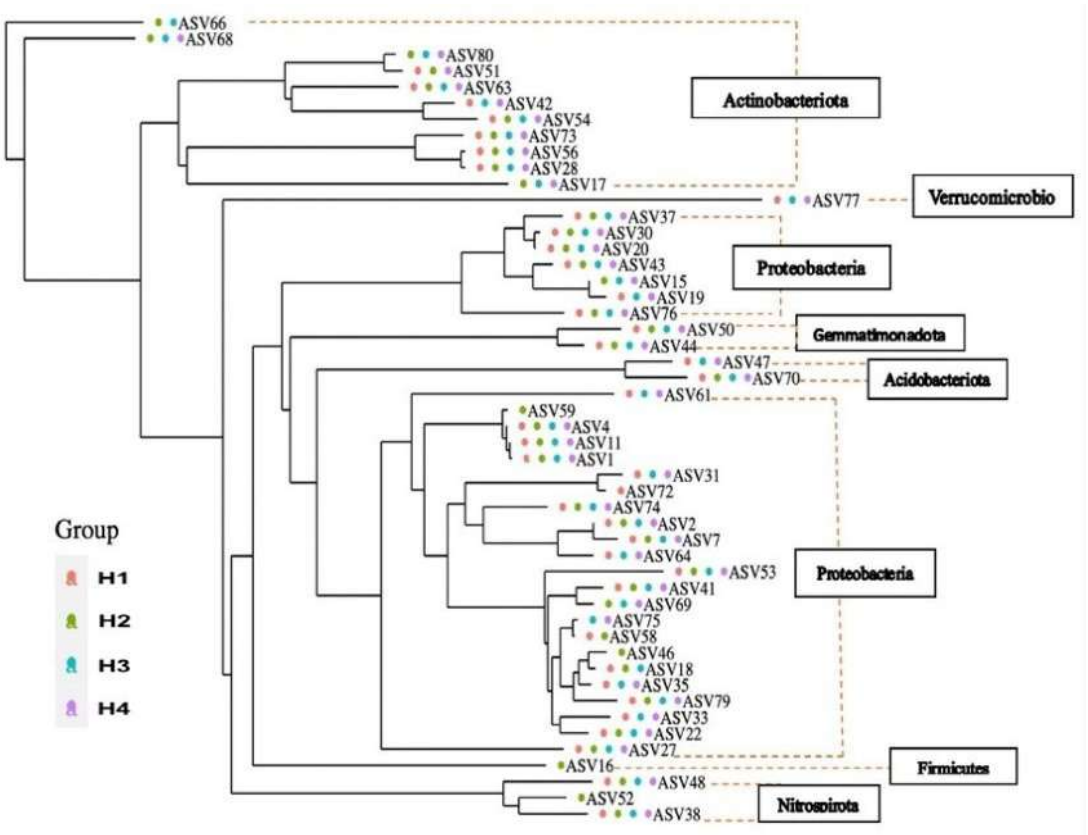


Fig. 5: Phylogenetic tree of dominant 16S rRNA gene sequences (ASVs) from the *H. celebica rhizosphere*, clustered by taxonomic affiliation. Major clusters corresponding to phyla and notable families are labeled 1 through 8. The tree provides an overview of the community's taxonomic breadth, with branch colors indicating different phyla and the legend denoting sample origins (H1: Karaenta; H2: Pattunuang; H3: Bantimurung; H4: Leang-Leang). Proteobacteria lineages form two separate clusters (Clusters 3 and 6), reflecting their high diversity

Ammoniphilus and spore-forming Actinobacteria buffer against extreme alkalinity and drought (Simarmata *et al.,* 2023). Finally, it contributes support for growth: these bacteria likely act as Mycorrhizal Helper Bacteria, collaborating with fungal networks to enhance the availability of scarce nutrients and combat pathogens (Skinner *et al.,* 1959). Overall, the karst forest rhizosphere microbiome uncovered in this study is both diverse and complex. The results demonstrate that even within a relatively small geographic area, each *H. celebica* rhizosphere harbors a unique community shaped by micro-environmental differences. Prior studies highlight that the variety of tree species and their diversity can significantly influence soil microbial communities (Girvan *et al.,* 2003; Tedersoo and Lindahl, 2016). Trees influence microbes via root exudates (unique chemical compounds released by roots) and through the quantity/quality of leaf litter entering the soil. Selective pressure is expected to be imposed on the rhizosphere microbiome of *H. celebica*; nonetheless, the impact is adjusted by disparities in tree size, health status, and site conditions, resulting in variability among the H1–H4 communities (Zhang *et al.,* 2019). While 16S rRNA amplicon sequencing provides robust taxonomic profiling, it does not supply experimental proof of metabolic activity. Consequently, any functional roles outlined in this document—like as nitrogen fixation, nutrient solubilization, plant growth promotion, and their contribution to ecosystem resilience—are solely speculative deductions based on the recognized

functions of related taxa in other environments (Shamim *et al.,* 2019). It is hypothesized that leading groups such as Actinobacteria (for instance, *Gaiella*) and Proteobacteria (specifically Rhizobiales) may establish cooperative networks to facilitate nutrient mobilization and mitigate environmental stresses in this delicate karst ecosystem. However, it must be explicitly acknowledged that these plant-microbe synergies remain speculative. As noted in the limitations, robust experimental validation through shotgun metagenomics, metatranscriptomics, and in vivo plant trials is required to confirm these specific microbially-mediated functions in the *H. celebica* rhizosphere (Vestergaard *et al.,* 2017). This study, while concentrating exclusively on bacteria, highlights that the *H. celebica* rhizosphere is a complex, multi-domain ecosystem. Karst soils are typically alkaline, shallow, and highly limited in bioavailable nutrients, particularly phosphorus. Compared to typical Dipterocarpaceae species that dominate acidic, highly weathered lowland tropical soils (Essene *et al.,* 2017), the bacterial microbiome of *H. celebica* appears distinctively shaped by its calcareous habitat. Alternatively, instead of the standard lowland forest soil assemblages, the *H. celebica* rhizosphere preferentially promotes extremophilic and oligotrophic taxa, such as *Gaiella*, which are capable of thriving in conditions of high alkalinity and extreme nutrient limitation (Simarmata *et al.,* 2023). In such challenging environments, mycorrhizal fungi are critical for Dipterocarpaceae, playing a vital role by extending the root absorptive network to scavenge resources (Zang *et al.,* 2020). The dominant rhizosphere bacteria identified herein (e.g., Proteobacteria and Actinobacteria) likely form synergistic relationships with these fungal hyphae as Mycorrhizal Helper Bacteria (MHB) (Singh *et al.,* 2024). For instance, phosphate-solubilizing bacteria can mobilize bound minerals found in the calcareous karst soil, which are subsequently transported to the plant via the fungal network (Simarmata *et al.,* 2023). Furthermore, certain rhizosphere bacteria can suppress pathogens by producing antimicrobial compounds or by outcompeting soil-borne pathogens, thereby protecting both the fungal partner and plant roots (Skinner *et al.,* 1959). These synergistic bacterial-fungal interactions are likely critical for maintaining nutrient availability and enhancing *H. celebica*'s resilience to environmental stress in karst landscapes. Additionally, it is probable that untargeted soil archaea enhance bacterial nitrification by oxidizing ammonia. Elucidating these cross-domain interactions represents a vital next step toward a holistic understanding of *H. celebica*'s ecological resilience.

Implications for conservation

A key finding of this study is that the *rhizosphere* of mature trees at the Leang-Leang site (H4) harbors the highest bacterial diversity. This is consistent with ecological theory, which posits that more mature ecosystems foster intricate microbial communities (Peng *et al.,* 2019). This stability fosters greater functional redundancy, equipping the microbial community to maintain essential ecosystem functions—such as nutrient cycling—despite environmental fluctuations (Kong *et al.,* 2023; Corinaldesi *et al.,* 2023). Conversely, the differences in community noted among the four sites emphasize the patchy nature of karst landscapes, where slight differences in soil pH, water retention, and mineral availability create distinct niches (Yuan *et al.,* 2022). Consequently, conservation strategies cannot rely on a one-size-fits-all approach; instead, they must adopt a holobiont perspective that integrates the endangered tree and its microbial partners as a single functional unit. In this context, the *rhizosphere* microbiome can function as an exceptionally sensitive diagnostic instrument and an early warning mechanism, reacting to environmental stressors prior to visible canopy decline in the host plant (Diaz *et al.,* 2025; Hawkins *et al.,* 2018; Peddle *et al.,* 2025). The healthy,

mature H4 site provides a biological benchmark for this monitoring. Specifically, the consistently abundant oligotrophic genus *Gaiella* serves as a crucial bioindicator; its dominance indicates a stable adaptation to karst environments, while its decline may signify systemic habitat degradation. Furthermore, observing the ratio of Proteobacteria to Actinomycota serves as a dependable indicator for assessing changes in soil nutrient cycling, which is critical in these oligotrophic karst ecosystems. While this taxonomic baseline highlights the potential of native microbes for active ecological restoration, it is explicitly acknowledged that no microbial isolates were obtained and no field restoration experiments were conducted in this study. Consequently, strategies such as developing host-adapted microbial inoculants (Das *et al.,* 2022; Peddle *et al.,* 2025; Alzate *et al.,* 2024) or implementing whole-soil translocations (Corinaldesi *et al.,* 2023) represent conceptual recommendations for future conservation, rather than proven methodologies. To close the divide between existing taxonomic conclusions and their practical applications in the field, future studies should emphasize thorough experimental validation. This strictly requires isolating key taxa via advanced culturomics, confirming functional genes through shotgun metagenomics, and conducting *in vivo* field trials to test the efficacy of these microbiome-informed interventions in degraded karst landscapes (Diaz *et al.,* 2025; Hawkins *et al.,* 2018; Kong *et al.,* 2023; Enea *et al.,* 2024).

Limitations and future direction

While this exploratory study provides critical first-step baseline data on the rhizosphere bacterial community of the endangered *H. celebica* in karst ecosystems, several methodological and ecological limitations must be acknowledged regarding statistical robustness and species representativeness. First, the present study is based on a limited sample size that includes four rhizosphere samples from various locations. The lack of extensive biological replication limits the statistical robustness required to draw definitive conclusions regarding beta diversity and the specific drivers of community differences among sites. Future microbial assessments need to integrate a larger quantity of individual plant replicates for each site and assess localized environmental parameters (for instance, soil pH, moisture, and organic matter) to establish statistically robust correlations between edaphic factors and microbial community structure (Hadija *et al.,* 2018). Second, the use of 16S rRNA amplicon sequencing is fundamentally limited to taxonomic profiling and cannot definitively confirm the metabolic or functional capabilities of the identified microbiota. Consequently, the ecological roles of the leading taxa—like asas nitrogen fixation, phosphate solubilization, and the ability to withstand stress in nutrient-scarce karst soils—remain hypothetical inferences (Kumar *et al.,* 2013; Kumar *et al.,* 2014). This cross-sectional study captures a single temporal snapshot and does not account for the temporal dynamics of the rhizosphere microbiome, such as seasonal shifts or variations across the complete developmental continuum of *H. celebica*. Additionally, since the sampling approach specifically aimed at soil physically adhering to the roots to obtain the intimately associated microbiome, the fine-scale spatial heterogeneity—like variations within individual root systems (intra-tree) and the microbial gradient between the immediate rhizosphere and the surrounding bulk soil (farther away)—remains uncharacterized. Furthermore, the lack of comparative rhizosphere sampling from co-existing plant species within the same karst habitat hinders a conclusive evaluation of whether the identified microbes establish host-specific or generalist associations with *H. celebica* (Hector *et al.,* 2007). The exclusive focus on bacteria also leaves a critical knowledge gap regarding the complementary roles of archaea and fungi—

particularly mycorrhizal fungi, which are known to be integral to nutrient acquisition in dipterocarps. To build upon this foundational blueprint, future research must transition from descriptive taxonomy to functional validation. The application of shotgun metagenomics and metatranscriptomics is strongly advised for the identification of active functional genes in the karst soil ecosystem (Li *et al.,* 2013). Crucially, progressing toward experimental validation through culturomics and in vivo plant growth promotion (PGP) assays in order to create and evaluate effective native microbial inoculants for nursery seedlings and extensive reforestation efforts (Kumar *et al.,* 2014). Finally, longitudinal studies assessing the impacts of anthropogenic disturbances—such as logging, quarrying, and agricultural encroachment—on these fragile microbial networks will be essential for shaping robust conservation policies. In the Maros karst ecosystem, such human activities physically destroy the shallow topsoil and severely alter its physicochemical balance (Husein *et al.,* 2005). The processes of logging and quarrying eliminate the host trees and their specific root exudates, thereby directly starving the highly adapted, oligotrophic taxa (such as *Gaiella*) and dismantling the core microbiome. Simultaneously, agricultural encroachment introduces agrochemicals and non-native vegetation, potentially shifting the microbial community toward competitive, ruderal, or pathogenic species that outcompete the indigenous symbiotic microbes. The enduring effects of these disruptions are significant; the permanent loss of these particular bacterial-fungal partnerships greatly diminishes the bioavailability of soil nutrients and the suppression of pathogens. Ultimately, this microbial degradation prevents the natural regeneration of *H. celebica* seedlings, accelerating the decline of this endangered species and leading to permanent ecosystem collapse in these vulnerable karst landscapes.

CONCLUSION

This study provides a first look at the *rhizosphere* bacterial community of the endangered *H. celebica* in Indonesia's Maros karst forest. A total of 89,862 bacterial sequences were identified across four distinct H. celebica sites using 16S rRNA metagenomic sequencing, spanning 12 phyla, 103 orders, 155 families, 204 genera, and 720 species. The *rhizosphere* microbiome is primarily composed of oligotrophic and ecologically adaptable groups, with Proteobacteria representing the most diverse and abundant phylum. Significantly, the *Gaiellaceae* family (genus *Gaiella*) was notably abundant, indicating adaptations to environments with low nutrient availability. Descriptively, alpha diversity was highest in the single composite sample from the *rhizosphere* of mature *H. celebica* trees at the leang-leang site (H4), which leads to the hypothesis that long-established tree stands might support richer microbial communities, possibly via improved soil microhabitats and nutrient accrual over time. The phylogenetic analysis identified unique clusters of bacteria that align with significant functional and taxonomic categories, suggesting a well-organized community in which particular clades (such as nitrogen-fixing *Rhizobiales*, Actinobacteria decomposers, Nitrospiraceae nitrifiers) likely play complementary roles in the soil ecosystem. The detection of unique bacteria, such as *Candidatus* Xiphinematobacter and Ammoniphilus, hints at specialized interactions (with soil fauna and under extreme conditions, respectively) in the *rhizosphere*. In summary, this exploratory metagenomic analysis indicates that *H. celebica* assembles a functionally specialized microbial consortium to thrive in its demanding environment. The significant prevalence of taxa associated with phosphate solubilization (such as *Gaiella*), nitrogen fixation (*Rhizobiales*), and stress tolerance (*Ammoniphilus*) offers initial functional insights into how this endangered dipterocarp may address the critical nutrient and moisture

constraints characteristic of delicate karst soils. Future research will examine microbial functional potential by identifying genes involved in nutrient cycling, plant growth promotion, and stress tolerance to clarify their roles in plant health and soil fertility. These insights can support conservation strategies by using dominant native taxa such as Gaiella as early-warning bioindicators and by developing host-adapted microbial inoculants to improve seedling survival during reforestation in degraded karst landscapes.

AUTHOR CONTRIBUTIONS

S.H. Larekeng, the corresponding author, contributed to conception and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, obtaining funding, and supervision. H. Sukri contributed to the acquisition of data, laboratory analysis, and drafting of the manuscript. M. Christita, contributed to data analysis, interpretation of results, and critical revision. R. Simarmata, contributed to acquisition of data, data curation, and technical support. Gusmiaty, contributed to field data collection and laboratory assistance. M. Nursaputra contributed to the acquisition of data and administrative support. Y. Khairina contributed to the acquisition of data and manuscript editing. R. Prayudyaningsih, contributed to conception and design, analysis and interpretation of data, critical revision of the manuscript, and supervision. A.H. Salman participated in drafting the manuscript, technical, or material support, and created a map. I. Rahim, contributed to supervision, obtaining funding, and critical 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 authors have fully addressed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS

%	Percent
°C	Degrees celcius
ANOVA	Analysis of variance
ASV	Amplicon sequence variant
BLAST	Basic local alignment search tool
bp	Base pair
BRIN	Badan Riset dan Inovasi Nasional
CC	Creative Commons
DNA	Deoxyribonucleic acid
DNBSEQ	DNA nanoball sequencing
H1	Karaenta, seedling *rhizosphere*
H2	Pattunuang, seedling
H3	Bantimurung, mature tree
H4	Leang-Leang, mature tree
InvSimpson	Inverse Simpson Index
ISSR	Inter simple sequence repeat
ITS	Internal transcribed spacer
IUCN	International union for conservation of nature
g	Gram
M	Meters
masl	Meter above sea level
MGI	Mega Gloryoung International
NCBI	National Center for Biotechnology Information
NGS	Next generation sequencing
OTU	Operational taxonomic unit
PCR	Polymerase chain reaction
PGP	Plant growth promoting
PGPR	Plant growth-promoting rhizobacteria
pH	Potential of Hydrogen
PICRUSt2	Phylogenetic Investigation of Communities by Reconstruction of Unobserved States versi 2
QIIME2	Quantitative insights into microbial ecology version 2
rRNA	Ribosomal ribonucleic acid
SILVA	Systematic Interactive Labeled Viewer of Alignments
SPAD	Soil plant analysis development
SRA	Sequence read archive
SYBR	Synchro blue-red
USDA	United States Department of Agriculture
V3–V4	Variable regions 3 and 4

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CASE STUDY

Carbon footprint and environmental management behaviors among students achieving sustainability in higher education

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ABSTRACT

BACKGROUND AND OBJECTIVES: Thailand's revised plan for carbon neutrality by 2050 and net-zero by 2065 directly aligns with the sustainable development goals, a universal roadmap for global sustainability. Education for Sustainable Development plays a vital role, as it prepares learners with the understanding and competencies to confront climate change and attain quality education. Integrating climate change into university curricula fosters responsible consumption, drives the university's environmental management strategies, in particular the low-carbon strategy, and helps achieve national climate goals. The study objectives were to evaluate the awareness levels of undergraduate students regarding the carbon footprint associated with their daily activities, environmental management practices, and sustainable development goals. In addition, it examined the correlations between awareness levels on the aspects mentioned.

METHODS: The study encompasses an extensive survey analysis involving 400 undergraduate students at Thepsatri Rajabhat University in Thailand, utilizing multiple regression analysis to ascertain the main determinants of sustainability alignment.

FINDINGS: Findings revealed that student awareness across daily carbon footprints, environmental management, and sustainable development goals reached a high level, falling within the 3.51–4.00 mean score range. Strong positive correlations existed between sustainable development goals alignment and both daily carbon footprints ($r = 0.88$) and environmental management ($r = 0.89$, $p < 0.01$). Multiple regression analysis confirmed that all seven variables significantly predicted sustainable development goals alignment ($p < 0.01$). Standardized Beta coefficients (β) indicated that household consumption (X1, $\beta = 0.412$) and waste management (X7, $\beta = 0.358$) were the primary predictors with the strongest relative association. Moreover, energy management, water management, and commuting footprint were analyzed, indicating the greatest comparative influence on student sustainability within the predictive model.

CONCLUSION: This study reveals that awareness of daily carbon footprints, particularly in household consumption and waste management, is a crucial factor in predicting students' adherence to sustainable development goals. Consequently, these priority dimensions should be integrated into university curricula to promote sustainable behavior and directly contribute to Thailand's national carbon neutrality and net-zero emission objectives.

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INTRODCUTION

Thailand has recently accelerated its plan to achieve carbon neutrality by 2050 and net-zero emissions by 2065, which implies Thailand's strong commitment to combat the country's severe vulnerability to climate change impacts (UNDP, 2022). In 2015, the United Nations (UN) adopted sustainable development goals (SDGs), which encompass 17 global objectives. These goals act as a universal framework aimed at eradicating poverty, protecting the environment, and secure prosperity for all by 2030. Globally, they provide a unified framework to tackle interwoven challenges like climate change, inequality, and health, demanding action from all nations. For Thailand, the SDGs are integrated into national plans like the 20-Year National Strategy, guiding development towards a high-income, sustainable, and inclusive society. Their relevance is centered on encouraging a "whole-of-society" strategy to confront complicated matters like inequality and environmental protection, making certain that no one is neglected (UN, 2025). Universities have set a low-carbon strategy in response to the global and national climate targets. Carbon footprint, a total greenhouse gas emission along the life cycle of the product/service, or organization, has been employed to measure the low-carbon strategy in several universities (Li *et al.,* 2021). Education for sustainable development (ESD) empowers learners by imparting the awareness, skills, values, and critical thinking required to confront and devise solutions for global challenges like climate change and inequality (UNESCO, 2025). Thailand's commitment to carbon neutrality by 2050 and net-zero emissions by 2065 directly hinges on the successful implementation of ESD, creating a mutual relationship with several SDGs. ESD is crucial since it ensures quality education by preparing all students with the understanding and competencies essential for a sustainable lifestyle. For universities, this translates to robust environmental management policies—reducing campus energy consumption and waste. By incorporating curriculum elements that emphasize climate change, ESD enhances university students' understanding of the carbon footprint associated with their daily activities. This heightened awareness empowers students, the next generation of professionals and consumers, to practice responsible consumption and production. This shift in behavior is a powerful approach for emissions reduction, supporting the national climate targets. Furthermore, these climate initiatives play a direct role in reducing greenhouse gas emissions and indirectly promote health and well-being by decreasing air pollution. Ultimately, achieving these national goals relies on strong partnerships, with higher education institutions collaborating across government and private sectors to share research, technology, and ESD best practices to ensure a comprehensive transition to a sustainable society (Villegas, 2025). Education is fundamental in nurturing environmental consciousness among the youth, who serve as key players in the pursuit of sustainable development in the future. In Thailand, the network of 38 Rajabhat Universities serves as a strategic mechanism for local development, empowering communities through the integration of local wisdom and modern sciences. These institutions are instrumental in fostering green behavior and environmental stewardship among undergraduate students, encouraging them to participate actively in natural resource conservation. Recent studies underscore that environmental awareness is an essential moderator that profoundly affects green performance and sustainable actions in educational settings (Yanti *et al.,* 2025a; Yanti et al., 2025b; Mansour, 2023). Daily human activities significantly contribute to the carbon footprint, which represents the total amount of greenhouse gases emitted into the atmosphere. Studies show that patterns of household consumption—spanning energy usage for heating and cooling as well as the functioning of electrical devices—significantly contribute to carbon emissions, highlighting the need for immediate policy actions and shifts in behavior towards the consumption of

environmentally friendly products (Jiang *et al.*, 2022; Rama *et al.*, 2024). Furthermore, transportation choices play a critical role; for instance, reliance on private vehicles powered by fossil fuels results in substantially higher emissions compared to public transportation or non-motorized modes like cycling and walking, a disparity that underscores the need for sustainable mobility solutions (Osorio *et al.,* 2024). Dietary habits are also an important consideration, since the production of meat, particularly beef, creates a significantly greater carbon footprint than that of plant-based foods, owing to land use and methane emissions (Cesari *et al.,* 2017). Effective environmental management (EM) is therefore essential to mitigate these impacts and requires a comprehensive approach covering air, water, energy, and waste management. Air Quality Management involves monitoring and controlling pollution sources to protect public health, a necessity underscored by recent studies on urban emission inventories (Hilly *et al.,* 2024). Water Management focuses on the equitable allocation and quality control of water resources for agricultural, industrial, and domestic use (Chen *et al.*, 2023). Energy Management focuses on enhancing consumption efficiency to lower expenses and minimize environmental impacts by utilizing advanced evaluation techniques (Jiang *et al.,* 2022). Finally, Waste management entails systematic processes for reduction, reuse, and recycling to minimize the volume of waste sent to landfills, thereby reducing methane emissions and environmental contamination (Chen *et al.,* 2023). Recent literature on university students' sustainability engagement has predominantly examined carbon footprint awareness and environmental management practices as separate constructs in relation to SDGs. A study by Ramli *et al.* (2024) investigated students' awareness of personal emissions. Ram *et al.* (2023) assessed the relationship between carbon literacy and pro-environmental actions. Furthermore, studies on environmental management have investigated students' awareness of the SDGs and their behaviors regarding campus sustainability. For example, Ando *et al.* (2019) and Hdeib *et al.* (2024) assessed awareness, attitudes, and actions toward SDGs. Cernicova-Buca *et al.* (2023) examined environmental protection awareness in campus life and analyzed sustainability awareness regarding energy management and climate change mitigation in higher education institutions. However, the study that combines students' awareness of both carbon footprint and environmental management, influencing SDGs alignment, has not been found. The deficiency of studies that investigate these two dimensions and their joint influence on students' comprehension and application of SDGs highlights a major shortcoming in the current body of sustainability education literature, calling for an examination of their combined impact on enhancing comprehensive SDG literacy and action among university students. To integrate a higher education curricula component focused on climate change, environmental management, and SDGs, it is essential to understand the relationships between these aspects and to design the appropriate content for ESD in the context of a Thai university. The present study seeks to evaluate the factors that affect the awareness levels of undergraduate students on SDGs. It also assesses awareness levels on the carbon footprint of daily activities and environmental management, and to find the correlations between levels of students' awareness on carbon footprint, environmental management, and SDGs. This study was carried out at Thepsatri Rajabhat University in Lop Buri Province in Thailand, in 2025. The findings from this study are also expected to be adopted in other regional universities with a similar context.

MATERIALS AND METHODS

The conceptual framework for this study was developed to determine the relationship between awareness, as well as attitudes, and behavioral

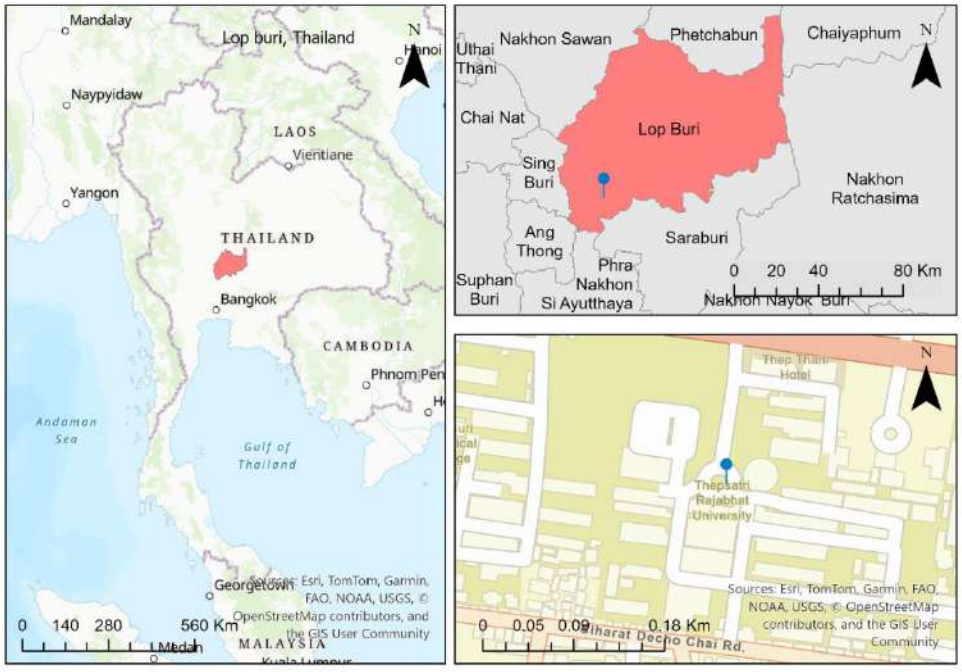

Fig. 1: Geographical location of the study area in Thepsatri Rajabhat University in Lop Buri province, Thailand

intentions, levels of the carbon footprint of daily activities (CfD), environmental management (EM), and SDGs of undergraduate students at Thepsatri Rajabhat University. It is developed based on integrating these two concepts of CfD, and EM (EPA, 2025a; EPA, 2025b; Stefaniec *et al*., 2024; SkootEco, 2025; Ahmadov, 2020; and IBM, 2025) to predict the level of awareness of students on SDG (UNEP, 2022; UN, 2025). The geographical location of the study area in Thepsatri Rajabhat University in Lop Buri province, Thailand (Fig. 1). In addition, the study's conceptual framework is shown in Fig. 2.

Population, Sample, and Sampling Technique

The study population consisted of 5,652 undergraduate students at Thepsatri Rajabhat University, Thailand. Using the Yamane formula (Yamane, 1973) with a 95 percent (%) confidence level (e = 0.05), a minimum sample size of 400 was required. To ensure that the sample is representative and to minimize selection bias, a simple random sampling (SRS) approach was utilized, allowing every student an equal opportunity for inclusion.

Research design and participants

This study adopted a quantitative cross-sectional design to analyze the predictive influence of environmental literacy on SDG alignment. This design is suitable for charting intricate attitudinal and behavioral intentions among a vast and varied student population within a constrained timeframe. Participants were selected based on their status as active undergraduate students at Thepsatri Rajabhat University. The criteria for inclusion mandated that students must enroll in the academic year 2025, whereas the criteria for exclusion aimed to eliminate incomplete or non-purposeful responses (for instance, straight lining).

Research Instrument

The research tool was developed to obtain a comprehensive perspective on student environmental literacy by assessing knowledge

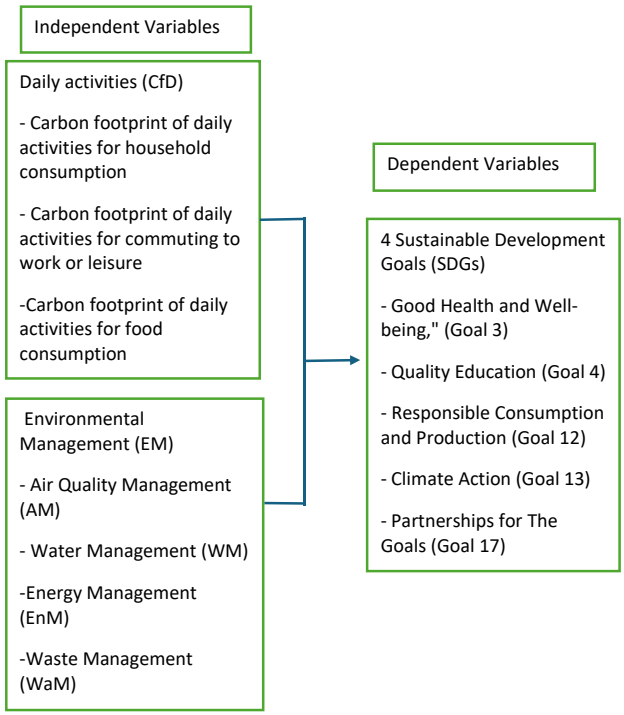

Fig. 2: The study conceptual framework

(for instance, comprehension of carbon metrics), attitudes (such as environmental values), and behavioral intentions (like, self-reported waste management practices). This structured approach ensures that the distinct psychological drivers of sustainability are analyzed independently before evaluating their collective influence on SDG alignment. The evaluation of the content validity of the research instrument was conducted by five experts utilizing the index of item-objective congruence (IOC). Through an iterative refinement process, items were revised based on expert feedback until a final unanimous consensus was reached, resulting in a final IOC score of 1.00 for all included items. This comprehensive pre-validation confirmed that each item precisely reflected the intended constructs of knowledge, attitudes, and behavioral intentions. To ensure psychometric integrity, reliability was quantified using Cronbach's alpha coefficients (Cronbach, 1951; Hair *et al.*, 2010), during a pre-test at a neighboring institution (n=40), the results of which are summarized in Table 1. It is important to note the exceptionally high internal consistency ($\alpha > 0.98$) observed across the study's scales. Additionally, while these values could be analyzed for potential scale redundancy, they are validated by the meticulous iterative improvement of the research tool during the pre-validation period. Furthermore, the high reliability indicates a high degree of conceptual unity among the sampled students, whose environmental awareness is shaped by a standardized institutional curriculum. The validity of the constructs is further supported by the distinct predictive contributions of each variable in the regression model, where household consumption (X1) and waste management (X7) emerged as unique drivers of SDG alignment.

Data collection procedure

Data collection was conducted over four weeks (August–September 2025) using a structured digital questionnaire. The survey was administered via the university's Learning Management System and official student groups to ensure a representative reach across all

Table 1: Reliability and validity of the research instrument

Variables	No of Items	Reliability	Validity	Code
CfD	21	0.938	1.00	CfD
Carbon footprint of daily activities for household consumption (X1)	7	0.867	1.00	CfH
Carbon footprint of daily activities for commuting to work or leisure (X2),	7	0.869	1.00	CfC
Carbon footprint of daily activities for food consumption (X3)	7	0.866	1.00	CfF
EM	28	0.974	1.00	EM
Air quality management (X4)	7	0.908	1.00	AM
Water management (X5)	7	0.924	1.00	WM
Energy management (X6)	7	0.933	1.00	EnM
Waste management (X7)	7	0.944	1.00	WaM
SDGs	35	0.983	1.00	SDGs
Good health and well-being (Goal 3)	7	0.942	1.00	GH
Equal Education (Goal 4)	7	0.944	1.00	EE
Sustainable consumption and sustainable production plan (Goal 12)	7	0.949	1.00	SC
Responsible Consumption and Production (Goal 13)	7	0.944	1.00	RC
Partnerships for Sustainable Development (Goal 17)	7	0.956	1.00	PS
Total No. of Questionnaires	84	0.986	1.00	

Table 2: Interpretation of students' awareness level on CfD, EM, and SDGs

Mean score	CfD, EM, and SDGs awareness level interpretation
1.00-1.50	Lowest
1.51-2.00	Low
2.51-3.00	Average
3.51-4.00	High
4.51-5.00	Highest

faculties. To resolve the challenge of incomplete data, the digital tool implemented 'forced-response' validation, guaranteeing that only fully filled-out surveys were eligible for submission. Post-collection, the dataset underwent a rigorous cleaning process; 12 incomplete or inconsistent 'straight-lined' responses were excluded, leaving a final sample of 400 valid responses for parametric analysis.

Data analysis and diagnostics

Statistical processing was executed via IBM SPSS (version 27.0) with an alpha level of 0.05 adopted for significance. To summarize student awareness levels, descriptive statistics, including mean values and standard deviations, were utilized. These levels were interpreted using the mean score benchmarks presented in Table 2. To investigate the interrelationships among variables, Pearson's correlation analysis was utilized. The robustness of these associations was measured in accordance with the criteria specified in Table 3. Furthermore, multiple linear regression analysis was employed to identify significant predictors of SDG alignment. To address potential bias inherent in self-reported data, Harman's Single-Factor Test was conducted; the resulting value was < 50%, suggesting that CMV is not a significant concern in this study. Furthermore, data normality and multicollinearity were confirmed via Shapiro-Wilk tests (Shapiro and Wilk, 1965), and variance inflation factor (VIF) diagnostics, respectively, to justify the use of parametric inferential testing. Descriptive statistics (Mean and S.D.) summarized student awareness (Creswell, 2014), interpreted through established score benchmarks. Pearson's correlation (Bland and Altman, 2011; Schober *et al.*, 2018) and multiple linear regression (Feldman and Sanger, 2007; Hair *et al.*, 2010) evaluated the relationships between variables. The application of Standardized Beta weights was meticulously carried out to evaluate the relative strength of the relationship between predictors and SDG alignment.

RESULTS AND DISCUSSION

Demographic characteristics of undergraduate students at Thepsatri Rajabhat University

The demographic features of undergraduate students at Thepsatri Rajabhat University, derived from a sample of 400 undergraduate students. It was revealed that most of the sample was female, numbering 235 people, accounting for 58.50%. The sample group was aged between 21 and 23 years, numbering 204 people, accounting for 51.00%. In terms of religion, it was found that most of the sample group was Buddhist, numbering 364 people, accounting for 91.00%. It was discovered that the sample group predominantly consisted of individuals from single-family households, totaling 240 people, which represents 60.00 %. The findings indicate that a significant portion of the participants, specifically 69 individuals, representing 17.30%, were affiliated with the Faculty of Education. The sample group was mostly studying in the third year, 145 people, or 36.30%. In terms of residence, most of them lived in private homes, 239 people, or 59.80%. For the mode of travel to university, most individuals opted for motorcycles, with 127 people representing 31.80% of the total. Regarding the average monthly income, data were collected in Thai baht, the currency used in Thailand. However, results are expressed in US dollars. It is significant to mention that the currency rate applied for the calculation was in January 2026. Most of the samples earned between 96.32 and 160.52 US dollars, accounting for 165 people, or 41.20%, as presented in Table 3**.**

The level of awareness on CfD, EM, and SDGs of undergraduate students

1) Carbon footprint of daily activities (CfD) awareness level was measured through 21 questionnaire items. The measurement was considered on 3 aspects, namely (1) Carbon footprint of daily activities for household consumption (CfH: X1), (2) Carbon footprint of daily activities for commuting to work or leisure (CfC: X2), and (3) Carbon footprint of daily activities for food consumption (Cf: X3). The findings of the analysis, as presented in Table 4, indicated that the CfH level was rated highly by the respondents (M=4.51, SD=0.45). The aspect of Carbon footprint of daily activities for commuting to work or leisure (CfC) (M=4.48, SD=0.40), and Carbon footprint of daily activities for commuting to work or leisure (CfC) (M=4.45, SD=0.39).

2) EM awareness level was measured through 28 questionnaire items. The measurement was considered on 4 aspects: Namely (1) air quality management (AM: X4), (2) water management (WM: X5), (3) energy management (EnM: X6), and (4) Waste Management (WaM: X7). The outcomes of the analysis, presented in Table 4, revealed that the respondents assessed the level of Waste Management (WaM: X7) as the highest (M=4.55, SD=0.40). Subsequences were the aspect of water management (WM:X5), (M=4.48, SD=0.38), energy management (EnM:X6), (M=4.45, SD=0.41) and air quality management (AM:X4), (M=4.40, SD=0.42).

3) SDG's awareness level was measured through 35 questionnaire items. The measurement was considered on 5 aspects: Namely (1) good health and well-being (Goal 3), (2) Equal Education (Goal 4), (3) sustainable Consumption and Sustainable Production Plan (Goal 12), (4) responsible consumption and production (Goal 13), and (5) partnerships for SDG (Goal 17).

The findings of the analysis, illustrated in Table 4, indicated that the level of equitable education (Goal 4) was rated at the highest level based on the respondents' evaluation (M=4.56, SD=0.46). Subsequences were aspects of responsible consumption and production (Goal 13), (M=4.54, SD=0.43), sustainable consumption and sustainable production plan (Goal 12), (M=4.48, SD=0.45), good health and well-being (Goal 3), (M=4.46, SD=0.47), and partnerships for sustainable development (Goal 17), (M= 4.41, SD=0.47).

Table 3: Demographic characteristics of undergraduate students at Thepsatri Rajabhat University

Demographic characteristics of undergraduate students		Undergraduate students	
Variable	Category	Mean/ frequency	%
Gender	Male	165	41.20
	Female	235	58.80
Age	Lower than 18 years	5	1.20
	18–20 years	150	37.50
	21–23 years	204	51.00
	More than 23 years	41	10.30
Religion	Buddhism	364	91.00
	Islam	14	3.50
	Christianity	17	4.30
	Others	5	1.20
Family characteristics	Single (nuclear)	240	60.00
	Extended	160	40.00
Faculty studied	Faculty of Management Science	74	18.50
Faculty studied	Faculty of Humanities & Social Sciences	64	16.50
	Faculty of Industrial Technology	63	15.80
	Faculty of Education	69	17.30
	Faculty of Information Technology	65	16.20
	Faculty of Science and Technology	65	16.20
Study year	First year	79	19.70
	Second year	107	26.80
	Third year	145	36.30
	Fourth year	69	17.20
Current residence	University dormitory	17	4.20
	Off-campus dormitory	141	35.30
	Private residence	239	59.80
	Others	3	0.70
Pattern of traveling to study	Walk	65	16.30
	Bicycle	25	6.20
	Motorcycle	127	31.80
	Car	58	14.50
	Public transport	124	31.00
	Others	1	0.20
Average monthly income	< 96.31 USD	84	21.00
	96.32–160.52 USD	165	41.20
	160.53–256.84 USD	76	19.00
	> 256.84 USD	75	18.80
Total undergraduate students		400	100.00

Relationship between Environmental Literacy and SDG Alignment

Bivariate correlation analysis was performed to examine the relationships between undergraduate students' awareness of CfD, EM, and their alignment with SDGs. The descriptive analysis summarized in Table 4 indicates that students demonstrated a high level of awareness across all dimensions observed. The Pearson's correlation coefficients (r) illustrated in Table 5 revealed strong, statistically significant positive correlations among all primary constructs ($p < 0.01$). Specifically, a robust correlation was observed between CfD and SDG alignment ($r = 0.878$), while the association between EM and SDG alignment was slightly higher ($r = 0.885$). The evidence demonstrates that elevated levels of environmental literacy are inherently connected to a stronger tendency among students to modify their actions in accordance with global sustainability initiatives. Students demonstrating advanced awareness of daily carbon impacts and resource management strategies consistently exhibited stronger identification with SDG principles. Consequently, the null hypotheses (Ho) were invalidated, verifying that localized environmental awareness functions as a key motivator for increased engagement in sustainable development within the university community.

Table 4: Latent variable observed variable. mean, S.D., and evaluation level

Latent variable	Observed variable	$\bar{X}$	S.D.	Evaluation level
CfD (X)	CfH (X1)	4.51	0.45	Highest
	CfC (X2)	4.45	0.39	High
	CfF (X3)	4.48	0.40	High
CfD	Total	4.47	0.42	High
EM (X)	AM (X4)	4.40	0.42	High
	WM (X5)	4.48	0.38	High
	EnM (X6)	4.45	0.41	High
	WaM (X7)	4.55	0.40	Highest
EM	Total	4.45	0.43	High
SDGs (Y)	GH (Goal 3)	4.46	0.47	Highest
	EE (Goal 4)	4.56	0.46	Highest
	SC (Goal 12)	4.48	0.45	High
	RC (Goal 13)	4.54	0.43	Highest
	PS (Goal 17)	4.41	0.47	High
SDGs	Total	4.49	0.48	High

Table 5: Correlation between CfD and SDGs, between EM and SDGs

Variables	(1)	(2)	(3)
CfD (1)	1	0.156	0.878
EM (2)		1	0.885
SDGs (3)			1

Results of multiple regression analysis of the correlation of students' awareness of the CfD and EM toward SDGs

The diagnostic tests for multiple linear regression analysis were used to test the influence of students' awareness on seven aspects of CfD and EM on the SDGs. To ascertain the reliability and accuracy of the multiple linear regression model employed to analyze the effects of seven components of CfD and EM on the SDGs, several diagnostic tests were performed. These tests included assessments of linearity, independence of residuals, multicollinearity, homoscedasticity, normality of residuals, and the presence of outliers. The validity of the regression model is largely contingent upon the satisfaction of these assumptions (Marshall and Karadimitriou, 2018). Linearity was evaluated through scatterplots and P-P plots. The scatterplot displayed no obvious pattern, suggesting that the residuals were randomly distributed. The P-P plot provided additional confirmation of a linear correlation between the dependent and independent variables, as the data points closely adhered to the diagonal line, suggesting that the errors were normally distributed. Independence of residuals was tested using the Durbin-Watson statistic. A value between 1.5 and 2.5 indicates no significant autocorrelation (Marshall and Karadimitriou, 2018). The analysis yielded a Durbin-Watson value of 1.969, which falls within the acceptable range, confirming the assumption of residual independence. The assumption of homoscedasticity was performed by qualitatively examining the scatterplot that relates studentized residuals to unstandardized predicted scores. This visual diagnostic was performed to confirm that the variance of the error terms remained constant across all levels of the independent variables, ensuring the reliability of the regression standard errors. The allocation of points seemed uniform throughout the values, implying that the hypothesis of equal variance (homoscedasticity) was fulfilled. This is critical, as heteroscedasticity can lead to biased estimates and incorrect conclusions regarding the significance of regression coefficients (Statistics Solutions, 2021). Outliers were examined using Cook's Distance in SPSS. The analysis indicated that there were no significantly influential data points, suggesting

that the dataset satisfied the assumption concerning the lack of problematic outliers (Marshall and Karadimitriou, 2018). Potential multicollinearity among the independent variables was investigated through the calculation of Tolerance levels and Variance Inflation Factors (VIF). The absence of significant collinearity was confirmed by VIF scores remaining strictly below the threshold of 10, complemented by tolerance values exceeding 0.1. The findings demonstrate that the predictor variables exhibit adequate independence to uphold the stability of the regression coefficients (Franke, 2010). The results confirmed that multicollinearity was not an issue in the dataset. This means that the regression model satisfied all critical diagnostic assumptions, thereby supporting the validity of the analysis in exploring the impact of students' awareness on the CfD and EM on the achievement of SDGs. The relationship between independent variables of CfD and EM affecting the dependent variable of awareness level on sustainable development goals of undergraduate students, as presented in Table 6 and Table 7. Multiple linear regression was conducted to evaluate the influence of seven independent variables (X1 to X7) on student alignment with Sustainable Development Goals. The model yielded a multiple correlation coefficient (R) of 0.831 and a coefficient of determination (R^2) of 0.754, indicating that the seven predictors account for 75.40% of the variance in the dependent variable ($p < 0.01$). When adjusted for the number of predictors, the Adjusted R^2 remained robust at 0.743. The variance ratio test (F-test) result of 277.889 ($p < 0.01$) confirms the overall statistical significance of the model, as detailed in Table 7. The multiple linear regression presented in Table 8, demonstrates that all seven independent variables—household consumption (X1), commuting (X2), food consumption (X3), air quality management (X4), water management (X5), energy management (X6), and waste management (X7)—serve as significant predictors of Sustainable Development Goal (SDG) alignment (Y) at a 0.01 confidence level. The overall effect of these factors on the variance of the dependent variable is articulated through the subsequent predictive model (Eq. 1), which is based on the study's empirical results:

$$Y = a + b1X1 + b2X2 + b3X3 + b4X4 + b5X5 + b6X6 + b7X7 \quad (1)$$

Where:
Y: Sustainable Development Goals as Dependent Variable
a: Constant value
b1: Coefficient relation of the carbon footprint of daily activities for household consumption as the independent variable
X1 = Carbon footprint of daily activities for household consumption as the independent variable
b2 = Coefficient relation of carbon footprint of daily activities for commuting to work or leisure as the independent variable
X2 = Carbon footprint of daily activities for commuting to work or leisure as the independent variable
b3 = Coefficient relation of the carbon footprint of daily activities for food consumption as the independent variable
X3 = Carbon footprint of daily activities for food consumption as the independent variable
b4 = Coefficient relation of air quality management as an independent variable
X4 = Air quality management as an independent variable
b5 = Coefficient relation of water management as an independent variable
X5 = Water management as an independent variable
b6 = Coefficient relation of energy management as an independent variable
X6 = Energy management as an independent variable
b7 = Coefficient relation of waste management as an independent variable
X7 = Waste management as an independent variable

Table 6: Results of analysis of the prediction power of students' awareness level on CfD and EM affecting SDGs

R	R-square	Adjusted R-square	Standard error (S.E.) of the estimate
0.831[a]	0.754[b]	0.743	0.186

a) Predictors: CfH, CfC, CfF, AM, WM, EnM, and WaM; b) Dependent variable: Sustainable Development Goals

Table 7: Multiple linear regression analysis of students' awareness level on CfD and EM affecting SDGs

Source	Sum of squares	df	Mean square	F	Sig.
Regression[a]	72.234	7	8.887	277.889	0.000[b]
Residual	23.623	392	0.060		
Total	95.857	399			

a) Predictors: CfH, CfC, CfF, AM, WM, EnM, and WaM; b) Dependent Variable: Sustainable Development Goals

Table 8: Coefficients of independent variables affecting SDGs

Independent variables	Unstandardized coefficients		Standardized coefficients	t	Sig.[b]
	B	S.E.	Beta		
	0.510	0.154	-	0.441	0.651
CfH (X1)	0.223	0.132	0.412	9.214	0.000**
CfC (X2)	0.254	0.141	0.312	9.727	0.000**
CfF (X3)	0.278	0.127	0.281	10.332	0.000**
AM (X4)	0.215	0.125	0.277	9.041	0.000**
WM (X5)	0.265	0.144	0.322	10.014	0.000**
EnM (X6)	0.267	0.138	0.301	10.089	0.000**
WaM (X7)	0.284	0.137	0.358	10.835	0.000**

a) Predictors: X1, X2, X3, X4, X5, X6, X7; b) Dependent Variable: Sustainable Development Goals (SDGs)
** Significant at the 0.01 level

The multiple regression analysis indicated that the seven predictors—ranging from waste management (X7) to air quality management (X4)—exerted a statistically significant influence on the Sustainable Development Goal (Y) awareness levels of undergraduate students ($p < 0.01$). Based on the unstandardized coefficients, the predictive model for raw scores is formulated as shown in Eq. 2. Furthermore, to demonstrate the significance of each predictor, the standardized regression model (Eq. 3) was created utilizing the computed beta weights obtained from the empirical data:

$$Y = 0.051 + 0.223X1 + 0.254X2 + 0.278X3 + 0.215X4 + 0.265X5 + 0.267X6 + 0.284X7 \quad (2)$$

The prediction in terms of standard score was demonstrated, using Eq. 3

$$Z_Y = 0.412X1 + 0.312X2 + 0.281X3 + 0.277X4 + 0.322X5 + 0.301X6 + 0.358X7 \quad (3)$$

The empirical findings of this study indicate that undergraduate awareness across all seven environmental dimensions serves as a statistically significant predictor of Sustainable Development Goal (SDG) alignment ($p < 0.01$). Based on the standardized Beta coefficients (β), Household Consumption (X1, β = 0.412) emerged as the most influential factor, followed by Waste Management (X7, β = 0.358) and Water Management (X5, β = 0.322). These findings highlight the essential significance of concrete, everyday behavioral decisions—particularly in how students handle household resources and waste—as the main factors in promoting alignment with sustainability targets. This hierarchy of influence aligns with recent research by Abubakar *et al.* (2022), which highlighted that effective solid waste management practices are fundamental to environmental sustainability, directly impacting multiple SDGs, including responsible consumption and climate action. Furthermore, Rama *et al.* (2024) emphasized that environmental awareness significantly moderates green purchase intentions. This is validated by Rustam *et al.* (2020), who affirmed that a rise in environmental awareness is directly associated with green

consumption behaviors, implying that intentional consumption and waste generation directly amplify a student's commitment to sustainable development. Beyond these primary drivers, the model revealed that systemic environmental management, such as Commuting Footprints (X2, β = 0.312), Energy Management (X6, β = 0.301), Food Consumption (X3, β = 0.281), and Air Quality Management (X4, β = 0.277), play vital supportive roles in the overall predictive framework. The multiple regression analysis revealed that Household Consumption (X1, β = 0.412) and Waste Management (X7, β = 0.358) are the most significant predictors of student alignment with Sustainable Development Goals. This observation agrees with the findings of Jiang *et al*. (2022), who contended that the activities performed by individual households and their energy consumption trends are critical factors in determining person's carbon footprint. The high predictive value of X1 suggests that when students understand the environmental costs of their domestic resource use, they are more likely to adopt broader sustainability values. This is additionally corroborated by Liebe *et al*. (2021), whose study illustrated that the adoption of "green defaults" in energy selections can result in lasting beneficial outcomes in both residential and commercial domains, thereby strengthening the possible influence of environmental initiatives spearheaded by universities. Furthermore, the significant role of Waste Management (X7) as a primary driver aligns with Chen *et al.* (2023), who confirmed that integrated environmental impact assessments covering waste and water sectors are crucial for optimizing resource allocation and minimizing ecological footprints in community settings. Beyond these direct behaviors, the study identified that systemic factors like Commuting Footprints (X2, β = 0.312) and Energy Management (X6, β = 0.301) play vital supportive roles. As highlighted by Haryanto *et al*. (2025), the assessment of personal carbon footprints is a tactical approach to encouraging sustainable behavior and minimizing emissions. Collectively, these results suggest that a holistic educational approach—integrating the seven factors identified—is essential for comprehensive sustainable development. This viewpoint is supported by Mansour (2023), who indicated that the environmental awareness among university members directly influences "green performance," implying that administrative support for environmental campaigns can lead to tangible behavioral changes across the campus. Furthermore, the transformation of student knowledge into practical sustainability achievements is often affected by considerable external and structural barriers. At the regional level, students may face infrastructure limitations, such as inadequate public transportation or a lack of accessible waste-sorting facilities, which hinder the execution of their environmental intentions. Moreover, economic restrictions and dominant cultural practices concerning consumption can function as policy impediments that lessen the influence of individual literacy. Recognizing these socio-economic constraints is vital, as they suggest that individual awareness must be supported by institutional and governmental policy interventions to achieve measurable carbon footprint reductions.

CONCLUSION

The findings of this study provide a comprehensive understanding of the relationship between environmental literacy and global sustainability within the Thai higher education context. By analyzing data from Thepsatri Rajabhat University, it is evident that undergraduate students possess a high level of awareness regarding the carbon footprint of daily activities, environmental management, and Sustainable Development Goals, with mean scores consistently exceeding the 3.51 threshold. This implies that the ongoing educational efforts have effectively established a robust foundational awareness. Most importantly, the study reveals a very strong positive correlation between SDG awareness and both carbon footprint awareness (r = 0.88) and environmental management skills (r = 0.89). Utilizing multiple regression analysis, the study adeptly pinpointed the areas of

awareness that exhibit the strongest relative correlation with the alignment to the SDGs. This study concludes that undergraduate students' literacy regarding daily carbon footprints and environmental management serves as a robust predictor of their alignment with Sustainable Development Goals (SDGs). The empirical data reveals that although students demonstrate a considerable level of theoretical understanding, their perceived dedication to the (SDGs is primarily profoundly impacted by their knowledge of household consumption (X1, $\beta = 0.412$) and waste management (X7, $\beta = 0.358$). These findings suggest that personal, high-frequency daily routines are the primary entry points for fostering sustainable behavior in higher education. Furthermore, the model's strong predictive capability suggests that incorporating carbon footprint analysis into the university curriculum can successfully address the 'knowledge-action gap' highlighted in previous literature. By prioritizing literacy in areas with the strongest relative association—specifically household consumption and waste—educational institutions can play a pivotal role in supporting Thailand's national targets for Carbon Neutrality by 2050 and Net-Zero Emissions by 2065. Although all seven variables were determined to be statistically significant at the 0.01 level, household consumption was identified as the most impactful predictor, with waste management and water management ranking closely thereafter. These results are particularly significant because they show that students prioritize tangible resource management as the most effective way to reach sustainability targets. The practical consequences of these findings are evident for university administrators and curriculum developers. Because awareness in these seven specific areas is a significant predictor of SDG alignment, they should be formally integrated into the university's core curricula rather than being treated as optional topics. In conclusion, this research highlights that the path toward aligning with the Sustainable Development Goals is deeply rooted in the environmental education of the youth. The robust empirical evidence indicates that understanding carbon footprints and being aware of environmental management are not merely academic topics, but rather vital instruments for contemporary citizenship. While this study provides significant empirical evidence of the links between environmental literacy and SDG alignment, several critical limitations must be acknowledged. First, the study was conducted exclusively at Thepsatri Rajabhat University, which presents a lack of institutional diversity. Due to the cultural and regional specificity of this single Thai public university, the findings may not be fully generalizable to the broader national higher education sector or to institutions in different geographic regions with varying institutional focuses. Second, the cross-sectional nature of the data represents a snapshot of student awareness at a specific moment in time and is mainly constrained by its dependence on self-reported Likert-scale data. Considering that these metrics evaluate perceived awareness instead of objective behavioral results, the significant correlations noted ($r > 0.85$) ought to be understood as a robust attitudinal alignment within this specific sampled population. Future research should employ multi-institutional designs and longitudinal approaches across diverse academic sectors in Thailand to observe how these reported intentions translate into tangible, long-term environmental impacts.

AUTHOR CONTRIBUTIONS

N. Kamolteeravit has collected the data, analyzed the data, interpreted the results, written and revised the manuscript. J. Prasara-A, the corresponding author, and N. Thiengkamol have contributed by supervising N. Kamolteeravit in research design, data collection, interpretation of the results, writing the manuscript, and manuscript revision. T.K. Thiengkamol has contributed by suggesting N. Kamolteeravit in the data analysis and the interpretation of the results.

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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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During the preparation of this work, the authors have used Artificial Intelligence (AI) [Grammarly] to improve the readability and style of writing. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

ABBREVIATIONS

%	Percent
CfC	Carbon footprint of daily activities for commuting to work or leisure
CfD	Carbon footprint daily activities
CfF	Carbon footprint of daily activities for food consumption
CfH	Carbon footprint of daily activities for household consumption
df	Degrees of freedom
EE	Equal education (Goal 4)
EnM	Energy management
EM	Environmental management
EPA	United States Environmental Protection Agency
GH	Good health and well-being (Goal 3)
IBM	International Business Machines
IOC	Item objective congruent
M	Mean
MRA	Multiple regression analysis
P–P plot	Probability–probability plot
PS	Partnerships for sustainable development (Goal 17)
RC	Responsible consumption and production (Goal 13)
S.D.	Standard deviation
SC	Sustainable consumption and sustainable production plan (Goal 12)
S.E.	Standard error
SDG	Sustainable development goal
SPSS	Statistical package for the social sciences
SRS	Simple random sampling
VIF	Variance inflation factor
WM	Water management
WaM	Waste management

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CASE STUDY

An Integrated real-time water quality monitoring system for sustainable management in tropical reservoirs

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ABSTRACT

BACKGROUND AND OBJECTIVES: The rapid deterioration of water quality in large tropical reservoirs threatens ecological integrity, water security, and socio-economic stability, particularly in developing regions with limited environmental monitoring capacity. Conventional approaches to water quality monitoring, predominantly based on manual sampling and stationary sensors, face limitations due to poor spatial and temporal resolution, which often obstructs timely detection and management of pollution incidents. The aims of the study were to create and validate a comprehensive, adaptive real-time monitoring system that combines static, stratified, and mobile sensing approaches into a scalable framework for sustainable reservoir management.

METHODS: Sixteen static (fixed-location) monitoring stations were strategically deployed across the Jatiluhur Reservoir, Indonesia's largest multipurpose water body, to continuously measure key parameters including dissolved oxygen, temperature, potential of Hydrogen, turbidity, and conductivity. Real-time data transmission was facilitated through Global System for Mobile based communication networks linked to a central analytical platform, where sensor data were verified against laboratory instruments that meet International Organization for Standardization-standard laboratory instruments to ensure accuracy and dependability.

FINDINGS: The system demonstrated an average operational reliability of 92.4 percent across sixteen monitoring stations, with eight stations consistently achieving data availability rates above 90 percent. It effectively identified hypoxic regions where dissolved oxygen concentrations fell below 2.5 milligrams per liter, turbidity levels surpassed 30 nephelometric turbidity units, and temperature stratification differences reached as high as 6 degrees Celsius between the surface and bottom layers during upwelling periods. Comparative analysis with international benchmarks revealed that the integrated system improved data consistency by 12–15 percent and reduced response time by 35 percent relative to conventional monitoring systems. The integration of real-time validation and AI-assisted analytics further enhanced predictive capability, achieving correlation coefficients greater than 0.92 between field sensors and International Standart Organization standard laboratory measurements.

CONCLUSION: The integrated real-time monitoring system provides a replicable model for adaptive and sustainable reservoir governance, supporting both environmental protection and operational efficiency. The system's execution aids in the formulation of environmentally sustainable policies based on data and effective reservoir management strategies, aligning with international water governance standards. These findings demonstrate the system's potential as a critical tool for achieving long-term water resource sustainability in tropical developing regions.

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INTRODUCTION

Water quality in large reservoirs is crucial for maintaining ecological balance, supporting freshwater biodiversity, and sustaining socio-economic activities, including raw water supply, irrigation, hydroelectric power generation, fisheries, and tourism (Bachmann *et al.,* 2022). Nevertheless, the increasing anthropogenic pressures, including urban development, industrial waste discharge, and intensive aquaculture practices, are swiftly deteriorating freshwater ecosystems worldwide (Wu *et al.,* 2023). According to the United Nations Environment Programme (UNEP), nearly two-thirds of the world's reservoirs are experiencing significant water quality deterioration due to pollution, eutrophication, and climate-induced hydrological changes (UNEP, 2021). These challenges represent considerable dangers to human health, food security, and economic stability, particularly in developing nations that rely on freshwater resources for numerous purposes. In this global context, the Jatiluhur Reservoir, Indonesia's largest multipurpose water body, serves as a critical case study that mirrors the widespread challenges faced by reservoirs worldwide in balancing ecological health with multi-sectoral demands (Lezzar *et al.,* 2020; Selomane *et al.,* 2019). Understanding and managing the deterioration of Jatiluhur provides insights relevant to freshwater governance in other tropical and subtropical regions. With a volume capacity of 3 million cubic meters (Mm^3) and a surface area of 8,300 hectares (ha), the reservoir serves as a key water source for agriculture, industry, hydroelectric power with 187.5 megawatt capacity (MW), and domestic consumption (Kurniasari *et al.,* 2020). Nonetheless, in spite of its strategic significance, the reservoir is confronted with increasing pollution issues mainly caused by pollutant inflows from the Cirata Reservoir, unprocessed residential waste, and the expansion of floating net aquaculture (Hamzah *et al.,* 2017). The aforementioned factors have hastened the occurrence of eutrophication, hypoxia, and harmful algal blooms (HABs), which have caused widespread fish mortality and economic detriment. The rapid expansion of floating net cage aquaculture, since 1988, has introduced excessive organic waste, primarily from uneaten fish feed and fish excretion (Anas *et al.,* 2017). This organic accumulation depletes dissolved oxygen (DO), creating hypoxic conditions that trigger algal blooms and fish disease outbreaks, including Koi Herpes Virus (KHV) (Nastiti *et al.,* 2018). Seasonal upwelling events, in which low-oxygen water ascends to the surface, worsen hypoxia and disrupt hydroelectric operations (Utami *et al.,* 2022). The degree of deterioration in water quality at Jatiluhur Reservoir has been extensively documented. DO levels fluctuate between 2.3 miligrams per liter (mg/L) and 7.8 mg/L, with critical thresholds often falling below the minimum required for fish survival in multiple zones of the reservoir (Mellyanawaty, 2024). Turbidity levels frequently exceed 25 nephelometric turbidity unit (NTU), posing risks to drinking water supply and hydroelectric efficiency (Lei *et al.,* 2022). Currently, the approaches for monitoring water quality chiefly utilize manual sampling, immobile sensors, and intermittent measurements that are depth-based. These traditional approaches suffer from spatial and temporal limitations, preventing real-time detection of water quality variations and timely intervention (Hamzah *et al.,* 2017; Pule *et al.,* 2017). Although recent developments in Internet of Things (IoT) sensor networks and AI-driven forecasting trends promise transformative capabilities for reservoir monitoring, most solutions remain fragmented, focusing on either fixed or mobile systems without integrating multiple methodologies (Pulungan *et al.,* 2020).

Furthermore, bolstering the online reservoir monitoring initiative is vital for fostering sustainable environmental governance. Digitalized, real-time monitoring platforms enable continuous assessment, stakeholder participation, and data transparency essential for integrated watershed management. Such systems enhance decision-making processes by integrating local activities with broader national sustainability initiatives, which helps maintain the ecological resilience of reservoirs over time (Farzana *et al*., 2024). Furthermore, numerous studies efforts lack effective validation techniques, resulting in a failure to compare data generated by sensors with measurements calibrated in a laboratory (Toha *et al.,* 2022). Without immediate action, the continuous degradation of large reservoirs like Jatiluhur threatens the achievement of critical sustainable development goals (SDGs), namely SDG 14 (life below water) and SDG 6 (clean water and sanitation), while also endangering water security, food production systems, and energy sustainability (UNEP, 2021). The use of real-time and data-driven monitoring directly promotes SDG 6 and SDG 14 by allowing for the early identification of contamination, enhancing transparency, and preserving aquatic ecosystems. Moreover, its adaptive and predictive framework strengthens climate resilience in reservoir operations, aligning with SDG 13 and demonstrating how technological innovation supports measurable progress toward sustainable water governance. Consequently, this study seeks to create a comprehensive and flexible water quality monitoring framework that integrates static, stratified, and mobile techniques to improve the management of extensive multipurpose reservoirs. This study addresses these critical gaps by developing a novel, integrated multi-method water quality monitoring system for the Jatiluhur Reservoir. The study approach combines static, stratified, and mobile monitoring methods to deliver real-time, high-resolution spatiotemporal data on water quality parameters, including potential of hydrogen (pH), DO, temperature, turbidity, and conductivity. This all-encompassing system not only addresses the spatial constraints of static monitoring but also offers real-time adaptability for stratified monitoring, thereby enhancing the operational consistency of mobile monitoring. To the best of our knowledge, few existing studies have integrated static, stratified, and mobile monitoring approaches into a unified framework that is also validated against internationally standardized laboratory reference tools. Subsequent efforts have predominantly highlighted either stationary or mobile platforms, which have led to constrained cross-validation and field-scale usage in in extensive tropical reservoirs. This study builds upon previous investigations by introducing one of the most thorough and completely integrated systems evaluated in actual tropical multipurpose reservoir conditions (Damidavičius *et al*., 2019; Jiang *et al*., 2022). The proposed monitoring system uses AI-driven predictive analytics and real-time data transmission to deliver actionable insights for proactive water quality management. Validation through comparison with laboratory-calibrated reference tools confirms the system's accuracy and reliability, establishing it as a scalable solution for managing large scale reservoirs. The novelty of this study is found in its integration of multiple methods, which successfully tackles the spatial and temporal deficiencies present in current water quality monitoring approaches. This study offers a replicable framework for real-time, data-driven reservoir management and aligns with global sustainability efforts. The system's design emphasizes scalability, adaptability, and cost-efficiency, making it applicable to other large-scale reservoir systems worldwide. This study presents practical suggestions for managing aquaculture

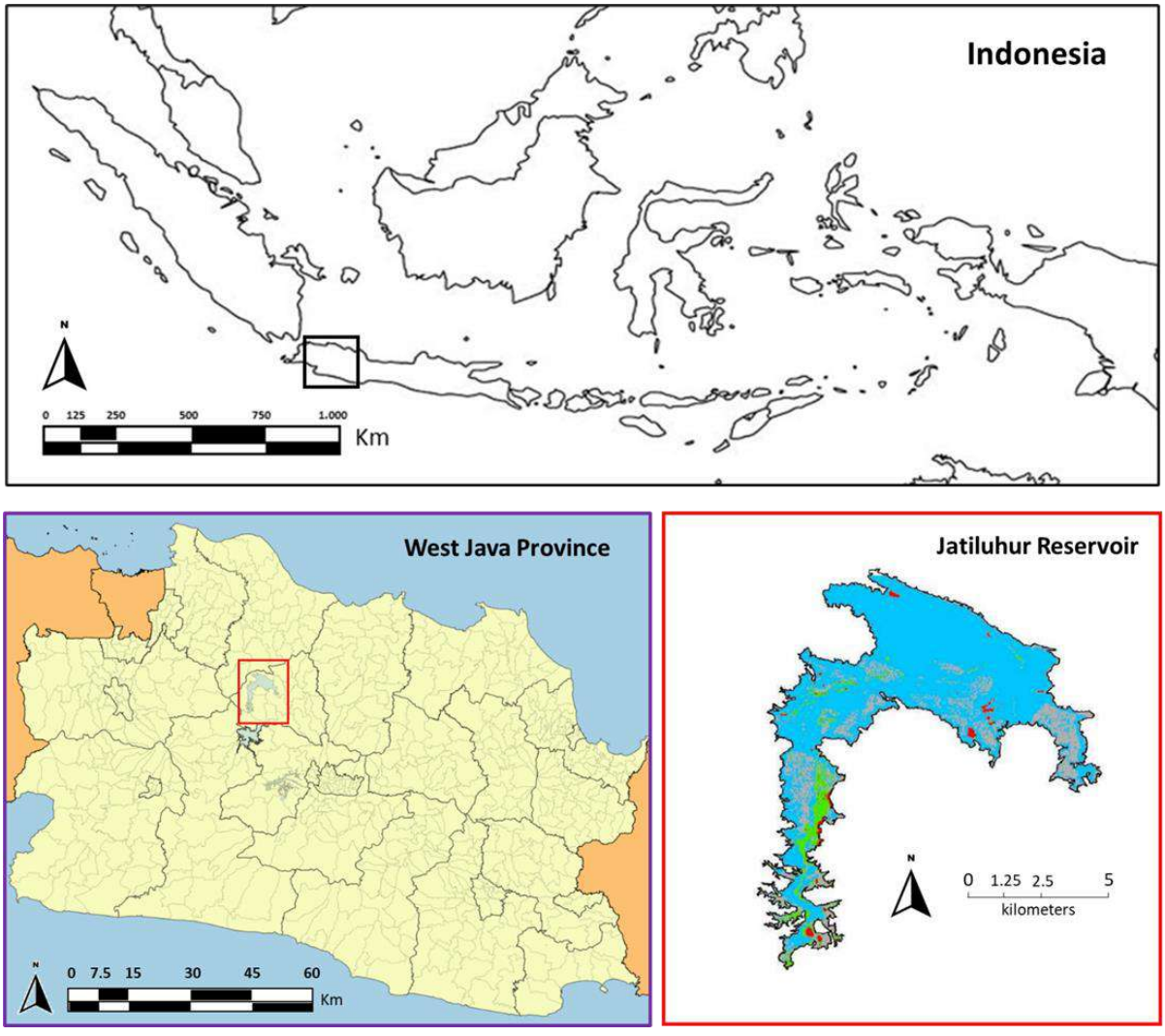


Fig. 1: Geographical location of the study area in Jatiluhur reservoir research in West Java Province's Purwakarta Regency, Indonesia

density, mitigating watershed pollution, and implementing AI-driven early warning systems, thus showcasing the possibilities for innovative and sustainable reservoir management solutions. This is the first study to integrate static, stratified, and mobile monitoring systems validated against ISO-calibrated instruments in a tropical multipurpose reservoir. In addition, the development of predictive and analytical models in this study is designed to assess the extent to which the resulting algorithms can be applied to other tropical reservoirs with minimal retraining and recalibration requirements, thereby supporting more efficient system replication across different ecohydrological contexts. This study aims to design and validate an all-encompassing real-time water quality monitoring system that merges static, stratified, and mobile sensing techniques for the adaptive management of extensive tropical reservoirs. The study evaluates system reliability, accuracy, and capability in detecting spatiotemporal water quality variations, while demonstrating its scalability as a data-driven tool for sustainable

reservoir governance. The present study was carried out at the Research Centre for Environment and Clean Technology, National Research and Innovation Agency, Indonesia in 2024.

MATERIALS AND METHODS

The study area

The study was carried out in Jatiluhur Reservoir in West Java Province's Purwakarta Regency, Indonesia (Fig. 1). The study procedure follows an organized, multidisciplinary approach encompassing conceptual design, system development, and rigorous validation. This methodology incorporates elements from environmental science, analytical chemistry, computational physics, and electrical engineering. The study workflow consists of three main phases: 1) Conceptual design and site selection; 2) System installation and calibration; 3) Field deployment, data collection, and validation analysis. This timeline establishes a coherent framework for development, diligent testing, and real-world confirmation.

Monitoring system design

The water quality monitoring system is designed based on a combination of three complementary data collection methods: static, stratified, and mobile monitoring, providing comprehensive, real-time insights into the reservoir's water quality. The static monitoring system is composed of durable, weather-resistant stations positioned at strategic fixed locations. These stations are equipped with multi-parameter sensors capable of continuous, high-frequency measurements of water quality indicators, involving DO, pH, temperature, salinity, conductivity, total dissolved solids (TDS), turbidity, ammonium, nitrate, oxidation-reduction potential (ORP), total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). To fully encapsulate the significant physicochemical features of the reservoir, the monitoring system perpetually measured several parameters across both temporal and spatial dimensions. The static, stratified, and mobile monitoring units were physically integrated through a centralized control and data acquisition system. Each station was equipped with microcontroller-based data loggers connected via global system for mobile (GSM) communication to a central server located at the reservoir management office. The static units supplied consistent surface-level data, whereas the stratified modules utilized multi-depth sensor arrays (0–30 m) connected through a vertical cable interface. Mobile platforms, consisting of sensor-equipped boats, transmitted near-surface measurements to the same server via wireless data relay. The primary control platform automatically synchronized inputs from every node, executing time-alignment, quality validation, and data fusion to create a cohesive, real-time reservoir monitoring dashboard. The summary of the observed ranges, associated standard references, and sensor accuracies for each monitored parameter during the 2016–2020 deployment period is presented in Table 1. The DO threshold of <1 mg/L applied in the expert system is supported by prior studies indicating that tropical freshwater fish experience acute hypoxic stress and mortality under such conditions (Boyd and Tucker, 2012). This value is consistent with field observations in Jatiluhur Reservoir, where fish kills regularly happened at DO levels beneath 1.2 mg/L, thus affirming its local significance. Real-time monitoring enables prompt detection of short-term variations and early warnings of water quality deterioration. Data obtained from stationary stations is relayed to a central data hub utilizing advanced data loggers that incorporate GSM communication devices, facilitating data transmission through short message service (SMS) or internet data packages. During

Table 1: An overview of water quality variables monitored by the system (2016–2020) (Dong *et al*., 2015; Jiang *et al*., 2022)

Parameter	Range observed	Standard reference	Sensor accuracy
DO (mg/L)	2.3–7.8	ISO 5814	±0.1 mg/L
Turbidity (NTU)	10–50	ISO 7027	±2% of reading
pH	6.2–8.5	ISO 10523	±0.1 pH unit
Temperature (°C)	24–32	ISO 5667	±0.3°C
Conductivity as micro-Siemens per centimeter (µS/cm)	120–360	ISO 7888	±1% of reading
Ammonia (mg/L)	0.1–1.5	APHA 4500-NH3	±0.05 mg/L

temporary GSM/SMS/internet outages, the smart data logger maintains continuity by buffering time-stamped measurements locally and transmitting them once connectivity is restored; data gaps are explicitly flagged in the database to prevent unreliable real-time escalation. Data transmission uses GSM via SMS and packet-based mobile data (internet/GPRS), with each record tagged by station/platform ID and measurement time stamp to enable consistent ingestion and synchronization at the central data center. Transmission latency is characterized as the gap between the time stamp of measurement and the relevant server ingestion time; thus, latency is contingent upon the network and may escalate in low-signal environments. To capture vertical dynamics in the reservoir, a stratified monitoring system is developed, which involves floating platforms equipped with sensors positioned at different depths, such as 0.5 meter (m), 5m, 10m, and beyond. These sensors continuously monitor critical parameters, including temperature, DO, turbidity, and depth. The stratified approach enables dynamic profiling, capturing variations caused by seasonal stratification, thermocline formation, and upwelling events. Monitoring vertical water quality changes allows the system to provide valuable insights into reservoir behavior, including potential hypoxia, thermal stratification, and algal bloom formation. The mobile monitoring system overcomes the spatial constraints associated with static and stratified monitoring by offering spatial flexibility. The spatial configuration of the sixteen stations was determined using a quantitative assessment of reservoir morphometry and hydrological dynamics. The reservoir authority's bathymetric and flow data were examined to determine representative zones according to depth gradients, inflow patterns, and circulation dynamics. The minimum spacing of 800–1,000 m between stations ensured adequate spatial coverage across the 8,300 ha surface area, while three stations were placed along the main inflow–outflow axis to capture longitudinal variation in water quality. Furthermore, stratified depth monitoring (0–30 m) was implemented at four stations situated in the deepest basins to consider vertical mixing and the development of hypoxia. This spatial optimization was validated through hydrodynamic modelling to ensure proportional representation of heterogeneous reservoir zones. Mobile platforms, such as boats or autonomous vehicles, are equipped with multi-parameter sensors to conduct spatially adaptive monitoring. This system compiles real-time data from diverse sites within the reservoir, facilitating spatially distributed measurements and adaptive coverage. It can be swiftly implemented in crucial circumstances, including pollutant discharges or algal bloom events. The integration of static, stratified, and mobile monitoring methods ensures comprehensive coverage, real-time analysis, and timely responses to water quality changes. The smart data logger aggregates data from all three methods and transmits it to the

central data center for analysis. All measurements from static, stratified, and mobile platforms were ingested into a centralized database through the smart data logger workflow. Each record was stored with time stamps and platform metadata (static/stratified/mobile), including station identifiers and, where applicable, depth information for stratified profiles. These standardized metadata facilitated the synchronization and integration of various observations at the central data center, which is essential for subsequent analysis and decision-making support.

Supporting infrastructure design

The monitoring system is designed to ensure resilience, reliability, and cost-effectiveness by incorporating protective infrastructure that enables continuous operation even under harsh environmental conditions. The monitoring stations are designed to withstand weather conditions and are fitted with protective casings to shield sensors from severe weather occurrences and acts of vandalism. Solar panels, backup batteries, and hybrid power solutions maintain uninterrupted operation in remote areas. In addition, stations were configured to prioritize low-power operation during reduced solar availability and to resume normal transmission automatically after power recovery, minimizing downtime during intermittent power conditions. Mobile vehicles, including boats and autonomous platforms, are optimized for stability, maneuverability, and efficient sensor integration, supporting reliable data collection and long-term system functionality. To mitigate the risk of data loss and to maintain continuous acquisition, transmission, and storage, the monitoring architecture was designed with various layers of redundancy in power supply, data logging, and communication pathways. Every station was outfitted with hybrid power modules that integrated solar panels, deep-cycle backup batteries, and overcharge/low-voltage protection, enabling autonomous functionality during extended periods of low radiation or power grid failures. Redundant data logging was implemented through local storage in the smart data logger and scheduled batch uploads to the central server, so that temporary GSM outages did not result in permanent data gaps. Communication reliability was further enhanced by configuring dual transmission channels (SMS and GPRS/Internet) with automatic failover, periodic heartbeat messages to verify connectivity, and retransmission routines for unacknowledged data packets. To ensure the protection of long-term archives, mirrored databases and regular data backups were implemented on the server side, allowing for the preservation and analysis of vital time series even during hardware or network disruptions.

Measurement data validation

A comprehensive validation strategy is employed to ensure the accuracy, reliability, and compliance of measurement data with international standards. The method of cross-validation assesses sensor data by comparing it with internationally validated reference instruments. Calibration was performed using standard laboratory instruments, including HACH (HACH Company, Loveland, Colorado, USA), DR3900 spectrophotometer for chemical parameters and Mettler Toledo In Lab Pure Pro Electrodes for electrochemical parameters, ensuring alignment with International Standard Organization (ISO) 5814 (DO measurement) and ISO 7027 (turbidity measurement) standards Cross testing with chemically analyzed water samples further ensures measurement consistency and accuracy. To maintain reliable sensor performance in the challenging and biofouling-prone conditions of a large tropical reservoir, the

monitoring system was subjected to a stringent calibration and maintenance schedule that merged routine field evaluations with laboratory reference assessments. Multiparameter probes were calibrated at least once every two weeks using traceable standard solutions, with additional event-triggered calibration conducted after extreme weather, severe biofouling, or unexpected signal drift were detected in the data stream. Preventive maintenance encompassed systematic cleaning of sensor heads, inspection and replacement of membranes and electrolytes for electrochemical probes, assessment of cable integrity and connectors, along with functional testing of data loggers and power supply units. Operational protocols specified standardized procedures for sensor handling, warm-up time, stabilization checks, and acceptance criteria for calibration curves, alongside detailed documentation of calibration logs and maintenance activities to support traceability and quality assurance. These practices were collectively established to mitigate measurement drift, minimize data gaps resulting from equipment malfunctions, and ensure long-term system reliability appropriate for ongoing real-time deployment in tropical reservoir environments. Throughout the deployment period, regular bi-monthly recalibration schedules and quality assurance protocols were put in place to sustain sensor accuracy and lessen drift phenomena, in accordance with best practices in remote sensing and environmental monitoring (Dong *et al*., 2015). Field quality control also included routine inspection and cleaning to mitigate sensor fouling/biofouling and waste-related contamination effects; stations showing abnormal stability loss or drift signatures were prioritized for maintenance and additional calibration checks before their data were used for decision support. System performance was quantified using continuity metrics (data acquisition performance and station-level data availability/capture rates) over the long-term deployment period, and agreement metrics against laboratory reference analyses using Pearson correlation (r) and root mean square error (RMSE). Additionally, the measurement uncertainty was framed in the context of the sensor accuracies that were documented for each parameter (Table 1).

Real-time data validation, anomaly detection, and early warning logic

The monitoring platform implements a real-time analytics workflow prior to alert generation. First, incoming sensor streams undergo real-time validation through laboratory-referenced quality assurance procedures. Sensor measurements are periodically cross-validated against ISO-aligned laboratory instruments, such as the HACH DR3900 spectrophotometer and Mettler Toledo electrodes. Additionally, the deployed sensors are recalibrated on a regular schedule to reduce drift and ensure the integrity of measurements. Predictive analysis in this study is implemented as an operational early-warning classification rather than a machine-learning forecasting model. Specifically, anomaly/event detection and early warning are performed using a rule-based expert system that maps multivariate conditions (including dissolved oxygen, turbidity, and stratification-related indicators such as temperature gradients across depth and persistence of adverse conditions) into four warning states (Safe, Alert, Standby, Critical). This rule-oriented method was adopted to provide clarity and facilitate practical implementation in operational settings.

RESULTS AND DISCUSSION

Table 2 showcases various study outcomes related to the Jatiluhur Reservoir, focusing on the reservoir's status, water quality assessment

Table 2: Research subjects in Jatiluhur Reservoir

No.	Research topics	Remark	Sources
1	Establishing Jatiluhur reservoir contamination load	Examining the effects of Cirata Reservoir and Cilalawi River wastewater discharge on Jatiluhur Reservoir's water quality. Understanding excessive nitrogen and phosphorus as eutrophication causes.	Pratiwi *et al.,* 2020; Lukman *et al.,* 2022
2	Mass fish death and retribution	Explains how the Jatiluhur Reservoir experiences huge fish mortality due to water agitation, or upwelling, which raises water masses containing harmful substances and low oxygen levels to the surface reservoir.	Jasalesmana *et al.,* 2023
3	Comparison between dynamic and static approaches to water quality monitoring	Analyzing dynamic boat-based techniques with static monitoring techniques at one location. Although dynamic monitoring offers greater flexibility, it necessitates standardization in sampling techniques and instruments.	Wang *et al.,* 2022
4	Application of IoT based sensors for environmental monitoring	Explains sensor systems based on the IoT for monitoring water quality in real time. High accuracy is a benefit, but expenses.	Lezzar *et al.,* 2020
5	Aquaculture practices using floating net cages (KJA)	Describing how fish aquaculture affects Jatiluhur Reservoir's rising levels of organic and inorganic pollutants. Waste management requires more stringent rules.	Garno *et al.,* 2011
6	Primary indicators of water quality	The primary markers of water quality are parameters like DO, pH, temperature, and ammonia concentration. Additionally, microplastics.	Ramadan and Sembiring, 2020
7	Effects of domestic waste	Investigating how domestic waste enters the Jatiluhur reservoir via drains. The primary goal of this research is to develop solutions like building an integrated waste processing system.	Wardhani and Sugiarti 2021
8	Deployment of GSM technology in environmental monitoring	The application of GSM based communication systems for transmitting real-time water quality data presents a cost effective and user-friendly solution. Despite its affordability and ease of implementation, this method often encounters limitations in signal coverage, particularly in remote or rural regions where telecommunications infrastructure is less developed.	Raja, 2017
9	Outbreaks of KHV in aquaculture systems	An investigation into the recurring outbreaks of KHV among farmed fish populations in the Jatiluhur Reservoir highlights the critical need for implementing environmentally sustainable aquaculture practices. Such approaches are essential in minimizing the risk of disease transmission and maintaining the overall health of the aquatic ecosystem.	Koesharyani *et al.,* 2017
10	Economic evaluation of IoT system Implementation	An analysis of the implementation of IoT based water quality monitoring systems reveals a range of benefits across immediate, operational, and long-term dimensions. The findings indicate that such systems contribute to overall cost savings by enhancing the efficiency and responsiveness of water quality management practices.	Ramadhan *et al.,* 2020
11	Pollution control strategy	This study underscores the pivotal role of government regulations in mitigating pollution originating from both industrial and domestic sources. Its further advocates for collaborative efforts among stakeholders to enhance the effectiveness and enforcement of these regulatory frameworks.	Mufrih and Hadiroh, 2022
12	Multilevel sampling method	Developing a sampling method structured according to the depth profile of the reservoir, which allows for a more precise depiction of vertical variations in water quality parameters.	Mellyanawaty *et al.,* 2024
13	The role of aquatic ecosystems	The importance of conserving the Jatiluhur Reservoir aquatic ecosystem to sustain its multifunctional roles as raw water and electricity sources.	Aryani *et al.,* 2021
14	Water flow patterns in reservoirs	Study the dynamics of water flow patterns in the Jatiluhur Reservoir. Hydrodynamic models should be used to anticipate flow, according to recommendations.	Hidayah *et al.,* 2023
15	Use of satellite technology	Research into the use of satellite technology to monitor water quality on a large scale. Although pricey, this method provides broad geographic data for water quality management.	Liu *et al.,* 2020

techniques, measurement criteria, technologies utilized, and additional critical aspects. The dominant contributor to pollution in the Jatiluhur Reservoir is the inflow of contaminants from the Cilalawi River and its tributaries, which traverse the reservoir and carry substantial loads of domestic, industrial, and agricultural waste (Pramaningsih *et al*., 2023). Compounding this problem is the existence of the Cirata Reservoir located upstream, which discharges both organic and inorganic pollutants that further deteriorate water quality in Jatiluhur (Utami and Puspaningrum, 2022). Another major source of pollution arises from floating net cage aquaculture, a practice that has expanded since 1988. The accumulation of organic waste from uneaten fish feed and fish excrement has progressively built up on the reservoir bed, initiating eutrophication processes (Astuti *et al*., 2018). The substantial organic load amplifies the frequency of upwelling, a natural occurrence in which deeper, low-oxygen water ascends to the surface, particularly noticeable during the rainy season (Sinarmata *et al*., 2017). Furthermore, occurrences of fish diseases, particularly Koi Herpes Virus (KHV), have caused economic harm to the aquaculture industry and additionally indicate a deterioration in the health of underwater ecosystems (Ariyanto *et al*., 2015). The Jatiluhur Reservoir, with a total storage capacity of approximately 3 Mm^3, spans up to 8,300 ha and has an average depth of 37.6 meters (m). These physical features give rise to a complicated aquatic setting defined by notable stratification in the quality parameters of water. Such structural features make the reservoir well-suited for multiple functions, including the provision of raw water, irrigation, hydroelectric energy generation with an installed capacity of 187.5 MW, as well as fisheries and tourism development (Nidyatami *et al*., 2023). Nonetheless, its role exerts considerable ecological strain. Specifically, the rise in KJA fishing activities often takes place in nations with high water quality, which facilitates effective hydroelectric energy operations. This demonstrates the need for a data-driven and integrated management technique that can address the complete function of the ecosystem in order to maintain the sustainability and production of the Jatiluhur reservoir (Dewantara *et al*., 2021).

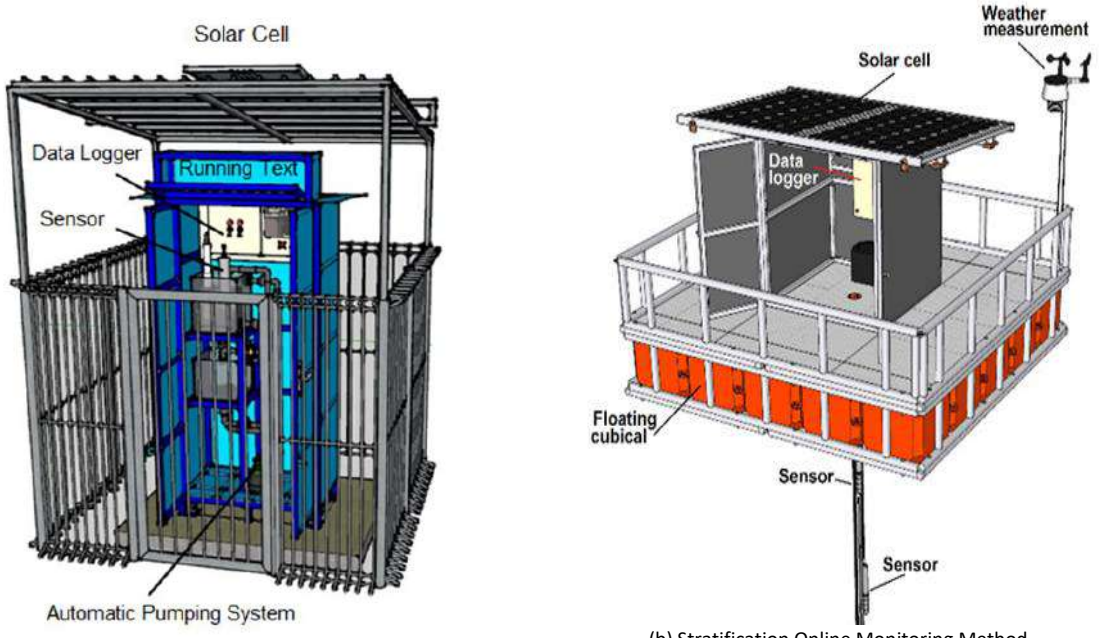
Flexible water quality monitoring system design

The Jatiluhur Reservoir's water quality data is accurate and representative reservoirs to the integrated monitoring method design, which includes static, multilayer, and mobile techniques. The static approach allows for highly accurate monitoring of vital parameters including pH, DO, and temperature by providing continuous data from key sites (Wardhani and Sugiarti, 2021). The stratified or multilevel monitoring approach offers significant insights into vertical fluctuations in water quality, facilitating a comprehensive examination of stratification dynamics within the reservoir. Simultaneously, mobile monitoring methods provide the benefit of gathering data from multiple sites, thus broadening the geographical scope of the evaluation (Alegria and Albuquerque, 2023). When these techniques are integrated, they ensure that the resulting data captures not only temporal and vertical dimensions but also horizontal distribution across the reservoir's surface (Ramadan and Sembiring, 2020; Alla and Liu 2021). However, each approach has its downsides; for example, the static method is less flexible in covering a large region, while the mobile method is prone to inconsistency in findings if not carried out regularly (Dong *et al.*, 2015). Consequently, the incorporation of these monitoring technologies establishes a supplementary system that improves the efficiency of adaptive monitoring customized to

the particular conditions of the Jatiluhur Reservoir. The system is equipped with advanced multiparameter sensors capable of monitoring essential physical indicators such as pH, DO, temperature, turbidity, and conductivity, alongside analyzers designed to detect key organic parameters like COD and BOD. These instruments are selected in accordance with international standards to ensure high precision, environmental sensitivity, and durability in demanding conditions such as changing temperatures and differing water pressure (Wang *et al*, 2019; Demuth *et al.,* 2016). Data collected by these sensors are transmitted in real time via smart data logger systems connected through GSM networks, utilizing services such as SMS, General packet radio service (GPRS), and internet based protocols (Zhang, 2023). This configuration allows for quick data retrieval for pertinent stakeholders, thereby promoting timely assessment and agile decision-making (Chen *et al.,* 2021). The application of this technology significantly minimizes the lag in data acquisition and processing, which is particularly critical during emergency events like sudden pollution surges or rapid water quality deterioration (Feller and Partsch, 2021). In addition, protective infrastructure plays a crucial role in ensuring the resilience of monitoring equipment against external threats. These structures (as depicted in Fig. 2) are meticulously designed to protect sensors, data loggers, and communication modules from vandalism, in addition to severe environmental conditions like heavy rainfall, high winds, and temperature variations (Dai and Liao, 2014). As noted by Martínez *et al*. (2018), both stationary and floating monitoring stations are equipped with casings made from corrosion-resistant and waterproof materials, designed to sustain long-term operational integrity. For mobile platforms like monitoring boats, additional reinforcement is provided through custom-built, shock-resistant, and waterproof enclosures, which help maintain the functionality of sensors and data loggers during active deployment (Zhu *et al.,* 2010). These protective components not only prolong the durability of the monitoring equipment but also ensure steady data collection by mitigating interruptions caused by environmental factors or human-related interference. The flexibility and scalability of the monitoring system further enhance its applicability to other reservoirs and lakes across Indonesia with diverse ecological profiles (Aryani *et al.,* 2021). By adjusting the number of deployed sensors, the extent of coverage, and the specific parameters measured, this system can be effectively implemented in water bodies with different depths or biodiversity characteristics (Nurdin *et al.,* 2023). Consequently, the system created for Jatiluhur functions not only as a tailored solution for that specific location but also as a model that can be replicated for the management of water quality in other significant reservoirs across the country, thereby contributing to wider objectives of freshwater ecosystem sustainability (Rubianti, 2023). Fig. 3 presents a schematic block diagram that outlines the data flow and interconnections between the key components of the monitoring system, encompassing static, mobile, and stratified measurement approaches.

Monitoring system performance

The integrated real-time water quality monitoring system was deployed successfully across sixteen monitoring stations for static station. Data acquisition performance was evaluated from 2016 to 2020, comparing the total amount of recorded measurements against theoretical data generation expectations. In this context, operational reliability is expressed in terms of data availability (data capture rate), which is defined as the proportion of recorded measurements to the theoretically anticipated

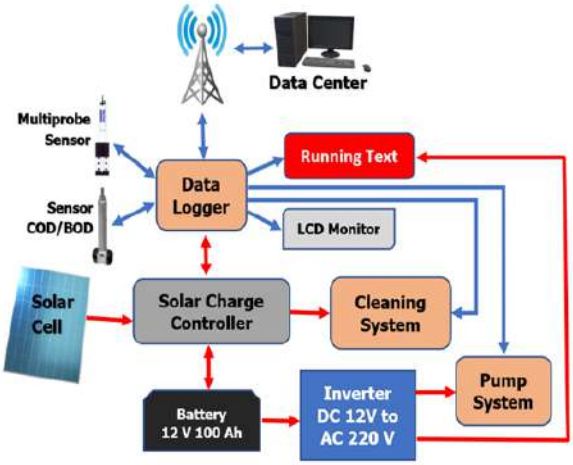


(a) Static Online Monitoring Method

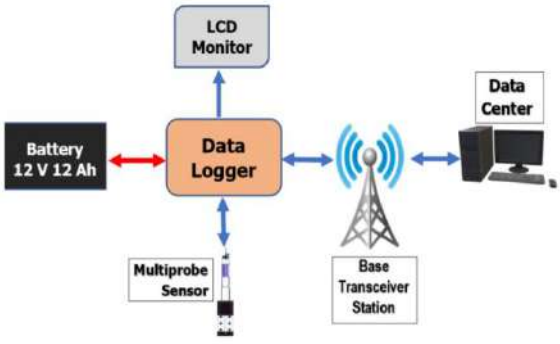
(b) Stratification Online Monitoring Method

Fig. 2: Design of a safe building for online monitoring methods on (a) Static online monitoring and (b) Stratification online monitoring

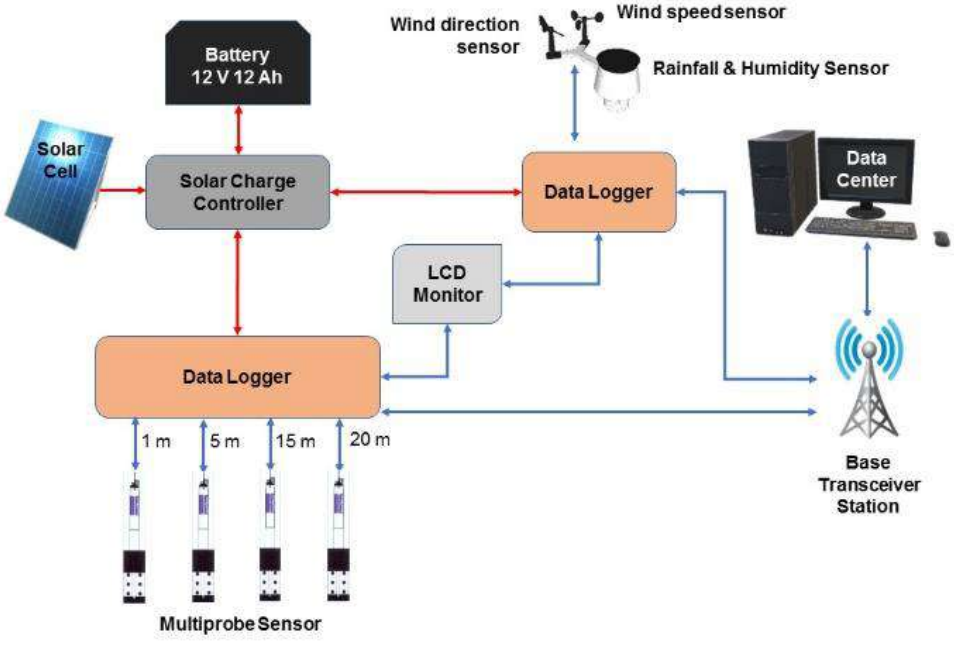
number of measurements throughout the monitoring period. Analysis showed that eight stations consistently achieved data availability rates exceeding 90 percent (%), with the Gerak Serayu Dam station demonstrating the highest reliability (Table 3). Remaining stations showed performance ranging between 50% and 80%, largely influenced by localized challenges such as biofouling and GSM signal instability. An evaluation of the operational stability of the deployed monitoring stations was conducted by analyzing data capture rates and identifying technical challenges at each location during the 2016–2020 deployment period. Table 3 provides an overview of the performance metrics associated with each station, drawing attention to critical operational problems and proposed remedial actions. Fig. 4 shows online monitoring stations that have been deployed statically, stratified, and mobile in rivers and lakes or reservoir waters like Jatiluhur Reservoir. Comparatively, international studies have reported lower consistency rates for real-time water quality monitoring in large aquatic systems. For instance, a real-time monitoring initiative in Lake Ontario attained a data reliability rate of around 85% as a result of environmental sensor fouling (Pule *et al.*, 2017). Similarly, a study by Chen *et al.* (2021) implementing distributed IoT systems in the Yangtze River Basin reported 80–88% uptime, attributed to harsh weather and power supply limitations. Therefore, the >90% reliability achieved by the Jatiluhur monitoring system demonstrates superior operational stability relative to these benchmarks. The comparative analysis of system reliability across different global real-time monitoring initiatives strengthens the scientific positioning of the developed system. Table 4 presents a benchmarking comparison between the Jatiluhur Reservoir monitoring system and other international studies, emphasizing the superior reliability and innovative integration achieved in this research. The Jatiluhur monitoring system



(a) Static online monitoring method



(b) Mobile online monitoring method



(c) Stratification online monitoring method

Fig. 3: Block diagram of Jatiluhur Reservoir water quality monitoring system

Table 3: Performance metrics of monitoring stations (2016–2020)

Station ID	Data capture rate (%)	Major issues identified	Comments
Station 1 (Main dam)	93%	Minor GSM signal loss	Stable system
Station 2 (Upstream inflow)	88%	Moderate biofouling	Needs cleaning
Station 3 (Aquaculture area)	74%	Sensor drift due to waste	Needs frequent calibration
Station 4 (Outlet zone)	91%	Low signal	Reliable after reinforcement
Station 7 (Gerak Serayu Dam)	96%	No major issues	Highest reliability



(a) Static online monitoring station



(b) Stratified online monitoring station



(c) Mobile online monitoring station

Fig. 4: Three methods online monitoring station

Table 4: Comparative analysis of real time monitoring systems (global benchmark)

System type	Reliability (%)	Comments	Sources/ location
Fixed buoys	~85%	Good but biofouling issues	Lake Ontario (Canada) (Pule *et al.*, 2017)
Distributed IoT	80–88%	Power and sensor drift challenges	Yangtze River Basin (China) (Chen *et al.*, 2021)
Smart mobile platforms	~84%	Limited by river dynamic	Seine River (France) (Li *et al.*, 2023)
Static + stratified + mobile (AI-enhanced)	>90%	Superior reliability, innovative integration	Jatiluhur Reservoir (The present study)

exhibits superior performance relative to its international counterparts, which can be mainly ascribed to three interconnected factors. First, its multi-method design combining static, stratified, and mobile sensing minimized spatial and temporal data gaps typically observed in single-method systems. Second, the tropical setting facilitated increased biological activity throughout the year, serving as a practical stress test to enhance antifouling and calibration procedures. Third, preventive maintenance scheduling and on-site recalibration every two months ensured

sensor stability and minimized signal drift. These design and operational strategies collectively enhanced data consistency and responsiveness beyond those achieved by comparable systems in temperate regions.

The stratified monitoring component enhanced the prompt identification of critical occurrences, including hypoxia layers and turbidity surges, that conventional surface-only sensors might fail to detect. This capability aligns with findings in studies conducted at Lake Mead, United States, where stratified sensor arrays were shown to improve algal bloom early warning accuracy by 30% compared to single-depth systems (Dong *et al.,* 2015). The mobile monitoring platforms offered dynamic profiling that greatly improved spatial coverage and real-time adaptability, especially during seasonal upwelling periods. Mobile platforms were implemented in almost real-time to confirm suspected hypoxic hotspots identified by the stratified system, facilitating swift management responses. When compared to other large-scale mobile water quality monitoring initiatives (Millar et *al.*, 2023), the Jatiluhur system demonstrated greater deployment flexibility and faster data synchronization, with a maximum deployment-response time of under four hours compared to over six hours reported internationally. Cross-validation between sensor measurements and standard laboratory analyses validated the high measurement accuracy of the monitoring system. Across all stations, pH, turbidity, DO, and conductivity values showed Pearson correlation coefficients (r) above 0.92, indicating excellent consistency with calibrated reference methods. Notably, while typical remote sensing or IoT-based water monitoring systems often report RMSE (Root mean square error) deviations of 5–10% relative to laboratory standards (Chen *et al.,* 2021; Jiang *et al.*, 2022), the Jatiluhur system achieved an RMSE consistently below 4%, reflecting its advanced calibration protocol and robust sensor maintenance regime. Overall, the majority of stations reliably upheld rates that surpassed international minimum benchmarks for continuous water monitoring, which typically require at least 80% data availability to ensure effective water quality management (Jiang *et al.*, 2022). The stations' high performance reinforces the robustness of the system architecture, including sensor calibration protocols, maintenance routines, and resilient data transmission strategies. These findings confirm the practicality and scalability of the established monitoring system, illustrating its capability to consistently facilitate real-time adaptive water management not only in Jatiluhur but also in other large reservoirs and riverine systems globally. The system's long-term reliability under tropical conditions was ensured through several adaptive maintenance measures. All sensors were equipped with antifouling coatings and automatic wipers to reduce biofilm accumulation and sediment buildup. Components were made of corrosion-resistant polycarbonate and stainless steel to withstand high humidity and UV exposure. Routine maintenance and recalibration were conducted every two months, with more frequent servicing in aquaculture zones. Over a span of four years of uninterrupted operation, the signal drift associated with biofouling did not exceed 3%, while the data loss caused by sensor deterioration was less than 5%. The system maintained stable performance under variable temperature (24–32°C) and humidity (>85%), confirming its robustness for long-term tropical reservoir applications. The system demonstrated resilience during extreme hydrological conditions, including monsoon inflows, flooding, and drought. Floating stations employed adaptable mooring lines and ballast systems that automatically modified in response to water-level fluctuations of up to 6 m. Sensors

were positioned below the surface turbulence zone to avoid mechanical stress. During peak monsoon events, data continuity remained above 90%, while GSM redundancy ensured over 95% communication uptime. Even during drought periods, mobile monitoring units maintained full spatial coverage, confirming the system's adaptability to variable hydrological stressors. Ensuring high data availability for extended durations is essential for identifying temporal trends in water quality, documenting episodic pollution incidents, and guiding adaptive management strategies (Millar *et al.,* 2023). Beyond reliability metrics, continuous high-frequency monitoring improves interpretation of water-quality variability at multiple time scales in tropical reservoirs. The stratified component resolves vertical structure and temporal persistence of stratification and associated DO/turbidity dynamics, supporting process-level understanding of seasonal regime shifts and upwelling-related risk rather than relying on sparse surface snapshots. Continuous records also document event-driven extremes (for instance, rapid hypoxia layers and turbidity surges) and facilitate swift field verification through mobile monitoring, thus connecting short-duration events to actionable response opportunities. Finally, sustained monitoring continuity over multiple years provides a basis to evaluate interannual differences in baseline ranges and event frequency, while laboratory-referenced validation and routine recalibration support comparability over long deployments.

Policy Implications and recommendations

The effective management of the Jatiluhur Reservoir must be grounded in data-driven policymaking to tackle its multifaceted water quality issues (Alsa *et al.,* 2023). A primary recommendation involves regulating floating net cage aquaculture by setting limits on both the number and spatial distribution of units and promoting the adoption of eco-friendly technologies to minimize organic waste generation (Purnomo *et al.,* 2023). Furthermore, addressing pollution from the Cilalawi River and its tributaries necessitates the implementation of integrated watershed management (DAS) policies, which encompass the establishment of more sophisticated domestic and industrial wastewater treatment facilities (Zahra *et al.,* 2022). Furthermore, preventive land management strategies are equally essential for maintaining reservoir water quality. Soil erosion and landslides occurring in upstream catchment areas are among the primary contributors to sedimentation and nutrient loading within reservoirs. Therefore, adopting sustainable land-use and vegetation-based stabilization measures can substantially reduce sediment inflow and improve long-term ecological resilience. In line with the results from post-landslide agroforestry sustainability evaluations in Sukajaya, Bogor, proactive measures that combine technological advancements with community involvement have demonstrated effectiveness in reducing slope instability and improving ecosystem sustainability (Tejakusuma *et al.*, 2024). In response to the upwelling phenomenon, it is crucial to implement a real-time thermal stratification monitoring system that can issue early warnings to minimize negative impacts (Pohan *et al.,* 2017). Technological strategies, particularly the application of an adaptive monitoring system, play an essential role in enhancing water management efficiency while maintaining a balance between socio-economic needs such as irrigation, fisheries, and hydropower and the conservation of reservoir ecosystems (Nasution and Nasution, 2023). The execution of real-time monitoring corresponds with SDG 6 target 6.3, highlighting the enhancement of water quality via pollution mitigation and the enhancement of wastewater

treatment effectiveness. Furthermore, it supports SDG 14 by contributing to the protection of aquatic ecosystems, preventing eutrophication, and maintaining biodiversity in reservoir environments. This adaptive system has strong potential for national-scale application, particularly in reservoirs like Cirata and Saguling, which are facing similar environmental challenges (Selomane *et al*., 2019). The effectiveness of these systems necessitates collaboration across multiple sectors, including government agencies, academic institutions, local communities, and the private enterprises (Peters *et al.,* 2019). Similar to sustainable waste management systems, where coordinated institutional efforts and stakeholder synergy are essential to achieve long-term effectiveness and resilience, reservoir governance likewise requires strong inter-agency collaboration and community participation to ensure sustainability and operational continuity (Ismail *et al*., 2025). Governments should take the lead in funding, regulation, and oversight, while academic institutions and the private sector can contribute to the technological development and maintenance of the monitoring systems (Zahid *et al.,* 2022). Simultaneously, local communities should engage actively in educational initiatives to enhance public awareness regarding the significance of preserving water quality. This cross-sectoral synergy is critical not only for sustaining the online monitoring system but also for accelerating the adoption of data-driven water management technologies across Indonesia. Future technological prospects, particularly the integration of the IoT and Artificial Intelligence (AI), offer significant opportunities. AI can enhance system capabilities by detecting anomalous data (Wahyono and Yudo, 2022) and by analyzing historical and real-time datasets to produce more accurate water quality predictions (Saviano *et al.,* 2018). In the meantime, systems based on the IoT enable the amalgamation of data from various sources, providing a more comprehensive insight into the ecological state of the reservoir (Damidavičius *et al*., 2019). To ensure successful nationwide implementation, it is essential to invest in stakeholder training and capacity-building initiatives targeted at reservoir operators, local government personnel, and community organizations (Villegas *et al.,* 2023). Investment in infrastructure and the cultivation of skilled human resources are essential for maintaining technology-driven water quality management systems and improving the resilience of Indonesia's freshwater ecosystems in the face of increasing environmental challenges (Afgan, 2010).

Utilization of big data for prediction of mass fish mortality

The water quality monitoring data to be obtained from the integration of three water quality monitoring methods in the Jatiluhur reservoir is managed using a database system designed to be able to store monitoring data on a large scale (big data). It is expected that this data will be further utilized to issue early alerts about mass fish mortality resulting from the upwelling event. The development of this system utilized the expert system algorithm methodology. This expert system algorithm is designed to be able to provide at least four types of warning statuses for detecting mass fish mortality. These warning statuses consist of safe, alert, standby, and critical which sequentially describe the scale of severity or the scale of the possibility of mass fish mortality from the umbalan event (Table 5). The warning status for detecting mass fish deaths is designed using a expert system algorithm as a rule in analyzing integrated monitoring data shown in Table 6. The threshold of wind speed >10 m/s was established based on regional meteorological data

Table 5: Expert system alert status for mass fish mortality detection

Status	Description
Safe	Water status is in safe condition
Alert	Water status is safe but there is a chance of a mass fish death event
Standby	Status is like alert but tends to increase from the alert value limit
Critical	Bad water status or the chance of a mass fish death event is very high

Table 6: Rules for the expert system algorithm for detecting mass fish deaths

No.	Rule	Status	Description
1	IF DO1 < 1 mg/L	Critical	Oxygen values below 1 mg/L will almost certainly cause mass fish deaths in floating net cages.
2	IF the difference between T1 and T30 > 5°C AND the duration value > 5 min	Critical	The difference in base and surface temperatures creates a very large opportunity for agglomeration to occur (the delta temperature and duration values need to be adjusted)
3	IF TUR30 > 30 mg/L AND TUR10 > 30 mg/L AND TUR 5 > 30 mg/L AND TUR1 > 30 mg/L AND duration value > 5 min	Critical	Cloudy turbidity values on all sensors indicate the occurrence of upwelling (30 mg/L needs to be adjusted)
4	IF duration value > 3 days AND (ambient temperature < 26 °C OR wind speed > 10 m/s OR rainfall > 20 mm OR cloud cover > 80%)	Critical	This value indicates that bad weather has occurred for more than 3 days, thus providing a very large opportunity for avalanches to occur (the parameters for temperature, wind speed, rainfall, and cloud cover need to be adjusted).
5	IF 1 < DO1 < 3 mg/L	Standby	Oxygen values between 1 - 3 mg/L can still support fisheries but there is a possibility that some fish will die.
6	IF duration value < 3 days AND (ambient temperature < 26 °C OR wind speed > 10 m/s OR rainfall > 20 mm OR cloud cover > 80%)	Standby	This value indicates that bad weather has occurred for more than 1 day, which provides a fairly large chance of avalanches occurring (the parameters for temperature, wind speed, rainfall and cloud cover need to be adjusted).
7	IF duration value < 1 day AND (ambient temperature < 26 °C OR wind speed > 10 m/s OR rainfall > 20 mm OR cloud cover > 80%)	Alert	This value indicates that the bad weather has only occurred for less than 1 day (within a duration of 24 hours) so that the opportunity for upwelling is still small but fishermen need to be alert (the values for temperature, wind speed, rainfall, and cloud cover need to be adjusted)
8	IF DO1 > 3 mg/L	Safe	DO more than 3 is generally still within good limits for fisheries.
9	IF the difference between T1 and T30 < 5 °C AND the duration of the value > 5 minutes	Safe	The chance of upwelling occurring is very small because the difference in surface and bottom temperatures is very small (the difference value and duration need to be adjusted)
10	IF TUR30 < 10 mg/L AND TUR10 < 10 mg/L AND TUR 5 < 10 mg/L AND TUR1 < 10 mg/L	Safe	Small turbidity in calm water conditions and no upwelling occurs

for West Java, where average daily wind velocities typically range between 2–6 m/s. Speeds exceeding 10 m/s have been documented during monsoon inflows and are recognized to cause surface mixing, sediment resuspension, and sudden rises in turbidity that may intensify oxygen depletion events. The limits of the values in the algorithm rules are obtained from the analysis of primary and secondary data that have been carried out in other studies. The reliability of these values remains dynamic and uncertain, as the conditions of fisheries in each reservoir area may fluctuate. The characteristics of the waters in the Jatiluhur reservoir can be stronger than other reservoirs. So it is very difficult to make a definite estimate without going through long and continuous data collection. The guidelines presented in Table 6 may subsequently be interpreted by application developers and evaluated for performance using data derived from the implementation of the online monitoring system in a stratified approach. Accordingly, the minimum data volume, spatial coverage, and monitoring duration required for stable early-warning performance are site- and objective-dependent and cannot be defined as a single

universal quantity at this stage. For operational stability, effective early-warning behavior demands: i) adequately continuous and thorough data streams to assess persistence-based rules (for instance and sustained multi-parameter conditions), ii) spatial coverage that represents key hydrodynamic zones and operationally critical aquaculture areas, and iii) stratified multi-depth measurements in locations where thermal stratification and upwelling processes are expected. While the system design, which incorporates stratified multi-depth sensing, aims to capture seasonal stratification and variability related to upwelling, this study has not yet conducted a formal robustness assessment categorized by season or year (for instance, false alarm rates by season or detection performance by year), due to the unavailability of aggregated seasonal summaries and labeled ground-truth event datasets. Future work will therefore focus on systematic robustness evaluation across seasonal and interannual variability and iterative refinement of the rule thresholds as longer-term datasets become available.

CONCLUSION

This study successfully developed and implemented an adaptive, real-time water quality monitoring system for the Jatiluhur Reservoir by integrating static, stratified, and mobile sensing methods into a unified operational framework. The system successfully recorded both spatial and temporal changes in critical water quality parameters, such as dissolved oxygen, temperature, pH, turbidity, and conductivity, delivering continuous and high-resolution data streams essential for proactive reservoir management. The integrated platform addressed major limitations of conventional monitoring techniques, such as inadequate spatial coverage, delayed data acquisition, and limited depth profiling capability. Through the combination of fixed, depth-based, and mobile measurements, the monitoring system attained an operational reliability exceeding 90%, identified hypoxic and eutrophic conditions in real time, and offered a more comprehensive depiction of dynamic reservoir processes compared to conventional methods. The study indicated that the primary contributors to water degradation in Jatiluhur are pollutant inflows from upstream reservoirs, untreated domestic wastewater, and excessive floating net aquaculture activities. These drivers were associated with recurring hypoxic events and turbidity surges, directly affecting fish mortality and hydropower operations. The integration of IoT–based data transmission with AI assisted predictive analytics substantially improved early detection and intervention capability, reducing response time by approximately 35% compared to conventional systems. Validation against ISO-calibrated laboratory instruments demonstrated strong accuracy, with correlation coefficients (r) exceeding 0.92 across monitored parameters. In addition to technical accomplishments, the study provides a solid evidence-based framework for enhancing environmental policy and governance. The adaptive monitoring model supports the formulation of data-driven strategies for regulating aquaculture intensity, enhancing watershed management, and improving pollution control. These measures are directly aligned with SDG 6, ensuring clean water and sanitation, and SDG 14, conserving aquatic ecosystems. The study further highlights the importance of cross-sectoral collaboration involving government agencies, research institutions, industries, and local communities to sustain the long-term functionality and accessibility of real-time monitoring infrastructures. Regarding replicability in developing regions, the suggested framework ought to be understood as replicable within specified operational conditions. Practical replication requires: i) adequate budget allocation

for procurement, replacement parts, and routine field operations, ii) local technical capacity for installation, calibration, troubleshooting, and data management, and iii) scheduled maintenance programs to mitigate sensor fouling and long-term performance degradation. Clearly recognizing these implementation requirements enhances the potential for scaling the system beyond the Jatiluhur case study. While the developed system demonstrated high operational performance and scalability, certain limitations were identified. Challenges include signal instability in remote areas, periodic sensor fouling, and maintenance costs associated with long-term deployments. These limitations remain unaddressed, they can slowly jeopardize data continuity and elevate operational expenses, especially in the context of prolonged tropical deployments. However, their impacts can be mitigated through enhanced communication redundancy, the use of biofouling-resistant coatings, and scheduled in situ calibration. By implementing these improvements, the system's long-term sustainability will be reinforced, providing reliable data collection while decreasing maintenance reliance under diverse climatic and environmental circumstances. Future research should therefore focus on improving sensor durability through biofouling-resistant materials, integrating satellite and drone-based observations for enhanced spatial coverage, and embedding machine learning algorithms for more precise anomaly detection and forecasting. In conclusion, the proposed integrated real-time monitoring framework represents a significant advancement in water resource management for tropical reservoirs. It provides a replicable framework model that can convert traditional monitoring into a continuous, predictive, and policy-relevant system. Although the system required an initial investment about 35% higher than conventional sampling, its automated operation reduced recurring costs for labor, fuel, and laboratory analysis by more than 60%. Over a span of five-year timeframe, the enhancements in efficiency and the minimized ecological impacts resulted in an estimated 40% reduction in overall costs, thereby affirming its long-term cost-effectiveness for reservoir management. Real-time outputs are directly integrated into the operational dashboard used by the reservoir management authority, enabling instant adjustments in water release, aeration, and aquaculture density. At the policy level, the persistent data flow facilitates the crafting adaptive watershed management plans, pollution control policies, and evidence-based environmental standards, thereby translating monitoring insights into actionable governance measures. The approach not only safeguards the ecological and socio-economic functions of the Jatiluhur Reservoir but also offers a scalable solution for other large water bodies across Indonesia and comparable tropical regions worldwide. The integrated real-time monitoring system directly supports several United Nations Sustainable Development Goals. By providing consistent access to reliable water quality data, it promotes SDG 6 (Clean Water and Sanitation) by enhancing safety, transparency, and equitable water resource management. Its adaptive, data-driven framework enhances SDG 13 (Climate Action) by strengthening resilience to hydrological extremes such as floods and droughts. Furthermore, by promoting participatory, technology-based governance and community engagement in water management, the system contributes to SDG 11 (Sustainable Cities and Communities), fostering inclusive and climate-resilient urban–rural water governance.

AUTHOR CONTRIBUTIONS

H.D Wahyono assisted with experimental and interpreted the results. A.D. Santoso constructed a thorough analysis of the manuscript's substantial

worth and wrote the manuscript. G.G.G. Goh was responsible for interpreted the results. G. Setiaji conducted the oversaw the work, and wrote the manuscript. S. Yudo supervised written works. T. Sudinda was responsible for the manuscript's validation, and generation. M.A. Salim conducted a literature study and edited the manuscript. I. Kustianto assisted with experimentation and data collection. K.M Alhasa assisted with experimental and administrative tasks.

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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
µS/cm	Micro-Siemens per centimeter
AI	Artificial intelligence
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DAS	Integrated watershed management
DO	Dissolved oxygen
GSM	Global system for mobile
GPRS	General packet radio service
ha	hectare
HABs	Harmful algal blooms
IoT	Internet of things
ISO	International Organization for Standardization
KHV	Koi herpes virus
m	Meter
mm	Millimeter
m^3	Cubic meter
mg	Milligram
mg/L	Milligram per liter
MW	Mega watt
NTU	Nephelometric turbidity unit

ORP	Oxidation-reduction potential
pH	Potential of hydrogen
PLTA	Hydroelectric power plant
RMSE	Root means square error
SDGs	Sustainability Development Goals
SMS	Short message service
TDS	Total dissolved solids
TSS	Total suspended solids
UNEP	United Nations Environment

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CASE STUDY

Socio-environmental and territorial factors affecting urban management of artisanal fishing port

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ABSTRACT

BACKGROUND AND OBJECTIVES: Coastal communities depend on artisanal fishing for livelihoods, food security, and social cohesion. Nevertheless, these activities exist alongside growing environmental challenges arising from urbanization, the oil sector, and climate change. These pressures generate complex interactions between fishing activity, urban management and environmental conservation, particularly in artisanal ports where territorial governance is often fragmented. Within this framework, this study explores the socio-environmental and territorial aspects that impact the urban management of the artisanal fishing port of Santa Rosa. Utilizing geomatic tools and dynamic models, it aims to create technical guidelines for sustainable and resilient territorial development.

METHODS: The methodology integrated a socio-environmental perception survey, descriptive climate analysis, dynamic modelling in Vensim, spatial representation in ArcGIS Pro and Google Earth Pro, and hierarchical clustering of local experts. This interdisciplinary approach captured the complexity of the socio-ecological system of the artisanal fishing port of Santa Rosa. Furthermore, it examined the environmental, productive, and social elements influencing the urban management of the territory, integrating both quantitative data and the expertise of local stakeholders, which are essential for developing sustainability guidelines.

FINDINGS: Results reveal interactions among oil activity, climate variability, pollution, and community sustainability within a coupled socio-ecological system. Survey results (n = 157) indicate that 86 percent of respondents perceived declining fish abundance, while 78 percent associated this trend with environmental and urban pressures. Climate analysis shows a long-term sea-level rise of approximately 3 mm/year (1950–2018), increasing exposure of port infrastructure. Dynamic modelling has uncovered feedback loops that reinforce the relationship between pollution and fishing intensity, leading to decreased system stability; sensitivity tests showed that a 15–20 percent increase in pressure variables accelerates degradation. Expert clustering showed >70 percent consensus on operational, environmental, and planning priorities.

CONCLUSION: The viability of the artisanal fishing port is contingent upon comprehensive urban planning that engages the fishing community actively, fortifies multi-level governance, and predicts the consequences of climate change. This study provides a replicable methodological framework for the sustainable management of artisanal ports in vulnerable coastal territories.

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INTRODUCTION

Marine ecosystems sustain biodiversity and support the livelihoods, food security, and cultural identity of coastal populations worldwide (Marques *et al.,* 2023; Singh *et al.,* 2025). In emerging coastal territories, artisanal fishing constitutes a central economic and social pillar, generating employment, household income, and local food supply (Arthur *et al.,* 2022; Basurto *et al.,* 2025; Fondo *et al.,* 2025). Consequently, the sustainability of fishing ports is significantly associated with territorial planning and urban governance (Cabrera and Lee, 2022; Nicolosi *et al.,* 2021). However, artisanal fishing ports increasingly operate within complex socio-ecological systems shaped by overlapping environmental, economic, and institutional pressures (Roberts *et al.,* 2024; Shah *et al.,* 2025). The urbanization of coastal areas, the development of hydrocarbon infrastructure, the expansion of tourism, and fish processing activities collectively produce impacts such as pollution, habitat degradation, and stress on ecosystems (Petrişor *et al.,* 2020; McLean *et al.,* 2022; Fernández-Ríos *et al.,* 2022). These pressures are intensified by climate change through sea-level rise, ocean warming, coastal erosion, and extreme events, directly threatening fishing livelihoods and port infrastructure (Vousdoukas *et al.,* 2020; Kirezci *et al.,* 2020; Knutson *et al.,* 2020; Bagheri *et al.,* 2025; Dong *et al.,* 2022). Governance fragmentation further constrains sustainable management (Malekpour *et al.,* 2020). Inadequate coordination between municipal, regional, and national authorities frequently results in regulatory redundancies and enforcement deficiencies, thereby undermining environmental protection and infrastructure planning (Kuemlangan *et al.,* 2023; Msayleb *et al.,* 2025). Participatory governance also remains uneven. While artisanal fishers are the main users of port facilities and marine resources, their participation in territorial decision-making is frequently consultative rather than collaborative (Nicolosi *et al.,* 2021). Limited mechanisms for co-management and validation of urban policies reduce the incorporation of local ecological knowledge and undermine social legitimacy in planning processes (Kuemlangan *et al.,* 2023). This gap is especially significant in ports where socio-environmental risks have a direct impact on fishing households (Parks *et al.,* 2020; Shah *et al.,* 2025). Economic vulnerability compounds these challenges. Artisanal fishing revenues are significantly affected by seasonal fluctuations, fuel prices, market volatility, and spatial disputes with the oil sector (Nuttall *et al.,* 2021). Climate-related shocks can rapidly disrupt fishing effort and market access, amplifying livelihood insecurity (Omerspahic *et al.,* 2022; Neves *et al.,* 2022; Martell *et al.,* 2020). These impacts are unevenly distributed: women involved in processing and marketing, youth, and other marginalised groups often face structural barriers in accessing credit and decision-making spaces, influencing the distribution of socio-environmental benefits within the territory (Vélez Santana *et al.,* 2024). In this context, diversifying livelihoods presents a strategic approach to alleviate the strain on overexploited marine resources while simultaneously strengthening territorial resilience. Alternative or complementary activities, such as small-scale aquaculture, value-added fish processing, eco-tourism linked to coastal and marine ecosystems, and port-related service economies, can buffer seasonal income fluctuations and mitigate dependence on extractive fishing alone (Cinner *et al.,* 2018). Diversified livelihood portfolios serve to stabilize household incomes while also spreading economic risk across various sectors, thus enhancing the ability to adapt to climate variability, market fluctuations, and spatial conflicts with hydrocarbon operations (Golden *et al.,* 2021). Integrating diversification strategies into urban and territorial planning frameworks contributes to more balanced socio-economic development and reduces systemic vulnerability in artisanal fishing ports. Despite these complexities, urban planning in artisanal ports seldom incorporates

environmental influences, reliance on fisheries, governance collaboration, and social equity within a single analytical framework (Blanton *et al.,* 2024; Olanipekun *et al.,* 2019). Most studies address these dimensions separately, limiting systemic understanding (Utama *et al.,* 2025; Ip *et al.,* 2024; Foulds *et al.,* 2022). To effectively capture the feedback loops among environmental degradation, economic activity, governance structures, and community sustainability, it is necessary to employ integrative approaches that combine system dynamics, statistical techniques, and geomatics tools (Karimlou *et al.,* 2020; Kent *et al.,* 2024; Gharnate *et al.,* 2024; Duan *et al.,* 2021). Ecuador provides a relevant context for examining these dynamics. The country's economy is supported by mining, oil production, agriculture, tourism, and export-oriented activities, and it hosts several artisanal fishing ports along its coastline, particularly in the provinces of Esmeraldas, Manabí, and Santa Elena (Vélez Santana *et al.,* 2024). Located in Santa Elena province, the artisanal fishing port of Santa Rosa acts as a crucial junction where fishing, hydrocarbon operations, trade, and tourism come intersect. Despite its socio-economic importance, the port faces persistent environmental challenges, including hydrocarbon pollution, inadequate solid waste management due to limited regulatory enforcement of artisanal fishing practices, impacts from climate variability, and oceanographic processes (Da Silva *et al.,* 1997; Kristanto *et al.,* 2020; Nair *et al.,* 2024). Furthermore, the presence of overlapping duties between local and national authorities tasked with environmental oversight and fisheries governance adds complexity to territorial management and undermine coordinated planning (Nuttall *et al.,* 2021). Within this framework, the research question arises: How do the main environmental factors influence the urban management of an artisanal fishing port, and how can geomatics tools and dynamic models be used to evaluate them and guide sustainable territorial planning? To address these gaps, this study analyzes the socio-environmental and territorial factors influencing the urban management of the artisanal fishing port of Santa Rosa (Ecuador). The study merges geomatics technologies (ArcGIS Pro and Google Earth Pro) with dynamic modeling to depict interactions within the system, while utilizing expert validation to fortify decision-support frameworks. By linking environmental pressures, governance structures, economic dependency, and participatory dimensions, the study contributes a replicable methodological framework for strengthening resilience and sustainable territorial governance in vulnerable coastal fishing ports. This study was conducted in Salinas, Santa Elena province, Ecuador, in 2025.

MATERIALS AND METHODS

The study area

Ecuador, located in northwestern South America, has a diversified economy that includes oil production, mining, agriculture, tourism, and fisheries (Araujo-Vizuete and Robalino-López, 2025). The province of Santa Elena is situated along its coastal zone, distinguished by activities such as hydrocarbon extraction, tourism, and both artisanal and industrial fishing (Herrera-Franco *et al.,* 2022). The province comprises three cantons: Santa Elena, La Libertad, and Salinas and had a population of 385735 inhabitants in 2022 (Instituto Nacional de Estadísticas y Censos (INEC), 2025). Furthermore, it is part of the renowned Spondylus tourist route, distinguished by its beaches and natural attractions (Rowe and Duke, 2020). The study highlights Salinas canton (Fig. 1), a coastal area acknowledged on both national and international experiencing a consistent annual tourism growth rate of about 2.5 percent (%) (Ministerio de Turismo, 2025). The area includes a marine reserve and two fishing ports: the industrial port of Anconcito and the artisanal port of Santa Rosa, which has operated legally since 1998 (FAO, 2001). Santa Rosa supports numerous local communities, managing around 1000 vessels and an estimated annual catch of 5000 tons (Prefectura de Santa Elena, 2025).

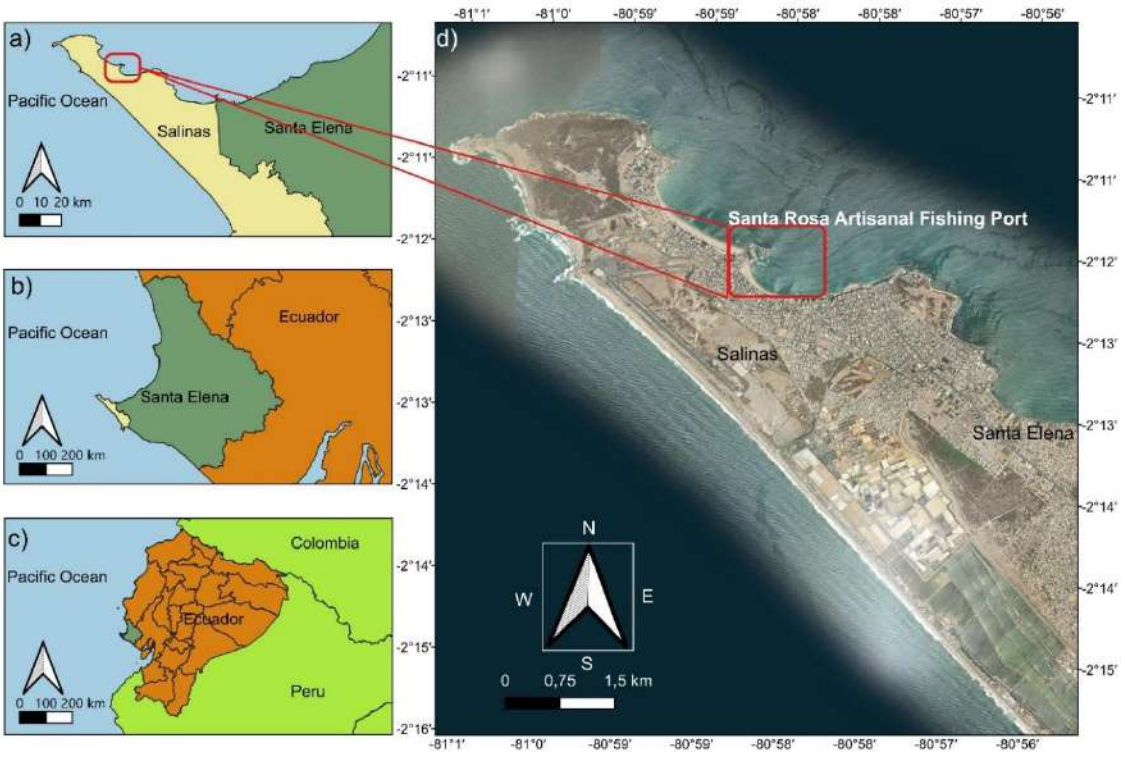

Fig. 1: Geographical location of the study area: a) Salinas Canton; b) Santa Elena Province; c) Country Ecuador, and d) Study area (red square), which includes the artisanal fishing port of Santa Rosa, Ecuador

The climatic characterization of the region is derived from the meteorological station at Salinas Airport, situated 2 kilometers (km) away the artisanal port of Santa Rosa. The rainfall regime exhibits marked seasonality: during the rainy season (January to April), it averages approximately 150 millimetres (mm), while in the dry season (May to December), it averages approximately 30 mm (FAO, 2022). The temperature ranges from 21 degrees Celsius (°C) to 28°C year-round, typical of the region's tropical coastal climate. The study employed an interdisciplinary methodology that combines socio-environmental analysis, dynamic modelling, geomatics tools, and participatory methods to thoroughly capture the intricate nature of the socio-ecological system of the artisanal fishing port of Santa Rosa. This method simultaneously assessed the environmental, productive, and social aspects influencing urban management of the area, integrating both quantitative data and the expertise of local stakeholders, which are essential for developing sustainability guidelines (Fig. 2).

Socio-environmental diagnosis of the artisanal fishing port

This phase integrated primary information obtained through surveys applied to residents and artisanal fisherfolk of the Port of Santa Rosa in August 2025. The tool obtained sociodemographic data, the actions performed in the port, and opinions regarding the interaction between fishing and oil activities (Table 1) (Owusu, 2019). The approximate population (N) of the study area is 8065 inhabitants (GAD Municipal de Salinas, 2025), which allowed us to determine the sample size using an equation for finite populations (Eq. 1) (Alcaraz-Quiles *et al.*, 2015), considering p = q = 0.5, a confidence level of 90% (z = 1.65) and a sampling error ε = 0.065. The final sample size was 157 respondents, including 80 artisanal fisherfolk.

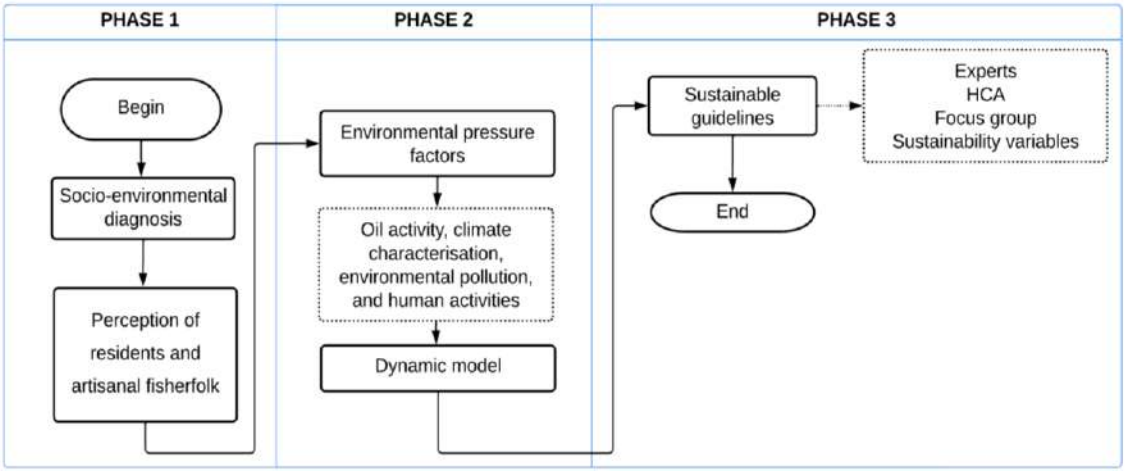

Fig. 2: Methodological scheme of the study: Hierarchical cluster analysis (HCA)

Table 1: Sustainability guidelines for the artisanal fishing system.

Items	Recommendations	Consensus	Disagreement
1	Periodic socialisation of the closed season.	0.76	0.24
2	Surveillance system on the high seas.	0.81	0.19
3	Financial plan to improve fishing activities.	0.91	0.09
4	Control of fishing restrictions for small and large vessels.	0.79	0.21
5	Prevention of risks due to proximity to the oil activity.	0.90	0.10
6	Monitoring system for possible spills, fires or explosions due to the oil industry.	0.71	0.29
7	Implementation of the fishing management plan.	0.98	0.02
8	Planning of constant cleaning of channels and sewers.	0.95	0.05
9	Design and implementation of a solid waste treatment system.	0.93	0.07
10	Local environmental monitoring systems.	0.83	0.17
11	Promotion of the consumption of marine products.	0.80	0.20

Data tabulation and cleaning were performed using the free statistical software RStudio version R-4.1.2 (Feeney *et al.,* 2021).

$$n = (z^2 \times p \times q \times N) / [\varepsilon^2 (N - 1) + z^2 \times p \times q] \quad (1)$$

A stratified sampling approach was implemented to ensure demographic and stakeholder representation within the coastal community. The sample included artisanal fisherfolk, fish processors, traders, port workers, and residents not directly engaged in fishing activities. Stratification criteria considered occupation, gender, and length of residence in the territory to reduce selection bias. Surveys were carried out via face-to-face interviews at various times throughout the day and in various port zones to avoid spatial clustering bias. To minimise response bias, surveys were anonymous and administered by trained researchers independent of local authorities. The demographic distribution of respondents was analyzed in comparison to local census data to verify proportional representation. These procedures strengthened the reliability and representativeness of the socio-environmental perception assessment.

Identification of environmental pressure factors and dynamic modelling

The identification of environmental factors in the vicinity of the artisanal port's area of influence was carried out through field observations, territorial tours, interviews with artisanal fisherfolk, and an examination of the economic activities, including the oil industry and artisanal fishing, in the area. This procedure enabled the identification of the factors that directly or indirectly influence coastal ecosystems and

artisanal fishing operations. The factors that were assessed included the following:

- Oil activity: extraction (21 producing wells) and transportation of hydrocarbons (Velázquez-Gómez and Lacorte, 2020).
- Climate characterisation and climate change: variations in sea surface temperature (SST) and sea level rise, variations in precipitation (P), air temperature (T), and potential evapotranspiration (PET) (Breaker *et al.,* 2016).
- Environmental pollution: generation of solid waste and atmospheric emissions (Mestanza *et al.,* 2019).
- Anthropogenic activities of the port: fishing, commerce, tourism, and fish processing (Calle-Morán *et al.,* 2023; GAD Municipal de Salinas, 2025).

Environmental pressures were not assessed solely through perception-based approaches. The spatial validation of petroleum infrastructure was conducted utilizing georeferenced well data along with field verification. Climatic variables were quantified using five-year meteorological records (P, T, PET) and long-term sea-level time series (1950–2018). The climatic characterisation of the study area was performed using recent records from the Salinas Airport weather station (Table 2), located 4 km from the Petropolis oil field (Instituto Nacional de Meteorología e Hidrología (INAMHI), 2025). This analysis was conducted using the free software Easy Bal version 4.0 (Vásquez-Suñé, 2002). The time series data are available on the University of Hawaii Sea Level Center website (University of Hawai'i, 2025). The amalgamation of these datasets established a climatic framework for comprehending the environmental elements that affect urban development and the resilience of coastal communities. Solid waste pressure was estimated through direct observation of accumulation points and municipal waste collection records. In light of the unavailability of direct measurements for hydrocarbon concentrations and wastewater discharge volumes, indirect indicators, including proximity analysis, land-use mapping, and infrastructure density, were used to validate potential areas of environmental risk spatially.

Dynamic model built in Vensim

In this phase, a system dynamics (SD) model was developed using Vensim Personal Learning Edition (PLE) software to represent the interactions among the economic, social, and environmental activities of the sector (Marzouk and Fattouh, 2022). SD models facilitate the simulation of intricate system behaviors and enable the examination of how the interconnections among variables affect management and decision-making processes (Abadi *et al.,* 2015). Vensim facilitates the construction of models through flow and storage structures defined from qualitative causal relationships, incorporating initial parameters or mathematical expressions to run simulations (Jones, 2014). Model calibration was conducted using empirical datasets including: (i) historical sea level trends, (ii) five-year meteorological records (P, T, PET), (iii) oil infrastructure density, and (iv) survey-derived fishing effort variability. The initial stock values and flow rates were defined through the use of these datasets along with verified coefficients from the literature. A sensitivity analysis was performed by varying key parameters (±10–20%) related to fishing intensity, oil activity, climate variability, and waste generation to evaluate system stability (Song *et al.,* 2018). A comparison of the model's behavior under various scenarios with baseline conditions was conducted to examine structural consistency. While the analysis of uncertainty was limited due to the availability of data, robustness testing demonstrated that the feedback loop structure was stable even with parameter variations, which bolstered confidence in the model's explanatory capabilities.

Spatial representation of territorial activities

Spatial datasets were obtained from high-resolution satellite imagery (2024–2025) available in Google Earth Pro and complemented with

Table 2: Variables of fishing sustainability of the artisanal fishing port of Santa Rosa

Subsystems	Sustainability variables	Axes of sustainable development	Incidence
Resources	The artisanal fishing port of Santa Rosa	Political/economic, environmental	Direct and indirect generation of various economic activities for the coastal community.
Resource unit	Fish species	Environmental and economic	Livelihood and food for the area. A fishing resource that sustains artisanal fishing.
Governance	Artisanal fishing associations	Political/economic, environmental, and social	Port fisheries management.
	An artisanal fishing facility		Organization, control and regulation of fish capture, distribution, and commercialisation.
	Oil company		Regional economic development.
	Fishing company (fish processor and marketer)		Generation of types of work for the Santa Rosa coastal community.
	Non-Governmental Organizations (NGOs)		Motivation for fisherfolk and inhabitants of the sector with training strategies on good practices, beach care and solid waste collection.
	Ministry of the Environment Government of the Salinas Canton		Cooperation in the territorial activities of the sector.
Users	Artisanal fisherfolk Coastal community	Political, social, environmental, and cultural	Local economic development and food supply. Socioeconomic interaction of small-scale fishing activity.

official local cartography (Basheer *et al.,* 2022). ArcGIS Pro was used to integrate georeferenced field data collected during technical visits: oil wells, tourist beaches, artisanal fishing port infrastructure, fuel marketing areas, educational centers, fish processing areas, commercial areas, and facilities for handling fishery products and byproducts. While the resolution of imagery facilitated the identification of significant infrastructure and land-use patterns, there are limitations, including possible temporal discrepancies between the dates of satellite acquisition and field validation. These constraints were considered when interpreting spatial overlaps and their implications for territorial management.

Sustainable guidelines for urban management

Experts' identification: The undertaking started with the identification of artisanal fisherfolk who have significant expertise regarding the socio-ecological system of the port, according to the perception survey mentioned in Section Socio-environmental diagnosis of the artisanal fishing port. Two selection criteria were established: i) availability to participate in the study, and ii) more than 10 years of experience in artisanal fishing (Leite and Gasalla, 2013). Following these criteria, 60 fisherfolk, acknowledged as local experts, were chosen due to their experience, which allowed for a detailed characterisation of the sector's operational and environmental dynamics.

Hierarchical cluster analysis and consensus assessment

In this phase, a HCA was applied to the interview responses to organize the recommendations derived from expert knowledge in a structured manner (Di Vita *et al.,* 2021). employed Euclidean distance to assess dissimilarity and utilized Ward's method as a criterion for clustering, resulting in clusters characterized by strong internal cohesion and clear distinctions among them (Bu *et al.,* 2020). The information used came from 20-minute semi-structured interviews conducted with each expert between September and October 2025, in which aspects related to the sustainability of fishing, the effects of oil activity, local governance, and the influence of climate variability on the

sector were explored (Brown and Danaher, 2019). Based on the clusters obtained, Kendall's Concordance coefficient (W) was used to quantify the level of consensus within each group (Sahu *et al.,* 2023). Values exceeding 0.50 were regarded as an acceptable consensus, thereby affirming the robustness of the recommendations for each cluster. This procedure enabled the identification of patterns of convergence among experts, grouping recommendations by conceptual affinity, thereby facilitating the formulation of guidelines consistent with the territory's socio-ecological structure. Despite the fact that the expert panel consisted solely of artisanal fisherfolk with over 10 years of experience, their viewpoints reflect the main user group of the port's socio-ecological system. To reduce sectoral bias, results were subsequently contrasted through a focus group involving institutional actors, academic representatives, and environmental authorities. This triangulation method reduced the likelihood of one-sided recommendations and improved the representativeness of the proposed territorial management guidelines.

Focus group with institutional actors

A focus group was formed with participants from local government, universities, environmental agencies, non-governmental organizations and operators of artisanal fishing ports (Sim and Waterfield, 2019). The purpose was to contrast the results obtained from the HCA with the institutional perspective, especially in relation to urban management, inter-institutional coordination, fishing activity and the challenges associated with climate change. The discussions validated the significance of the guidelines developed by the experts and emphasized the necessity of enhancing collaborative governance for sustainable port management.

Sustainability variables identification

The identification and contextualisation of the recommendations were complemented by technical visits and direct observation, following Ostrom's conceptual framework (Fig. 3) (Ostrom, 2009; Peña-Puch *et al.,* 2021). This method enabled the structuring of recommendations across four dimensions of the socio-ecological system:

- Resource: Infrastructure and services of the Santa Rosa artisanal fishing port.
- Resource units: Fish species, seabirds, and marine ecosystems.
- Governance: Management by the Salinas local government, the Ministry of Environment, Water and Ecological Transition (acronym in Spanish, MAATE), non-governmental organizations (NGOs), and the oil company.
- Users: Fisherfolk and residents of the area whose livelihoods depend on artisanal fishing and related activities.

This analysis enabled the identification of the factors that condition the sustainability of fishing activity and its urban environment. This organization facilitated the positioning of the clusters and recommendations within an extensive framework designed to enhance the sustainability of the coastal system and the communities that depend on it. For adaptive territorial management, socio-environmental indicators should be updated at least annually. Simultaneously, climate and spatial datasets ought to be evaluated every three to five years or following significant environmental occurrences. Continuous monitoring strengthens evidence-based planning and reduces institutional lag in decision-making processes.

RESULTS AND DISCUSSION

Artisanal fishing activity perception

Fig. 4 shows the sociodemographic profile of the inhabitants engaged in artisanal fishing in Santa Rosa. The analysis indicates a diverse community regarding academic qualifications, with basic education being the most common (46.57%) and a lesser percentage lacking formal education

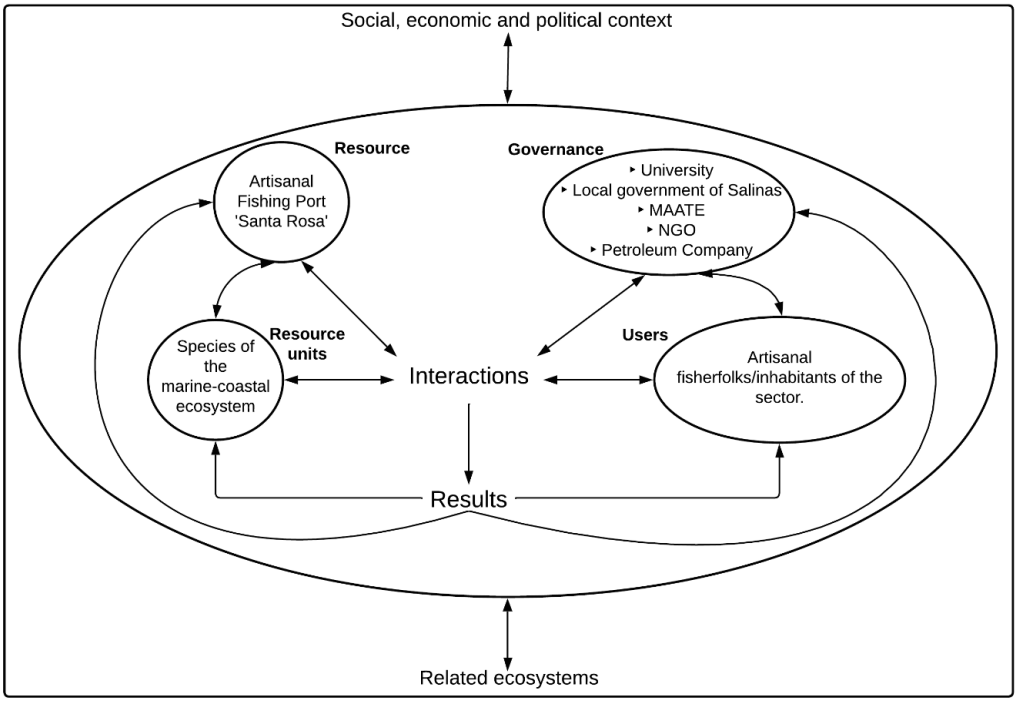

Fig. 3: Sustainability variables for artisanal fishing activity (Ostrom, 2009; Peña-Puch *et al.*, 2021)

(23.53%), highlighting structural barriers to accessing educational systems (Fig. 4a). Regarding livelihoods, fishing and associated trades (65.69%) constitute the central axis of local economic activity, complemented by occupations related to trade and tourism (34.31%) (Fig. 4b). The age distribution shows a working-age population with extensive participation in artisanal fishing (Fig. 4c). Simultaneously, the gender distribution indicates a predominantly male sector (71.57%), which aligns with trends noted in other coastal communities in the region (Fig. 4d). Taken together, these elements reflect a social structure strongly articulated around fishing as an income-generating activity and a cohesive force within the community. The depiction of the functional structure of artisanal fishing within the sector underscores the prevalence of active fisherfolk engaged in the activities, along with the evident commercial orientation of the extraction (Fig. 5a and Fig. 5b). The time spent in the activity reveals a community with accumulated experience (>11 years), indicating intergenerational transmission of technical knowledge and traditional practices (Fig. 5d). Additionally, it is recognized that the conditions under which operations occur are shaped by the space available for activities like storage, unloading, and vessel preparation, presenting a continual challenge in ports with high activity levels (Fig. 5c). These results demonstrate a consolidated activity, supported by local capabilities, but also limited by territorial factors that condition its operational efficiency. Fig. 6 integrates the perceptions of fisherfolk and inhabitants regarding the environmental impacts associated with both oil activity and the port's fishing dynamics. The participants recognized multiple elements that influence the environmental quality of the region, such as the impacts resulting from the functioning of oil wells (for instance, gas emissions, noise, and fire hazards), as well as the existence of solid waste and other issues associated with adjacent economic activities (such as insecurity) (Fig. 6a and Fig. 6c). These perceptions reflect a growing concern about pollution and risks that directly

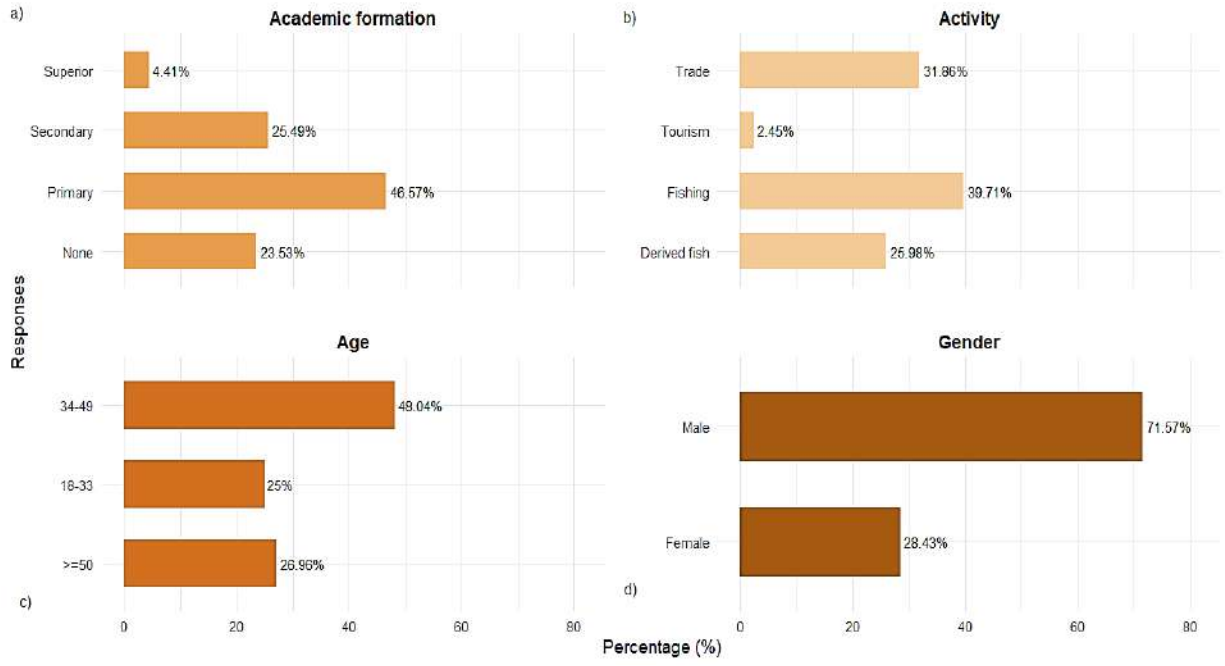

Fig. 4: Sociodemographic characteristics of the inhabitants of the sector. (a) Educational level. (b) Occupation of the inhabitants. (c) Age. (d) Gender

affect the health of the marine ecosystem and community well-being (Fig. 6b). Furthermore, the limited participation in environmental training workshops offered by public entities, such as local government and MAATE, or by private entities, such as the oil company, suggests the need to strengthen governance and environmental education processes in the territory (Fig. 6d). These components indicate that the combined pressures of industrialization and urbanization lead to a complicated environmental challenge that influences the viability of artisanal fishing and the living standards of the local community over the long term.

The study area climatic characterisation

Recent P and T records indicate that the study area has a warm, dry climate regime, characterised by average annual temperatures of 26–27 °C and precipitation concentrated in short seasonal events. The PET values were persistently greater than the annual precipitation, which validates the water-deficit conditions commonly found in the southwestern coastal strip of Ecuador. Additionally, the review of historical tide gauge data revealed a sustained trend of rising mean sea level since the mid-20th century, with the highest values observed in the last two decades (Winckler *et al.,* 2024). Historical sea-level trends were combined with IPCC regional projections to simulate gradual sea-level rise in the dynamic model. While extreme events such as storms were not explicitly modelled, sensitivity tests incorporated parameters to assess territorial exposure to increased climate variability. These forecasts guided spatial planning considerations, especially concerning the closeness of infrastructure to the coastline and areas susceptible to flooding.

Dynamic model between oil activity, artisanal fishing, the environment and the coastal community

The recommended dynamic model combines the key environmental, social, and productive elements that define the interaction between oil

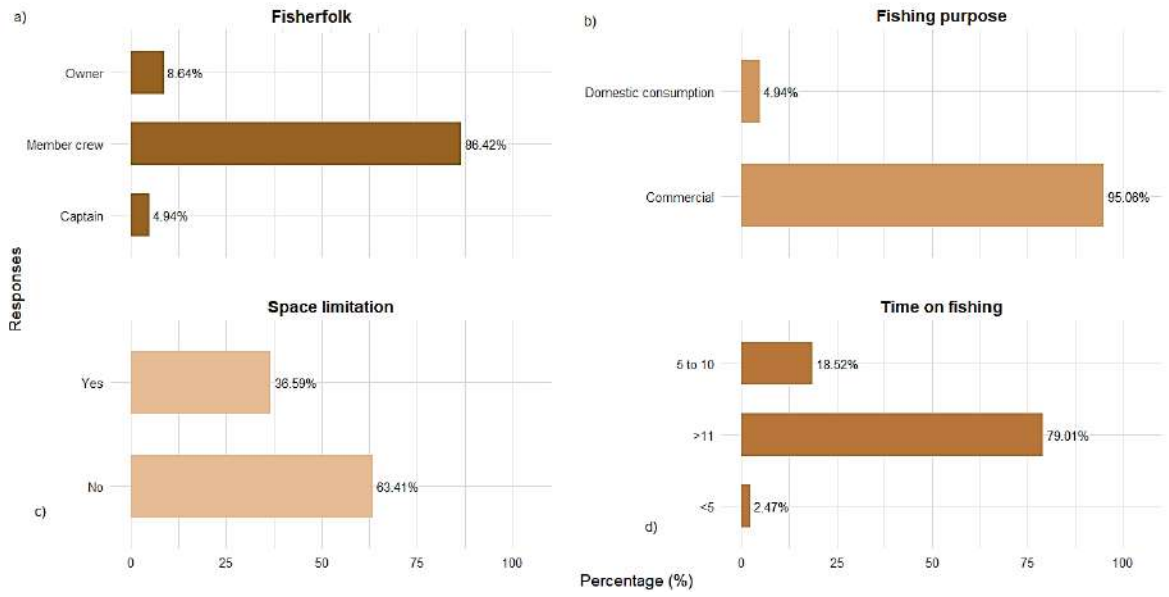

Fig. 5: General aspects of artisanal fishing activity in the Santa Rosa sector. (a) Fisherfolk type. (b) Purpose of fishing. (c) Space limitations for fishing activity. (d) Time spent in fishing activity

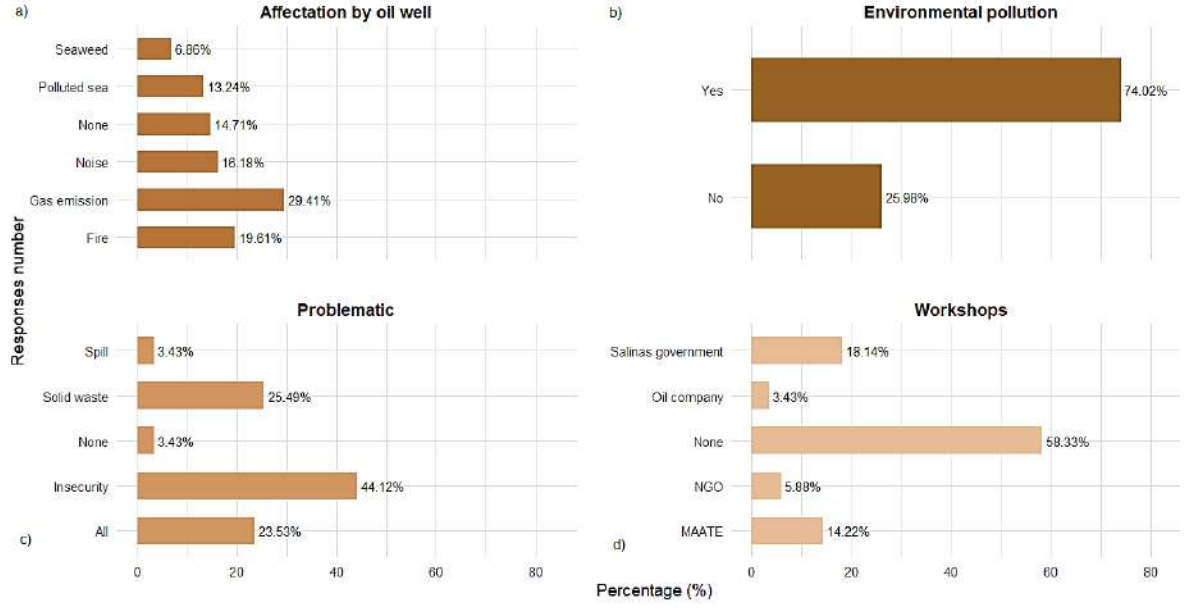

Fig. 6: Fisherfolk's and the community's perception of environmental pollution associated with oil activity and artisanal fishing. (a) Impact of oil wells; (b) Environmental pollution; (c) Other problems; (d) Workshops. NGO: Non-Governmental Organizations. MAATE: Ministry of Environment, Water and Ecological Transition

operations and artisanal fishing, forming a tightly linked socio-ecological system that is susceptible to external disturbances (Fig. 7). The causal diagram identifies seven feedback loops (R-1 to R-7) that describe the propagation of direct and indirect impacts through the productive, climatic, and community subsystems. The mathematical formulation of the causal relationships and their

corresponding parameters is detailed in Table 3. In this context, the sustainability of the coastal community emerges as an integrating variable that connects the social and economic subsystems. The R-1 reinforcement loop signifies the advantageous correlation between community sustainability and the vitality of local economic activities: as improvements occur in the social, organizational, and security aspects of the fishing sector, both productive capacity and the diversification of related activities are fortified, which subsequently strengthens the economic stability of the community. This process promotes the continuity of artisanal fishing and its production chains. Artisanal fishing maintains direct links with commercial, processing, transportation and service activities. This economic framework is linked to the R-2 reinforcing loop, through which increased economic activity increases demand for urban management, land-use planning, and the provision of basic infrastructure and services. Once these stipulations are properly fulfilled, advancements in urban management facilitate the organization of the territory, decrease conflicts of use, and enhance the port's operational conditions, thereby positively impactingthe performance of local economic activities. However, the operation of the Petropolis oil field, with 21 active wells, is a critical exogenous factor that imposes environmental and social pressures on the territory. The increase in operational intensity raises community stressors (gas emissions, machinery noise, spill risks, and psychosocial impacts), strengthening the R-4 reinforcing loop, in which oil activity affects environmental quality and amplifies perceptions of risk. Despite the management of recorded spill events through contingency plans, the ongoing release of combustion gases leads to heightened levels of greenhouse gases, thereby adding further feedback into climate change mechanisms. The climate subsystem acts as a modulating force, altering the operational and ecological conditions of artisanal fishing. 75% of fisherfolk with more than a decade of experience reported a perceptible trend of rising sea levels, consistent with documented evidence for the Ecuadorian and South American coast. This process, represented in the R-5 loop, intensifies the marine-coastal impact factors, affecting fishing infrastructure and manoeuvring areas. Artisanal fishing in the study area constitutes the core of the local economy and maintains productive linkages with commercial, processing, transport and service activities. Nevertheless, the escalation of these activities leads to a rise in solid waste production, which, without formal management systems in place, exacerbates the pollution of the surrounding environment. This process is represented in the reinforcing loop R-6, where increased fishing activity increases environmental pressure, reducing ecosystem quality and, potentially, the sustainability of the production system itself. Long-term sea-level records (1950–2018) indicate a sustained upward trend, while five-year SST and meteorological variability confirm increasing climatic stress in the coastal system. In addition, although continuous long-term biomass datasets are not available at the local scale, regional fisheries statistics and independent ecological assessments from the Colombian Caribbean reveal a steady decline in catch-per-unit-effort and shifts in species composition over the past two decades, which correspond with thermal stress, habitat modification, and escalating anthropogenic pressures (Doria-González *et al.,* 2022). These regional trends provide an external empirical reference that supports the perception-based findings and reinforces the interpretation of progressive ecosystem stress in the study area over recent decades.

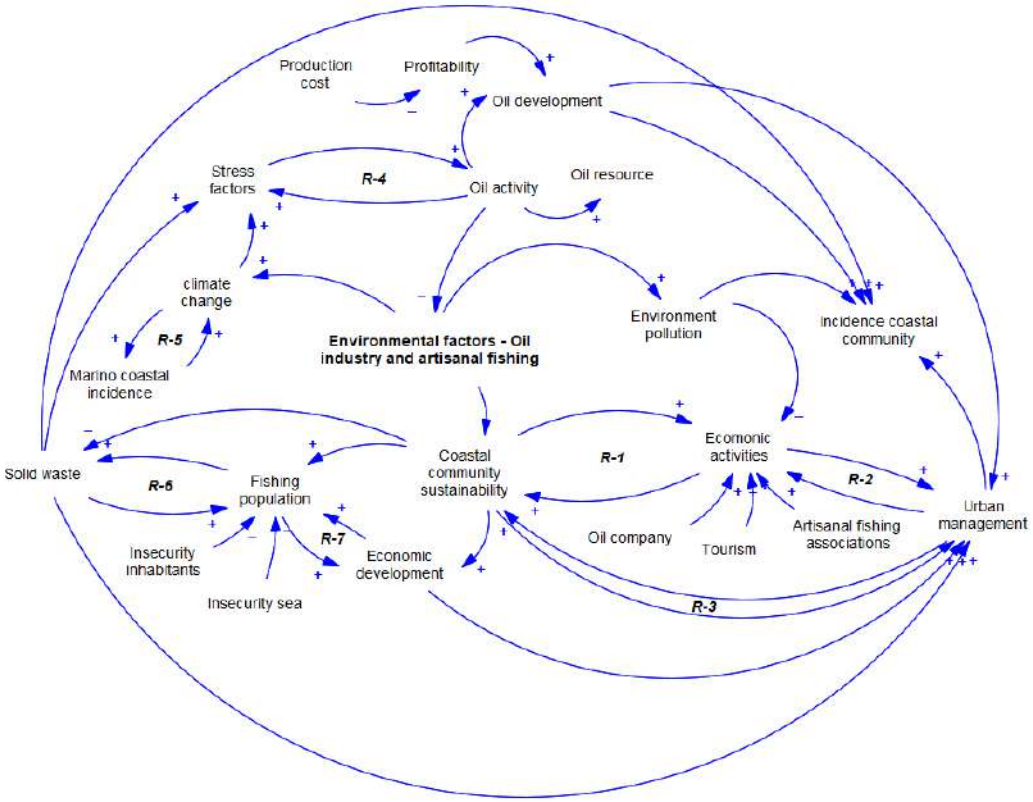

Fig. 7: Dynamic interactions between oil activity, artisanal fishing and the coastal community

Together with historical sea-level rise and increasing sea surface temperature variability, these patterns suggest cumulative long-term impacts on ecosystem resilience. Despite the absence of historical quantitative fish stock series at the local level, 86% of knowledgeable fisherfolk have indicated a decrease in abundance or alterations in species composition over the past decade. This perception is consistent with documented SST-related species redistribution patterns in the Eastern Pacific (Liu *et al.,* 2025). The dynamic model links these long-term climatic and pollution pressures with fishing intensity and waste generation, suggesting cumulative ecosystem stress rather than isolated impacts. Tourism, propelled by the port's closeness to high-traffic recreational areas, positively impacts economic dynamics (R-3), yet it can also create new environmental challenges if not effectivelyregulated. Finally, the social subsystem incorporates structural vulnerability factors linked to insecurity on land and at sea. Common crime on the coast and attacks on vessels by pirate groups introduce disturbances that affect the economic stability of fisherfolk and increase operational risk. These dynamics, integrated into the R-7 loop, affect community sustainability by reducing income-generating capacity and increasing losses associated with fishing activities. The unavailability of health and life insurance for fisherfolk exacerbates social vulnerability when confronted with such occurrences, heightening risk exposure and diminishing the overall resilience of the system. Although precise ecological carrying capacity thresholds could not be quantified due to limited biomass and water-quality datasets, the model identifies critical pressure points associated with waste accumulation, oil-related risk exposure, and increased fishing effort. Sensitivity analysis

indicates that when parameters related to fishing intensity or pollution increase by more than 20%, the stability of the system declines at an accelerated rate. These observations imply precautionary benchmarks that should direct urban planning and port operation decisions. The model assumes linear parameter variation within tested sensitivity ranges, stable institutional conditions during simulation periods, and the absence of abrupt structural economic shocks. Limitations include limited ecological time series, the lack of direct hydrocarbon concentration measurements, and the qualitative representation of behavioral variables. Results should therefore be interpreted as approximations of systemic trends rather than predictive forecasts.

Spatial dynamics

Fig. 8 presents the spatial distribution of the main areas of the territory, including the artisanal fishing port, the beaches of Chipipe and San Lorenzo, and the Petropolis oil field with its 21 producing wells (Fig. 8a). Furthermore, the locations related to tourism on Santa Rosa beach, the fuel distribution points, the fish processing area, and the commercial district situated less than 1 km from the port have also been recognized, in addition to multiple educational institutions (Fig. 8b). Artisanal fishing, in addition to its productive role, also stimulates complementary commercial activities that increase pressure on the environment and indirectly contribute to the effects of climate change. Spatial overlap analysis indicates that artisanal port infrastructure, fuel storage points, and fish processing areas within 1 km of the shoreline exhibit the highest exposure to sea-level rise and storm surge risks. Fisherfolk households that rely directly on daily landings represent the most socioeconomically vulnerable demographic. Educational centers and commercial zones adjacent to operational oil infrastructure also represent sensitive receptors requiring preventive spatial zoning measures.

Perception patterns and structuring of guidelines: HCA

The HCA classifies the technical recommendations according to the degree of similarity in the perceptions of the 60 selected experts. Of the eleven guidelines evaluated (Table 1), all showed high levels of consensus ($W > 0.70$), which supports their validity as priority proposals for the management of the artisanal port of Santa Rosa. The dendrogram obtained in Fig. 9 shows three well-defined groups, supported by Ward's method and Euclidean distance, revealing differentiated approaches to sustainability, risks, and governance of the fishing territory.

Cluster 1: "Operational and functional approach of the port" groups recommendations 3, 5, 7, 8 and 9. This group brings together guidelines to improve port operations, infrastructure, and safety related to fishing activities. Experts assert that the operational capacity of the port is crucial to the socio-ecological framework, and they stress the significance of refining unloading procedures, minimizing risks related to oil operations, and ensuring sufficient cleaning and waste management practices. This conglomerate demonstrates a vision focused on operational efficiency as a pillar for sustaining artisanal fishing productivity and the sector's economic stability.

Cluster 2: “Environmental governance and risk control” brings together recommendations 2, 4, 10 and 11. The objective of these proposals is to fortify environmental management and mitigate the vulnerabilities that emerge from the interaction among the port, the urban area, and the oil industry. Experts emphasize the need to consolidate coastal surveillance systems, regulate fishing activities by vessel type, establish robust environmental monitoring protocols, and promote good practices to reduce pollution of the marine environment. This conglomerate demonstrates deep apprehension regarding

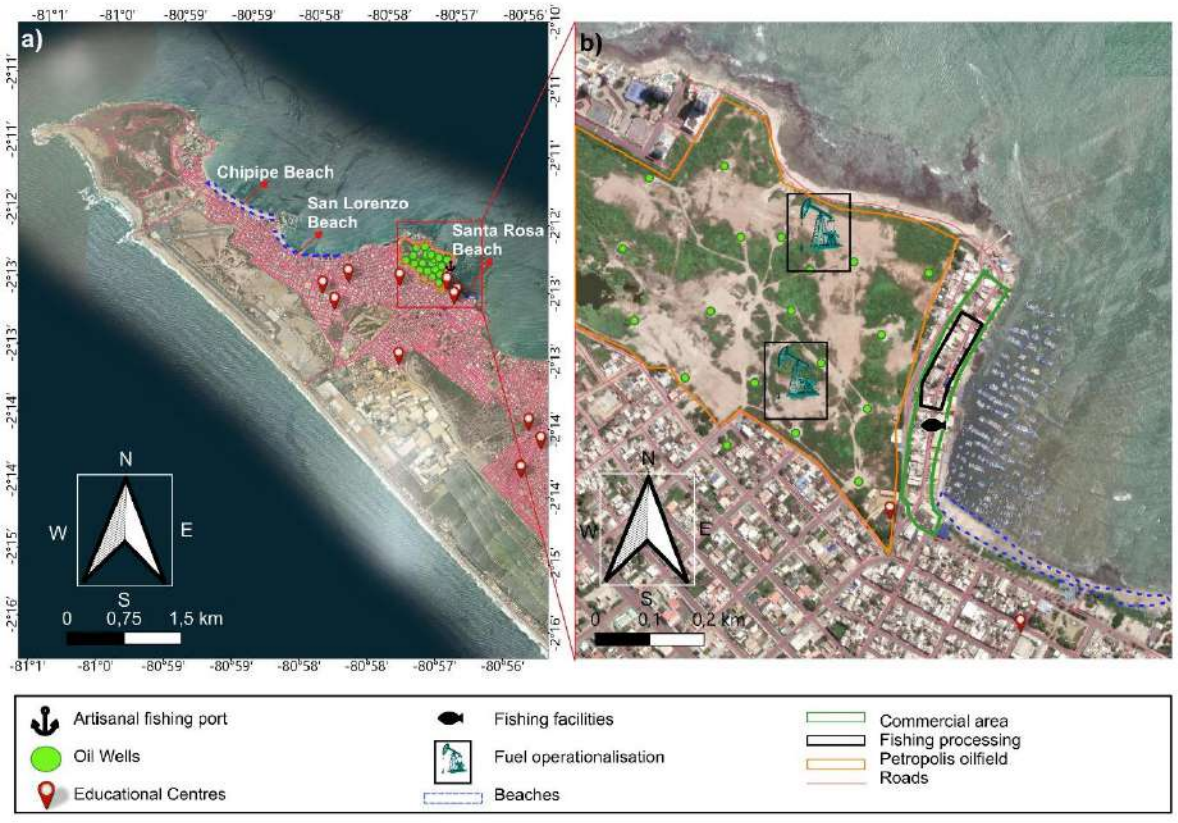

Fig. 8: Spatial distribution of territorial activities: (a) Santa Rosa Artisanal Fishing Port, Petropolis oilfield with 21 producing wells and tourist beaches (Chipipe Beach, San Lorenzo Beach and Santa Rosa Beach). (b) Commercial areas near some educational centers, fishing processing zones and fuel operationalisation sites

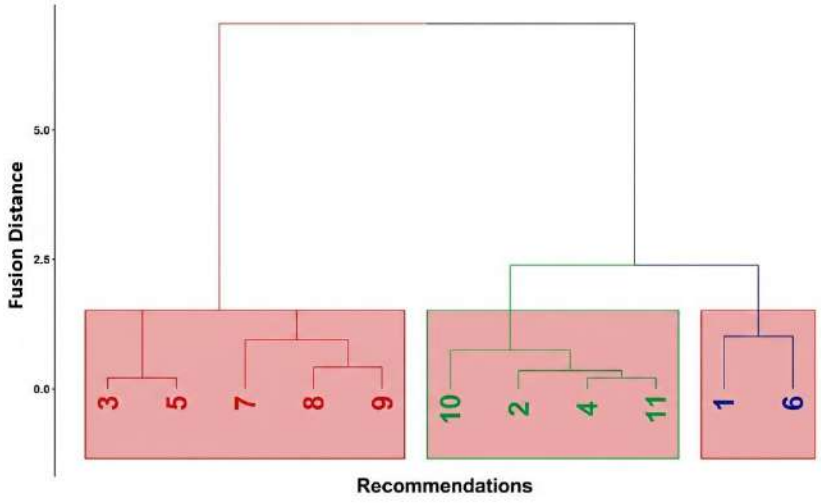

Fig. 9: HCA dendrogram applied to the technical recommendations for the sustainable management of the artisanal fishing port of Santa Rosa. Each cluster represents sets of coherent guidelines for governance, environmental management, and the strengthening of fishing activity

the environmental standards of the region and for executing initiatives aimed at predicting and reducing risks linked to spills, fires, or pollution.

- Cluster 3: "Territorial planning and institutional strengthening" is structured around recommendations 1 and 6, which are linked to the structuring of public policies and long-term planning processes. Expert opinions highlight the importance of incorporating artisanal fishing within formal land-use planning tools, enhancing coordination between the fishing sector, local government, and national agencies, and reinforcing institutional capacity to handle significant events, including possible spills or crises in the oil industry. This conglomerate represents a strategic approach to consolidating territorial governance and ensuring coherence among the economic activities that coexist in the area. The proposals concerning monitoring systems (Items 6 and 10) suggest that the current early warning and environmental monitoring mechanisms are considered inadequate. While contingency plans for oil spills exist, no integrated multi-hazard early warning system currently operates at the port level. Strengthening institutional coordination and real-time monitoring is therefore necessary to address future climate and socio-environmental risks. Overall, the three clusters offer a multi-scale view of the system, from the daily operations of the port (Cluster 1) to environmental control and risk reduction (Cluster 2), to the integration of artisanal fishing into urban and coastal planning (Cluster 3). This framework illustrates the variety of local expertise and emphasizes the necessity of integrating it into decision-making processes to establish a sustainable land management model.

Integration of clusters with socio-ecological system variables

Table 2 summarises the sustainability variables that characterise the socio-ecological system of the artisanal fishing port of Santa Rosa, following Ostrom's conceptual framework. The relationship established between the recommendations derived from the HCA clusters and these variables facilitated for a comprehension of how expert perceptions impact each aspect of the system.

- Resources: The infrastructure and services of the port are included, as their operation is essential for ensuring safety and productivity in fishing. Cluster 1 is closely linked to this dimension, as it prioritises operational improvements, maintenance, and the organization of port space, essential elements for sustaining fishing activity and reducing risks associated with port use.
- Resource units: Formed by the marine species that sustain the fishing economy. The recommendations regarding the environment from Cluster 2 are fundamentally linked to this dimension, underscoring the importance of improving waste management, initiating ecological monitoring, and managing activities that impact biodiversity and fishery resources.
- Governance: Includes fishing associations, public institutions, NGOs, fishing companies and the oil industry. Cluster 2 and Cluster 3 pertain to this dimension; their suggestions highlight the importance of collaboration among stakeholders, environmental oversight, management of coastal space utilization, and the incorporation of the fishing industry into territorial planning frameworks.
- Users: These consist of fisherfolk and the coastal community, who rely on fishing for their source of income. The three clusters

converge on this dimension, as they all address aspects related to security, economic stability, access to resources and risk reduction that directly affect users in the territory.

The combination of HCA with socio-ecological analysis enabled the conversion of expert perceptions into management guidelines consistent with the SDGs (11, 13 and 14), strengthening the resilience of the fishing system and promoting more inclusive, safe and environmentally responsible urban planning. This study demonstrates that the sustainability of the artisanal fishing port of Santa Rosa is determined by the concurrent interactions of environmental, productive, and institutional systems functioning within a shared coastal region. By integrating local ecological knowledge with spatial analysis and system dynamics modelling, the research translates community perceptions into structured analytical inputs that inform urban and coastal governance decisions. The findings confirm that the coexistence of artisanal fishing and oil activity generates cumulative socio-environmental pressures. Gas emissions, operational risks, and perceived insecurity contribute to environmental stress and psychosocial vulnerability (Fig. 6). Comparable patterns have been documented in coastal regions of the Gulf of Mexico (Andrews *et al.,* 2021), West Africa (Agbonifo, 2022), and Southeast Asia (Fabinyi *et al.,* 2022), where proximity to oil infrastructure has been associated with ecosystem degradation and disruptions to traditional livelihoods (National Oceanic and Atmospheric Administration (NOAA), 2025). In Santa Rosa, these pressures are not isolated events but persistent conditions reinforced by institutional fragmentation and limited cross-sector coordination. Dynamic modelling demonstrates the existence of reinforcing feedback loops that associate oil operations, fishing intensity, climate variability, and territorial planning (Fig.7). These interactions clarify the reasons behind the limited enhancements in governance performance resulting from incremental policy adjustments. Community organization emerges as a stabilising component within the system, supported by evidence from international cases showing that participatory governance mechanisms enhance resilience to socio-environmental disturbances (Finkbeiner and Basurto, 2015; Dudayev *et al.,* 2023; Gammage *et al.,* 2025). Nonetheless, the efficacy of these mechanisms is contingent upon the institutional capacity and ongoing collaboration among stakeholders. Climate change operates as a cross-cutting driver that amplifies existing vulnerabilities. Historical sea-level trends and observed increases in sea surface temperature are consistent with regional climate projections and directly influence port infrastructure exposure, species distribution, and fisheries productivity (FAO, 2025; IPCC, 2025). Ports situated in areas susceptible to flooding or at low elevations encounter increased structural vulnerabilities, underscoring the necessity for urban planning based on empirical climate data and adaptive infrastructure strategies (Slovic *et al.,* 2024). HCA analysis identified substantial consensus among fisherfolk regarding the prioritisation of environmental monitoring, operational regulation and integrated territorial planning (Fig. 9). The selection of participants was based on their fishing experience, active operational engagement at the port, and leadership positions in local associations, thereby enhancingthe contextual validity of the recommendations (Asio *et al.,* 2026; Micha and Kelling, 2025). Nevertheless, the expert group was primarily composed of active male fishers, potentially underrepresenting women engaged in post-harvest processing, youth participants, private sector actors, and municipal planners.

While the consensus achieved (Kendall's W > 0.70) indicates strong agreement within the group, expanding stakeholder diversity in future applications would reduce potential bias and enhance deliberative robustness. It is essential to include multiple viewpoints, particularly in contexts where territorial decisions have implications for differing social and economic interests. The distribution of costs and benefits within the port system remains uneven. Although oil activity contributes to regional revenues, environmental risks and operational disruptions disproportionately affect artisanal fishing households. Women engaged in fish processing and retail experience indirect economic losses when declining landings reduce processing volumes and daily income stability. These varied effects demonstrate that governance measures need to include equity-sensitive standards and acknowledge the complete value chain of artisanal fisheries. Feedback-loop analysis suggests that climate variability and oil activity exert the strongest systemic influence through cascading effects across ecological, economic, and infrastructural subsystems. Comparative sensitivity testing within the system dynamics model indicates that variables associated with oil infrastructure density and climate variability exhibit the highest elasticity in system behavior, amplifying feedback effects on fishing productivity and spatial vulnerability indicators. In contrast, pollution accumulation and community organizational capacity functioned primarily served as mediating or buffering variables, moderating the system's instability rather than structurally driving it. Monitoring the system, therefore, requires measurable indicators linking environmental exposure, productive performance, and governance effectiveness. Relevant indicators include fishing effort variability, landing volumes, historical sea-level records, spatial proximity of infrastructure to risk zones, waste accumulation points, and participatory governance metrics. These indicators offer a foundational basis for adaptive management strategies. Despite the model being mainly qualitative, calibration using empirical datasets and sensitivity testing (±10–20%) has validated structural stability amidst parameter variation. The model's value lies in clarifying causal relationships and identifying leverage points rather than generating deterministic forecasts. Future studies that incorporate high-resolution climate monitoring, remote sensing data, and quantitative ecological metrics would bolster predictive capabilities and facilitate long-term validation. Regarding methodological transferability, the integrated framework developed for Santa Rosa is adaptable to other artisanal fishing ports, particularly those facing overlapping pressures from extractive industries and climate variability. However, replication depends on contextual factors including governance structure, institutional coordination capacity, data availability, ecological characteristics, and the organizational strength of fishing communities. In scenarios characterized by restricted spatial or climatic datasets, simplified causal-loop modeling and participatory mapping could replace components that require more data. Where institutional capacity is weak, phased implementation involving capacity building and inter-agency coordination mechanisms would be necessary. Ecological differences, including hydrodynamic regimes, species composition, and baseline pollution levels, necessitate the recalibrating model parameters. Thus, the framework should be understood as a flexible analytical architecture rather than a fixed template. In summary, the combination of participatory methods, geomatics tools, and dynamic modelling provides a cohesive and

flexible strategy for enhancing territorial planning in artisanal fishing ports. By explicitly recognizing contextual limitations, stakeholder diversity, and institutional capacity as determinants of successful implementation, the study advances a more nuanced understanding of sustainability governance in complex coastal systems.

CONCLUSION

This study provides an integrated socio-ecological assessment of the artisanal fishing port of Santa Rosa by identifying four strategic systems: oil activity, climate change, environmental pollution, and the coastal community, which shape fisheries sustainability and territorial governance. The interplay between these systems generates reinforcing feedback processes that influence fishery productivity, environmental quality, infrastructure vulnerability, and socio-economic stability. The port, therefore, serves as a key territorial interface where environmental variability and anthropogenic pressures converge, requiring coordinated, evidence-based urban planning. The dynamic modelling method elucidates how minor fluctuations in oil operations, climatic stressors, or the degree of community organization can lead to significant systemic effects. By identifying feedback loops and leverage points, the model serves as a decision-support tool that can anticipate risk scenarios and evaluate policy alternatives in complex coastal environments. In conjunction with geomatics analysis and participatory consensus-building, this method enhances the analytical foundation for sustainable territorial management. To evaluate the effectiveness of the proposed sustainability and governance interventions over time, the study identifies a set of measurable monitoring indicators. Monitoring implementation should involve coordinated action among municipal governments, national fisheries authorities, environmental agencies, and organized fisher associations. Establishing inter-institutional monitoring committees would enhance adaptive management and enable regular assessment of policy results. The HCA analysis revealed strong consensus among expert fisherfolk regarding operational improvements, environmental monitoring, and strengthened governance mechanisms. This analysis emphasizes the significance of integrating local knowledge into planning processes. However, expanding stakeholder participation in future applications, including women involved in post-harvest activities, youth, municipal planners, and private-sector actors, would enhance representativeness and deliberative robustness, particularly where management decisions affect diverse socio-economic interests. The unified framework that merges geomatics tools, participatory techniques, and system dynamics modeling reveals substantial potential for adaptation to various artisanal fishing ports. Nevertheless, its scalability depends on contextual conditions. Replication requires a minimum availability of spatial and climatic datasets, functional fisher organizations capable of structured participation, and institutional capacity for inter-agency coordination. Governance frameworks that promote transparency and data-driven planning are equally significant. In contexts with limited data availability, simplified causal-loop models and participatory mapping techniques may serve as substitutes for more data-intensive components. Where institutional capacity is limited, phased implementation with capacity-building measures would be necessary. Ecological variability, including variations in hydrodynamics, species composition, and pollution baselines, also requires local recalibration of model parameters. This study presents a transferable methodological approach that enhances resilience, improves

governance effectiveness, and promotes sustainable development in artisanal fishing ports confronted with cumulative socio-environmental pressures by articulating participatory knowledge, spatial evidence, and dynamic modelling. The framework should be understood as an analytical architecture that requires contextual calibration and progressive refinement, adaptable to diverse socio-political, environmental, and economic settings. Methodological limitations concerning the time allocated for stakeholder engagement, the consistency of data, and the quantification of models highlight the significance of ongoing enhancement and capacity development. Continued empirical testing across diverse artisanal fishing ports will strengthen its predictive reliability and consolidate its role as a scalable decision-support tool for sustainable coastal governance.

AUTHOR CONTRIBUTIONS

M. Díaz-Ponce contributed to the conceptualisation, research, formal analysis, methodology, software, drafting of the original document, project management, and supervision. S. Villón-Perero contributed to the study, methodology, and drafting of the original document. J. Escandón-Panchana contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing. R. Pico-Saltos contributed to the conceptualisation, research, formal analysis, methodology, 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.

CONFLICT OF INTEREST

The authors declare no conflicts of interest related to the publication of this manuscript. Furthermore, the authors addressed ethical issues such as plagiarism, informed consent, misconduct, data fabrication or falsification, duplicate publication or submission, and redundancy.

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ABBREVIATIONS

%	Percent
°C	Degrees Celsius
ε	Sample error
CLD	Causal loop diagram
ENSO	El Niño-Southern Oscillation

FAO	Food and Agriculture Organization
HCA	Hierarchical cluster analysis
IPCC	Intergovernmental Panel on Climate Change
Km	Kilometer
MAATE	Ministry of Environment, Water and Ecological Transition
mm	Millimetres
N	Population
n	Representative sample
NGO	Non-governmental organization
p	Success probability
P	Precipitation
PET	Potential evapotranspiration
PLE	Personal Learning Edition
q	Failure probability
R-1 to R-7	Feedback loops
SD	System dynamics
SDG	Sustainable development goal
SST	Sea surface temperature
T	Temperature
W	Ward's method and Euclidean distance
z	Z-score

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SURVEY STUDY

Plastic waste management for a green university campus initiative by students

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ABSTRACT

BACKGROUND AND OBJECTIVES: Campuses have the position to encourage the practice of sustainability among students. Earlier studies regarding campus sustainability primarily concentrated on waste management policies, waste generation, and waste utilization. However, studies on green campus initiatives and students' pro-environmental practices in plastic waste management are still relatively rare. Investigating plastic waste management practices has become an important study to conduct as a basis for policymaking and providing appropriate recommendations. The study aimed to explore how students manage plastic waste by reviewing their strategies for segregation, reduction, reuse, recycling, and disposal, all within the context of the waste management hierarchy.

METHODS: A survey approach was implemented, characterized by a descriptive-quantitative framework, involving the distribution of closed questionnaires to a total of 1,038 students selected via proportionate stratified random sampling, following the guidelines of the Isaac and Michael formula. The collected data were analyzed using the Weighted Mean technique to assign scores to answer choices based on predetermined weights corresponding to the Likert scale to indicate the level of constructs of student practices in plastic waste management.

FINDINGS: The findings demonstrate that students have plastic waste management practices classified as "good" across the three green campuses. The study indicates that students at the three green campuses are generally more involved in reuse practices (68.17 percent), reduction (67.92 percent), segregation (64.17 percent), and disposal (62.83 percent). Nevertheless, they exhibit a lack of effectiveness in recycling practices (56.67 percent), which suggests a requirement for increased attention. This study emphasizes the need for educational efforts focused on recycling practices, with implementation aligned with the sustainable development goals.

CONCLUSION: Through plastic waste management practices, students can be empowered to contribute as agents of change in solving environmental problems. This analysis reveals that the approach of managing plastic waste via reduction and reuse is more readily embraced by students, given that it is easier to implement both psychologically and structurally in a green campus environment. Developing students' skills, participation, and recycling practices through the curriculum and various programs integrated with environmental education can provide long-term experiences to achieve sustainable green campuses.

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105	10	5

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INTRODUCTION

The increase in plastic waste has become a significant global challenge, with widespread impacts on ecological, economic, and social aspects (Borrelle *et al*., 2020). This issue is exacerbated by a surge in global plastic production, which rose by 12 million tons (MT) over a one-year period, reaching a total of 360 (MT) in 2018 (Lee *et al*., 2024). By 2022, this figure climbed further to 400.3 MT, with approximately 40–50 percent (%) till not fully collected and thus potentially causing negative environmental impacts (Burelo *et al*., 2024; Köse *et al*., 2024). Recent studies suggest that, without effective management, plastic waste is projected to double by 2035, and nearly quadruple by 2050 (Twagirayezu *et al*., 2024). These trends may potentially result in increased threats of pollution, disturbances to ecosystems, and imbalance in the global carbon cycle (Celis-Hernández *et al*., 2021; Kumar *et al*., 2021). Moreover, the accumulation of unmanaged plastic waste in landfills or the environment leads to the breakdown of plastics into smaller particles (microplastics), indirectly threatening human health (Gall and Thompson, 2015; Kehinde *et al*., 2020). The challenge posed by plastic waste is not merely a global issue; it is also a matter of national and local significance, including in university settings. The infrastructure within a campus forms a comprehensive system comprising lecture buildings, student dormitories, sports facilities, libraries, and laboratories (Amaral *et al*., 2015). The multitude of activities occurring on campus that require significant energy and resources may result in waste production, particularly plastic waste (Adeniran *et al*., 2017; Zen *et al*., 2016). The flexible, practical, durable, lightweight, cheap, and economically valuable nature of plastic makes it easy to produce and widely used. Furthermore, the advantages of plastic are overshadowed by its substantial environmental impact, as its inherent characteristics complicate the biodegradation process and lead to decomposition times spanning centuries (Salam *et al*., 2023). This suggests that plastic waste could become a future disaster if no sustainable management measures or strategies are implemented. Effective and proper management is essential for mitigating and minimizing the effects of plastic waste issues. The efficiency of plastic waste management encompasses several factors, including management practices and a commitment to achieving sustainable plastic waste management (Nguyen *et al*., 2023). Adopting sustainable practices for plastic waste management can substantially affect the growth of a nation's economy. According to the European Union (EU) and the United States Environmental Protection Agency (EPA), sustainable plastic waste management prioritizes prevention and reduction, with other alternatives including reuse, recycling, energy recovery, and disposal as a last resort (Fayshal, 2024). Therefore, to achieve sustainable plastic waste management, the involvement of stakeholders, companies, private parties, and producers is necessary, as well as the active role of campuses in educating and increasing participation in segregation, reusing, and recycling (Pambudi *et al*., 2025). Higher education institutions or campuses are essential to sustainability, especially as educational centers that can offer scientific solutions to the issues related to plastic waste. Specifically, campuses have the position to encourage the practice of sustainability among students, aiming to contribute to environmental preservation efforts (Findler *et al*., 2019). Campuses can adopt various sustainability initiatives through green campus programs (Maçin *et al*., 2024), activities aimed at reducing plastic waste, or by incorporating these initiatives into the curriculum (Filho *et al*., 2019). A green campus is a program initiated by the University of Indonesia in 2010 through the UI GreenMetric World University Rankings, aiming to integrate environmental management into higher education institutions by promoting sustainable behavior through education and environmentally

friendly practices. Recent studies have aimed to investigate the degree to which the notion of sustainability is integrated within higher education institutions (Lee *et al*., 2024), especially regarding how educated individuals excel in their environmental behaviors and actions (Torroba Diaz *et al*., 2023). Literature studies indicate that integrating sustainability into practices or real actions can foster a culture of environmental responsibility, including among students (Barth and Rieckmann, 2012; Lozano *et al*., 2019). Students play a significant role and make a valuable contribution to achieving sustainable development. However, most students tend to be unaware of their roles in managing plastic waste on campus (Bautista, 2019). Studies conducted in India indicate that students possess a solid understanding of plastic pollution and exhibit a favorable attitude towards the use of eco-friendly products; nevertheless, merely one-third of the students engage in appropriate waste management practices (Srinivasan *et al*., 2019). Research in Indonesia reveals that students exhibit high awareness, good knowledge, and positive behavior, yet they have low skills and limited participation in managing plastic waste (Shaherani *et al*., 2024). Other studies also indicate that students' awareness of plastic ban regulations is generally satisfactory, but their actual practice in daily life is poor (Sujitha *et al*., 2020). Literature reviews demonstrate that only 49.5% of students display a serious level of attention and concern for waste management practices (Ifegbesan *et al*., 2017). Previous research has shown that waste management solutions are often implemented without involving community input, despite its importance (Yukalang *et al*., 2018). To date, there is still limited research discussing the extent to which students have implemented and practiced environmental concepts (Reyes and Madrigal, 2020). Literature reviews highlight that despite the significant role campuses play in fostering environmental sustainability, there are only a limited number of studies that have investigated this issue from the viewpoint of university students (Owojori *et al*., 2022), particularly in terms of plastic waste management practices. Previous studies, particularly in developing countries, have conducted similar investigations; however, most focus on urban waste management practices (Azevedo *et al*., 2021; Breukelman *et al*., 2019; Chowdhury *et al*., 2020; Debrah *et al*., 2021; Serge Kubanza and Simatele, 2020). Other research also tends to be fragmented on topics of practice such as waste policy (Xuan Son, 2021), waste production and consumption (Liu *et al*., 2021; Nguyen *et al*., 2021; Pham Phu *et al*., 2018; Su *et al*., 2021), as well as marine litter (Kerber and Kramm, 2021; Xuan Son, 2021). Several studies conducted in the Philippines have investigated solid waste management practices among students, yet they concentrate solely on a single university (Bautista, 2019; Diestro, 2022; Paghasian, 2017). As agents of change, studies on students' perspectives have been widely reviewed in the campus sustainability literature (Heiskanen *et al*., 2016; Hesselbarth and Schaltegger, 2014), but hardly any studies have been conducted to explore them from a practical standpoint (Mohamad *et al*., 2021). Further studies show that efforts related to green campuses and student actions that support the environment are still commonly disregarded in earlier studies, particularly within developing countries (Wang *et al*., 2022). Therefore, this study addresses this gap in three main ways. First, it specifically investigates plastic waste management practices, whereas previous research has focused on waste management in general. Second, it involves three of the largest universities in Malang City, specifically those categorized as green campuses, thus increasing the generalizability of the findings. Third, it explores student behaviors concerning the waste management hierarchy, which covers the facets of segregation, reduction, reuse, recycling, and waste disposal. Investigating plastic waste management practices has become an important study to conduct as a basis for policymaking and providing appropriate

recommendations (Fayshal, 2024). Beyond cross-campus comparisons, this study provides a structured behavioral benchmark that maps student good practices across different stages of the plastic waste management hierarchy. This study provides actionable insights for formulating evidence-based green campus policies and contributes to the literature by framing student practices within a behavioral perspective based on the waste management hierarchy and the Theory of Planned Behavior (TPB), and by conceptualizing the interconnected stages of separation, reduction, reuse, recycling, and disposal. By incorporating plastic waste management into campus sustainability initiatives, it is projected to play a vital role in achieving the Sustainable Development Goals and to highlight the critical role that green campuses play in advancing environmental conservation and sustainable practices. This study aims to assess the student practices in segregation, reduce, reuse, recycle, and disposal aspects of plastic waste management to achieve sustainable green campus. This study has been carried out in Malang City during 2024-2025.

MATERIALS AND METHODS

A survey-type research design was employed in this study, utilizing a descriptive-quantitative approach to describe the phenomenon using numerical data. The descriptive-quantitative design enables structured measurement of behavioral tendencies in plastic waste management, facilitating objective comparisons of student practices across institutions based on a waste management hierarchy that includes segregation, reducing, reusing, recycling, and disposing of plastic waste. The strategies implemented in this study encompass data gathering, categorization, and examination of that data, which aim to focus on the answers provided by respondents to deliver a holistic interpretation of how students manage plastic waste within a sustainable campus environment.

Study area

Indonesia is one of the largest contributors of plastic waste in the world, with an estimated 9,128,000 metric tons in 2016, placing it in the category of a plastic waste emergency. As one of Indonesia's major "education cities," Malang boasts high-quality education and is home to over 60 universities with 150,000 students annually. These features render Malang a significant site for investigating student behaviors, particularly in the realm of plastic waste management. As an education city, Malang generates 104.47 tons per day (t/d), or 13.66 % of the total plastic waste, and student activities also contribute to the increasing volume of plastic waste. Brawijaya University, State University of Malang, and University of Muhammadiyah Malang were selected as specific research locations because these three campuses are among the largest universities in Malang City, each of which accommodates more than 37,000 students. Furthermore, the three campuses are recognized for their sustainability efforts via green campus programs and are positioned within the top 30 of the UI GreenMetric 2025 University Rankings, which also aids in promoting sustainable development practices. The green campus was chosen as the research location because it represents the integration of environmental science into all aspects of management, serving as a best practice in sustainable development. Based on this background, Malang City was designated as the study area, as shown in Fig. 1.

Research Sample

The population in this study consisted of active students in semesters 1-8 from the 2020 to 2023 intake, across various majors, ranging from diploma to doctoral and professional levels, totaling 160,533 students from Brawijaya University, State University of Malang, and University of Muhammadiyah Malang. The sampling technique applied is proportionate stratified random sampling, which acknowledges the varied nature of the population and is derived

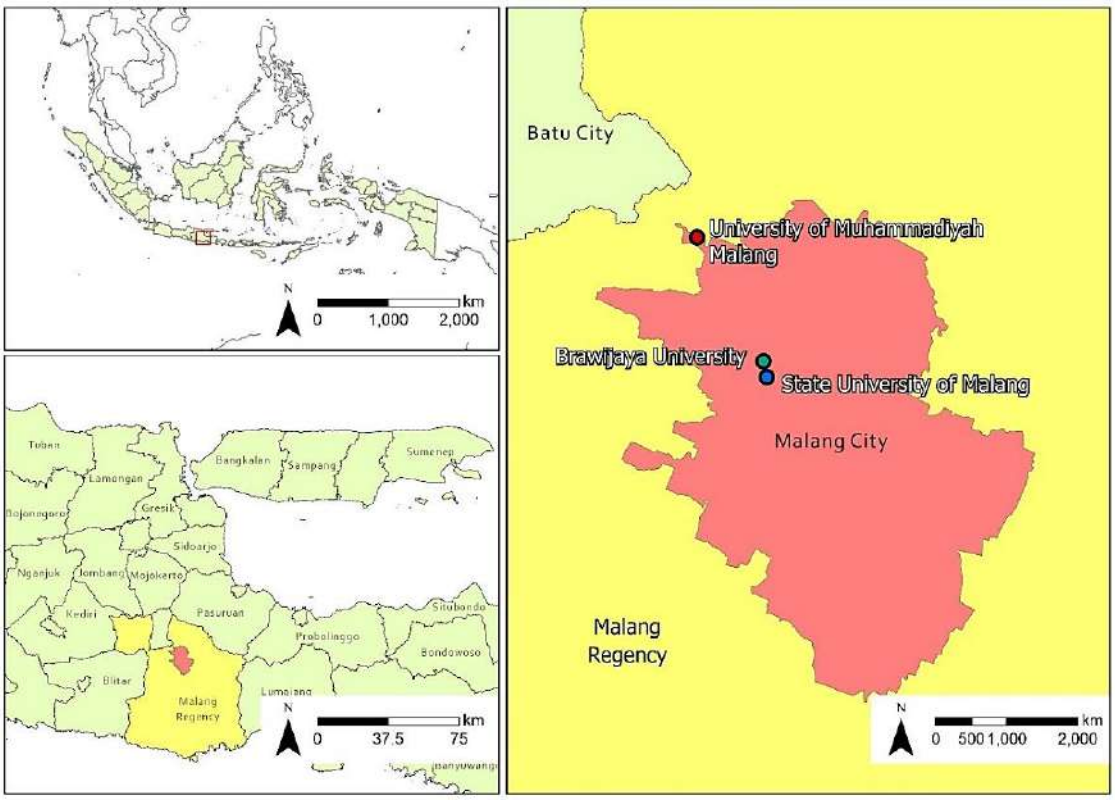


Fig. 1: Geographical location of the study area on three green campuses in Malang City, Indonesia

from the formula proposed by Isaac and Michael (Wilmoth, 1982). The findings are displayed in Table 1.

$$s = \frac{x^2 .N.P.Q}{d^2 (N-1) + x^2 .P.Q} \quad (1)$$

where, s = number of samples; N = population size; d = 0,05; P = Q = 0,5; x^2 = Chi Square; and dk=1, error level 1%, 5%, 10%.

The total number of samples in this study was 1,038 respondents including 414 male students and 624 female students, proportionally adjusted from each faculty of every campus, resulting in 347 students from Brawijaya University, 346 students from State University of Malang, and 345 students from University of Muhammadiyah Malang.

Research Instrument

This analysis performs an in-depth investigation into the formulation of instruments designed to evaluate the management practices of plastic waste. The focus is on segregation, reduction, reuse, recycling, and disposal. These five indicators were selected according to Sustainable Development Goal 12. Plastic waste management practices align with target 12.5, which aims to significantly reduce waste generation through prevention, reduction, recycling, and reuse by 2030 (Widyatmika *et al*., 2025), disposal serves as the final step (Fayshal, 2024). In the context of the campus under review, the act of disposal is still behaviorally important as it demonstrates the obligation to properly dispose of plastic waste produced by students in the designated disposal facilities.

Table 1: Population and research sample

No	UB			UM			UMM		
	Faculty	P	S	Faculty	P	S	Faculty	P	S
1	Law	3,082	14	Economics and Business	5,490	40	Law	2,648	24
2	Economics and Business	6,731	31	Engineering	5,244	39	Economics and Business	5,175	47
3	Administrative Science	6,785	31	Mathematics and Natural Sciences	5,084	37	Engineering	7,127	65
4	Agriculture	6,660	31	Vocational Studies	2,082	15	Social and Political Sciences	5,710	52
5	Animal Science	3,685	17	Postgraduate	12,712	93	Health Sciences	3,402	31
6	Engineering	6,165	28	Science Education	4,248	31	Postgraduate	1,466	13
7	Fisheries and Marine Science	5,243	24	Literature	5,203	38	Psychology	2,431	22
8	Mathematics and Natural Sciences	4,388	20	Sport Science	3,081	23	Teacher Training and Education	5,940	54
9	Agricultural Technology	4,589	21	Social Science	3,916	29	Agriculture-Animal Science	2,749	25
10	Social and Political Sciences	6,172	28	-	-	-	Islamic Studies	1,313	12
11	Cultural Sciences	4,272	20	-	-	-	-	-	-
12	Communication Science	4,076	19	-	-	-	-	-	-
13	Vocational Studies	4,593	21	-	-	-	-	-	-
14	Postgraduate	9,071	42	-	-	-	-	-	-
Total		75,512	347		47,060	346		37,961	345
Total population					160,533				
Total sample					1,038				

Table 2: Indicators selected for assessment of students' practices in plastic waste management

Component of practices	No.	Question indicators
Segregation	1	How often do you sort plastic (bottles, glasses) and non-plastic (paper, glass, wet waste) on campus as part of waste management practices?
	2	How often do you actively separate recyclable plastic waste from other waste while on campus?
	3	How often do you mix all types of garbage in one trash in the campus?
	4	How often do you separate recyclable plastic waste for collection as a more effective management effort?
Reduce	5	How often do you borrow, share, or rent the items you need as a commitment to reducing waste and creating sustainability?
	6	How often do you practice the habit of only buying things you need to reduce plastic waste on campus?
	7	How often do you bring provisions to reduce the use of packaged food on campus?
	8	How often do you choose to bring water in a personal bottle instead of buying water in single-use plastic bottles on campus?
	9	How often do you consider, be careful, and take responsibility for any plastic waste that you generate?
Reuse	10	How often do you choose to reuse items that are still usable rather than buying new ones?
	11	How often do you store plastic bottles or cups for reuse as crafts in an effort to reduce plastic waste?
	12	How often do you reuse plastic waste of detergent/soap/shampoo as pots?
	13	How often do you reuse washable food containers as an effective way to reduce plastic waste?
	14	How often do you use a totebag to reduce the use of plastic bags?
Recycle	15	How often do you change or redesign plastic waste into new products as an effective step in reducing plastic waste?
	16	How often do you make decorations out of plastic wrap as a creative and effective way to recycle plastic waste?
	17	How often do you tend to overlook the opportunity to recycle the items you use?
	18	How often do you collect/donate the plastic waste that you generate?
Disposal	19	How often do you tend to dispose and leave your plastic waste in just any place?
	20	How often do you feel that burning plastic waste as a disposal method is the solution to waste removal?
	21	How often do you dispose plastic waste in the trash that matches the label?
	22	How often do you implement a self-service culture for cleaning up the canteen waste you produce and disposing of it in the provided trash bins?

Furthermore, disposal remains a crucial component of the hierarchy, representing the final stage in waste management. The indicators were developed based on the contemporary waste management hierarchy, adapted from the United Nations Environment Programme (UNEP) and International Solid Waste Association (ISWA) (UNEP and ISWA, 2015; Whiteman *et al*., 2021; Wilson, 2023), then modified based on the research needs. The basis for calculating the indicator questions in this study was designed according to previous research (Lalamonan and Comighud, 2020), which was then adjusted to the situation and conditions of green campuses in Indonesia, resulting in 22 questions (Table 2). Each question indicator is measured using a 1-4 Likert scale, with assessment criteria as shown in Table 3. The instrument validation process was carried out both qualitatively and quantitatively to ensure each question indicator met consistency and validity criteria. First and foremost, qualitative validation included evaluations by expert validators that emphasized the pertinence of each question indicator to the research goals and reviewed the language employed. The expert validator is a Professor from State University of Malang, an environmental geographer with more than 11,000 citations, and the head of a green campus, which is the basis for the qualifications as a validator. Second, quantitative validation was achieved through a small-scale trial, which verified statistical validity and reliability using responses from 10 students at Brawijaya University, 10 from State University of Malang, and 10 from University of Muhammadiyah Malang (N = 30) (Johanson and Brooks, 2010; Hertzog, 2008). The trial data were evaluated through IBM SPSS version 26; a choice made to increase accuracy and mitigate human error. Questionnaire items were considered empirically valid and reliable when the significance value (2-tailed) was <0.05 and Cronbach's Alpha in reliability statistics was >0.60.

Table 3: Assessment criteria

Scale	Assessment criteria
1	Never
2	Rarely
3	Often
4	Very often

As presented in Table 4, the instrument trial results confirmed the validity and reliability of the questionnaire.

Data collection

Observation, field surveys, and the distribution of closed questionnaires were conducted as methods of data collection. The questionnaires were structured to collect data regarding the identities of the respondents and their methods of handling plastic waste on campus. Data collection was conducted in person, through face-to-face meetings on campus with respondents. Questionnaires were distributed to students at Brawijaya University, State University of Malang, and University of Muhammadiyah Malang using Google Forms, by scanning a QR code during the in-person session. The survey link was further disseminated through WhatsApp during the time the respondents were in the physical presence of the researcher. Therefore, data collection remained within the researcher's reach, helping to minimize self-selection bias. To mitigate the risk of self-reporting and social desirability bias in survey responses, the researcher was present during the completion of the questionnaire by the respondents. The researcher verbally explained the questionnaire procedure and explained each question's indicators. The study permitted participants to pose questions regarding the content of the questionnaire and also uses secondary data sourced from various literature reviews, including books, articles, the official websites of three related institutions, and field documentation, which serve as supporting literature for the background and discussion of the findings. This study was conducted over a period

Table 4: Results of instrument validity and reliability tests

Aspect	Item	Sig.(2-tailed)	Result	*Cronbach's Alpha*	Result
Segregation	1	0,002	valid	0,928	reliable
	2	0,000	valid	0,924	reliable
	3	0,000	valid	0,926	reliable
	4	0,001	valid	0,927	reliable
Reduce	5	0,000	valid	0,926	reliable
	6	0,000	valid	0,924	reliable
	7	0,000	valid	0,924	reliable
	8	0,000	valid	0,926	reliable
	9	0,000	valid	0,926	reliable
Reuse	10	0,001	valid	0,927	reliable
	11	0,000	valid	0,926	reliable
	12	0,000	valid	0,926	reliable
	13	0,001	valid	0,927	reliable
	14	0,011	valid	0,929	reliable
Recycle	15	0,000	valid	0,924	reliable
	16	0,000	valid	0,925	reliable
	17	0,000	valid	0,924	reliable
	18	0,000	valid	0,926	reliable
Disposal	19	0,000	valid	0,925	reliable
	20	0,000	valid	0,926	reliable
	21	0,000	valid	0,926	reliable
	22	0,000	valid	0,926	reliable

of five months, from February to April 2024, during the active academic semester, to minimize potential bias related to student absences, and from August to September 2025, during which additional field observations and documentation were conducted, was intended to strengthen the interpretation of the findings, not to collect new respondent data.

Data analysis

Data analysis was conducted using percentages and the Weighted Mean technique to determine students' practices in managing plastic waste. The Weighted Mean method is employed to allocate scores to response options according to established weights, which align with a Likert scale (1, 2, 3 and 4), reflecting the degree of the construct being assessed. This study presents and describes the data obtained through weighted mean calculations analyzed using Microsoft Excel. Although the dataset comprised 1,038 respondents, the study was descriptive rather than inferential. Consequently, the data analysis concentrated on examining student behaviors across the three green campuses instead of assessing statistical significance. This study provides a presentation and description of the data obtained in an objective manner through the application of weighted mean calculations analyzed via Eq. 2 (Paghasian, 2017; Bautista, 2019):

$$\mathrm{WM} = \frac{\sum(fixi)}{\sum fi} \tag{2}$$

where: WM = weighted mean; f_i = frequency of responses; x_i = assigned weight of each Likert scale category; and $\sum f_i$ = total number of responses.

The interpretation of students' practices in plastic waste management is categorized into four performance levels. A mean score ranging from 3.25 to 4.00 is interpreted as very good; a score between 2.50 and 3.24 is considered good; a score from 1.75 to 2.49 is categorized as poor; and a score between 1.00 and 1.74 is interpreted as very poor (Bautista, 2019; Paghasian, 2017). An increase in the score and interpretation result reflects a more favorable approach by students towards plastic waste management practices, encompassing segregation, reduction, reuse, recycling, and disposal. Reverse-coded items, such as indicators for questions 3, 4, and 20 (Table 2),

were marked prior to analysis to maintain a consistent direction of assessment before calculations using the weighted-mean technique were performed.

RESULTS AND DISCUSSION

Student practices in plastic waste management

The campus serves as a center for education and innovation, not only enhancing students' academic abilities but also setting a model for sustainable practices (Purcell *et al*., 2019; Sugiarto *et al*., 2022). Through the adoption of plastic waste management strategies, students can be enabled to serve as catalysts for change in confronting environmental challenges (Bennett and Alexandridis, 2021). Studies have shown that hands-on experience and practical involvement in plastic waste management during college can play a significant role in shaping students' pro-environmental behavior in the future (Alazaiza *et al*., 2024). Students' direct engagement in sustainability programs can stimulate responsible behaviors towards the plastic waste they generate (Gao *et al*., 2017). Evaluating students' practices in managing plastic waste can be utilized to design targeted sustainability programs (He and Yu, 2023). Prior studies have demonstrated that analyzing students' practices can shed light on how significantly their habits involve single-use plastics, thereby enabling campuses to devise policies that are more environmentally conscious (Truelove *et al*., 2022). The research results indicate that students' practices in managing plastic waste are positively categorized as "good" at all three green campuses (Table 5). The closeness of the scores, as seen in Table 5, indicates that the three green campuses are in comparable performance categories. This consistency suggests that universities participating in green campus programs can appears to support students to adopt similar plastic waste management practices. This is due to the availability of adequate facilities and infrastructure, as well as intensive environmental education and green campus program policies at Brawijaya University, State University of Malang, and University of Muhammadiyah Malang, in line with sustainable practices (Fig. 2). Recent investigations propose that these three components can markedly boost students' approaches in reduction, reuse, and recycling (Budihardjo *et al*., 2021; Gursoy Haksevenler *et al*., 2022). While student plastic waste management practices appear similar across the three green campuses, Fig. 2 shows that sustainability infrastructure and facilities vary across universities. Variations in the implementation of plastic waste management systems indicate that comparable practical results may arise from diverse institutional models of execution. Literature studies also reveal that various facilities and plastic waste management systems provided by campuses serve as evidence of commitment to sustainability, such as integrated waste management centers, provision of waste bins according to type, education delivery, and environmental campaigns (Belleflamme and Ha, 2024; Kala and Bolia, 2021; Yu *et al*., 2022).

Table 5: Student Practices in Plastic Waste Management

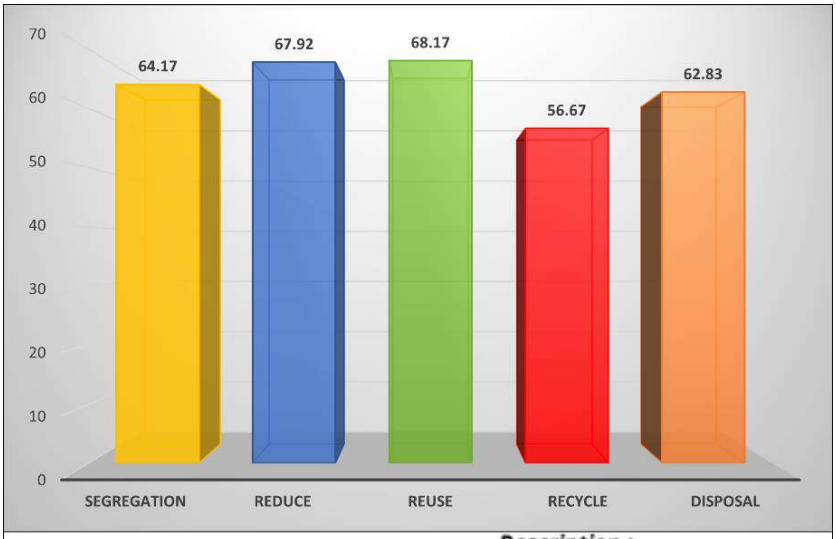
University	Weighted mean	Interpretation
Brawijaya University	2.59	Good
State University of Malang	2.58	Good
University of Muhammadiyah Malang	2.56	Good

Research in the Philippines indicates that, in the implementation of plastic waste management practices, students tend to be more active and engaged in aspects such as segregation and reduction, but still lack proficiency in disposal practices (Paghasian, 2017). Studies in Malaysia reveal that students' approaches to managing plastic waste are more focused on recycling rather than on reduction and reuse (Moh and Abd Manaf, 2017). Studies conducted in Japan suggest that students demonstrate a greater tendency to participate in recycling activities rather than to



Fig. 2: Plastic waste management facilities at three green campuses in Malang City include integrated waste-disposal sites, separate waste bins, plastic waste-sorting equipment, and reverse vending machines

repurpose the plastic waste they produce (Moshkal *et al*., 2024). On the other hand, the results of this study show that students in the three green campuses tend to be more active in participating in reuse practices (68.17%), reduction (67.92%), segregation (64.17%), and disposal (62.83%), but still perform poorly in recycling practices (56.67%), as can be seen in Fig. 3. These findings align with the Theory of Planned Behavior, which suggest that human behavior is influenced by three key factors: intention, subjective norms, and behavioral control, all of which can trigger pro-environmental actions. Consequently, actions that are viewed as simpler to execute are more likely to be selected (Ajzen, 1991; Truelove *et al*., 2014). Based on Fig. 3, students tend to be more actively involved in reduction and reuse practices because these two practices are perceived as easier to carry out and capable of encouraging contributions compared to recycling practices, which require formal recycling technology and systems. This is also consistent with the Waste Hierarchy Framework, which prioritizes segregation, reduction, reuse, recycling, recovery, and disposal. The framework explicitly prioritizes reduction and



$$\text{Percentage} = \left(\frac{\text{Weighted Mean}}{\text{Maximum Scale Value}}\right) \times 100$$

Description :

81.25-100%	**Very Good**
62.50-81.00%	**Good**
43.75-62.25%	**Bad**
25.00-43.50%	**Very Bad**

Fig. 3: Bar chart related to the results of student practice in managing plastic waste on campus, including segregation, reduction, reuse, recycling, and disposal

reuse practices over recycling practices, whereby students on green campuses who understand the principles of sustainability are likely to adopt them normatively and consider them the most ecologically sound choice. This study indicates that students are more inclined to adopt plastic waste management practices, such as reduction and reuse, due to their psychological and structural ease of implementation in a green campus context, especially in certain developing countries that have not yet put in place an optimal recycling framework.

Question item distribution

The questionnaire contained questions that were used to evaluate trends in student responses. Fig. 4 shows the distribution of question items and responses from students ranging from "*very good, good, poor, to very poor*". Based on the results from Brawijaya University and State University of Malang, there is strong recognition or very good practices regarding students' contributions to reducing and disposing of plastic waste. Students generally favor using personal drinking bottles instead of buying beverages in single-use plastic containers (Question 8). In addition, most students have also adopted a "*self-service*" culture by cleaning up the canteen waste they generate (Question 22). Students at State University of Malang also demonstrate a strong tendency to use food containers that can be washed and reused over a long period (Question 13).

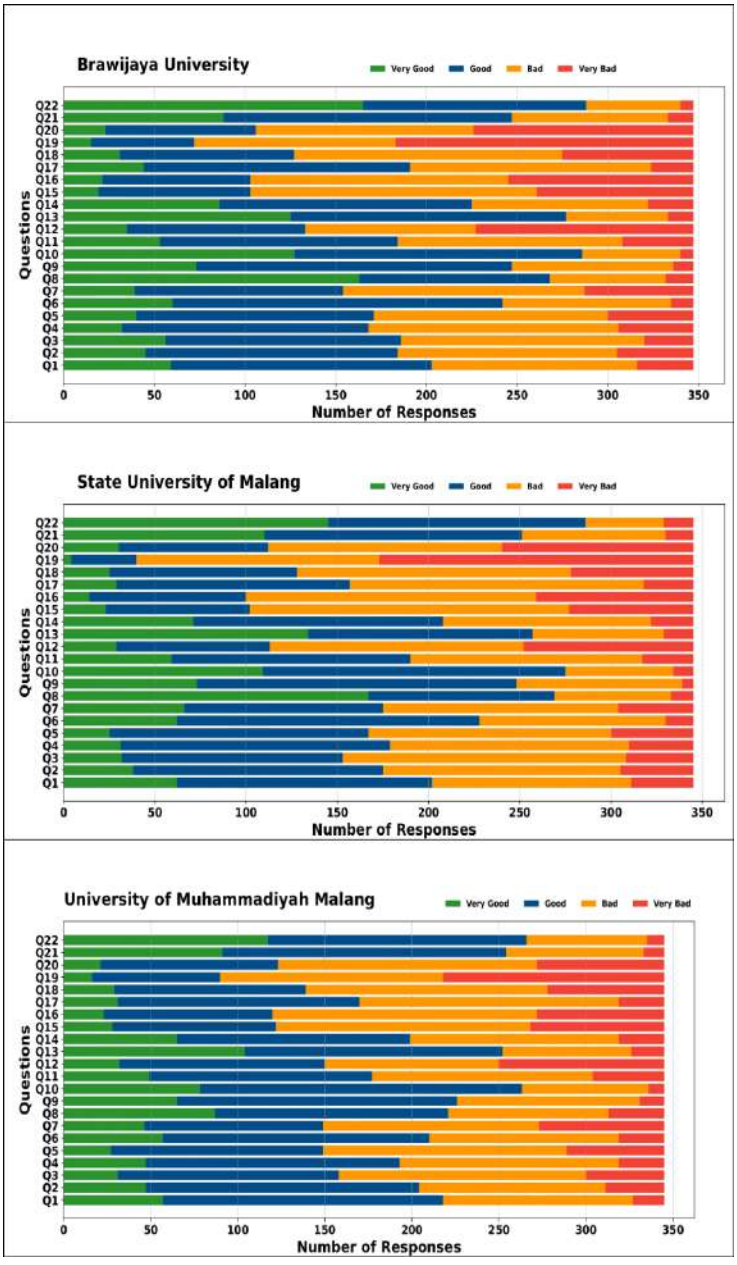


Fig. 4: Distribution of questionnaire item responses to student practices in plastic waste management based on Likert scale measurements

Conversely, students at the University of Muhammadiyah Malang express positive feedback and acknowledgment regarding the practice of reusing, as they prefer to utilize plastic items that are still functional instead of purchasing new ones (Question 10). In addition, they have also become accustomed to properly disposing of plastic waste into the appropriate bins according to its type (Question 21). The feedback from students at the three campuses showed significant variation, suggesting inadequate practices in managing plastic waste. Notable practices were reflected in questions 12, 17, and 19. Students tend not to reuse used items, such as detergent or

cooking oil plastics, in polybags or similar containers (Question 12). Students confessed that they commonly disregard the value of recycling plastic waste (Question 17). Additionally, students also responded that they frequently litter or leave their trash in open environments (Question 19). These results underscore the significance of enhancing comprehensive environmental education within the campus. Additionally, it underscores the importance of educational initiatives centered on recycling and disposal practices, with their execution aligned with the Sustainable Development Goals (SDG), notably SDG 4 (quality education) and SDG 12 (responsible consumption and production).

Waste segregation

In alignment with the modern version of the Waste Hierarchy Framework, the primary focus in addressing plastic waste is on prevention (UNEP and ISWA, 2015; Whiteman *et al*., 2021; Wilson, 2023). Segregation practices are one of the preventive activities that play a crucial role in supporting efficient plastic waste management, which involves collection and separation at the source (Ravishankar *et al*., 2021; Sivaranjani *et al*., 2024). In plastic waste segregation practices, the three green campuses fall into the "*good*" category, with University of Muhammadiyah Malang showing the highest average score of 2.60, followed by Brawijaya University (2.57) and State University of Malang (2.53), as shown in Fig. 5. This corresponds with studies findings in the Philippines, indicating that students are involved in segregation practices in both campus and home environments, especially those who live in campus dormitories (Dolipas *et al*., 2018). Based on the observation results, segregation practices at University of Muhammadiyah Malang are carried out daily and divided into seven categories: plastic bottles, plastic cups, food containers, HVS paper, cardboard, bottle caps, and organic waste. Brawijaya University and State University of Malang also demonstrate a genuine commitment to sustainable practices. Segregation of waste at Brawijaya University emphasizes the separation of bottles and cardboard, conducted weekly in the Integrated Education Laboratory. Segregation at State University of Malang focuses on segregation plastic waste (bottles and plastic cups), organic waste, and cardboard waste, as evidenced by the presence of 3R Waste Management Facilities, reverse vending machine facilities, and plastic bottle collection points at various locations. This demonstrates that appropriate facilities can promote sound segregation practices among students (Gursoy Haksevenler *et al*., 2022; Tangwanichagapong *et al*., 2017; Uehara *et al*., 2022). This conclusion implies that the separation of plastic waste at its source is a key factor in establishing a sustainable green campus. Furthermore, besides decreasing the strain on landfills, segregation also helps to inform students about the necessity of environmental responsibility, starting with their individual contributions (Priti and Mandal, 2019). Segregation plastic waste can also enhance recycling efficiency to achieve better quality (Lubongo *et al*., 2024). The practice of segregation emphasizes that in the hierarchy of plastic waste management, this process plays a primary role, enabling reuse, reduction, recycling, and disposal practices to become more efficient, thereby minimizing negative impacts on the environment.

Waste Reduction

The involvement of students is essential for minimizing the use of single-use plastics. Studies in Thailand reveal that students act as proactive social agents who can effectively help in lowering plastic waste (Supakata, 2018; Vassanadumrongdee *et al*., 2020). Studies confirm that students generally have positive attitudes and practices regarding plastic waste reduction (He and Yu, 2023; Nguyen *et al*., 2024; Situmorang *et al*., 2020). Consistent with these

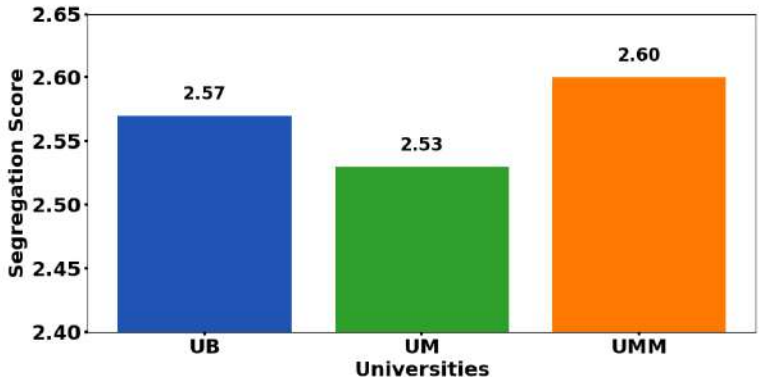


Fig. 5: The weighted mean scores for student practices related to segregation at the three green campuses

findings, this study also found that students demonstrate good plastic waste management practices, particularly in the reduction aspect. State University of Malang scored 2.79, followed by Brawijaya University (2.76) and University of Muhammadiyah Malang (2.60), as shown in Fig. 6. Students are actively demonstrating their commitment to reducing single-use plastics are evident through specific actions, including carrying reusable water bottles, food containers, and tote bags to campus (Fig. 6). Utilizing these items in daily life can reduce the amount of single-use plastic and contribute to the sustainability of a green campus. A study conducted at a Japanese University indicated that the utilization of reusable water bottles could lead to a potential reduction of 45,191 single-use plastic bottles on campus, with 58.8% of students expressing their willingness to engage in this initiative (Uehara and Ynacay-Nye, 2018). Research at Imam Abdulrahman Bin Faisal University (Saudi Arabia) also stated that using reusable water bottles could reduce PET bottle waste on campus by 90% and actively encourage student participation (Saleem *et al*., 2019). Conversely, campaigns focused on education and the facilities available on campus play a vital role in directly motivating students to adopt positive measures to minimize plastic waste (Sumarmi *et al*., 2024). Similarly, research in Thailand and China also shows that intensive education and campus policies actively motivate students to participate in plastic waste reduction (He and Yu, 2023). These conclusions underscore the importance of targeted education and the sharing of information about the necessity of minimizing plastic waste to foster pro-environmental actions among students.

Waste reuse

The practice of reuse dominates plastic waste management initiatives in universities (Rodríguez-Guerreiro *et al*., 2024). This study reveals that students demonstrate 'good' practices in the reuse category, with Brawijaya University achieving a weighted average score of 2.76, State University of Malang at 2.74, and University of Muhammadiyah Malang at 2.68 (Fig. 7). These results indicate that students most commonly engage in reuse practices. Students repeatedly use items that are still usable, either for the same purpose or for a different one. They do not use disposable items but replace them with more durable alternatives. The achievements of these three environmentally friendly campuses are bolstered by amenities including water refill stations at UB, drinking fountains at UM, and accessible ready-to-drink taps at UMM (Fig. 7). A green campus has the opportunity to reduce plastic waste by providing high-quality drinking water taps, which can minimize the use of bottled water and encourage the switch to reusable water bottles.

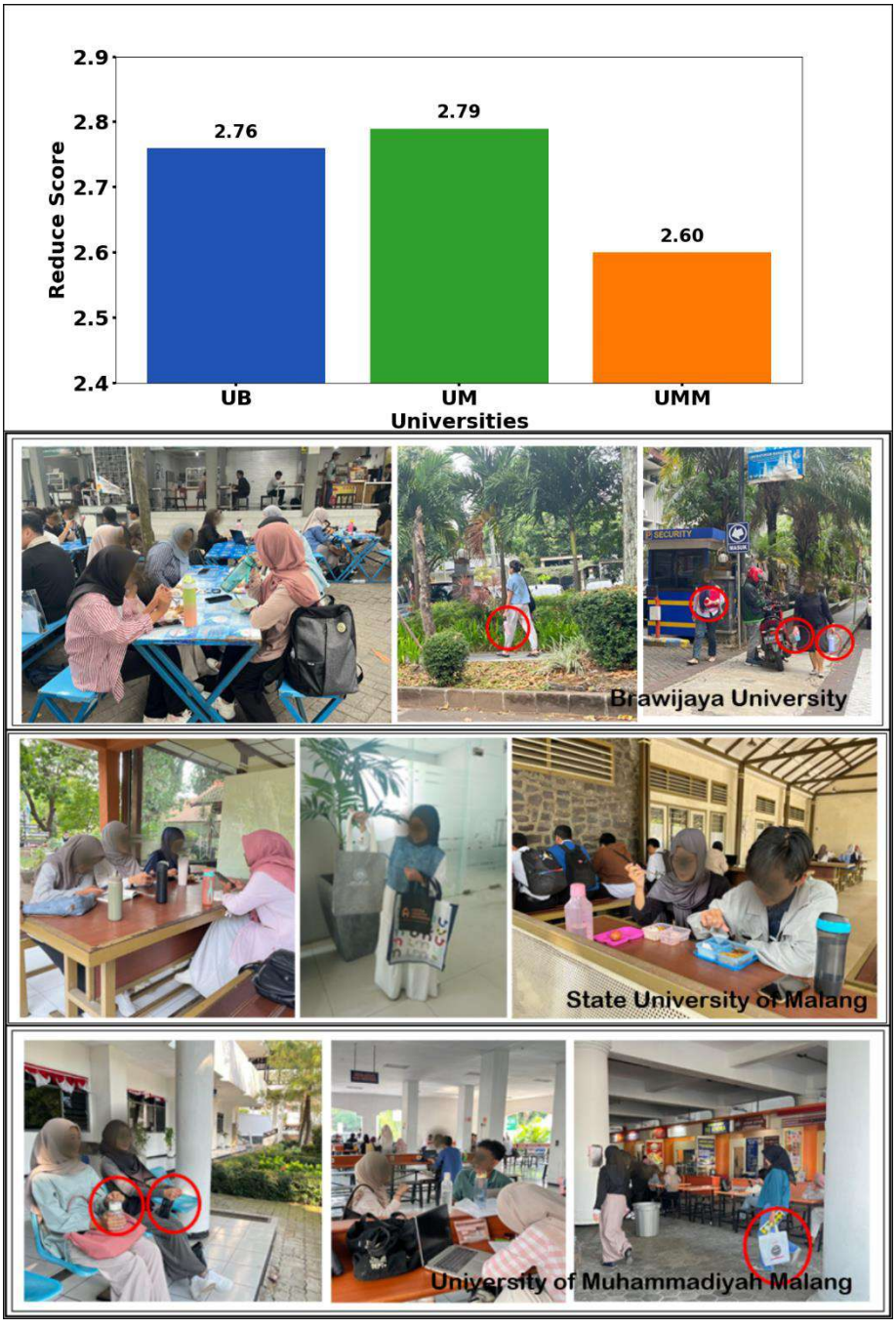


Fig. 6: Bar chart related to the weighted mean score results of students' plastic waste reduction practices at three green campuses, accompanied by field documentation of the reduction efforts made (such as bringing personal bottles and food containers, and tote bags)

Studies indicate that the installation of water fountains has proven effective in minimizing the use of single-use bottles, promoting opportunities for reuse practices, and encouraging students to regularly utilize their personal water bottles (Bethurem *et al*., 2021; Uehara and Ynacay-Nye, 2018). This approach has been successfully implemented in several developed countries, such

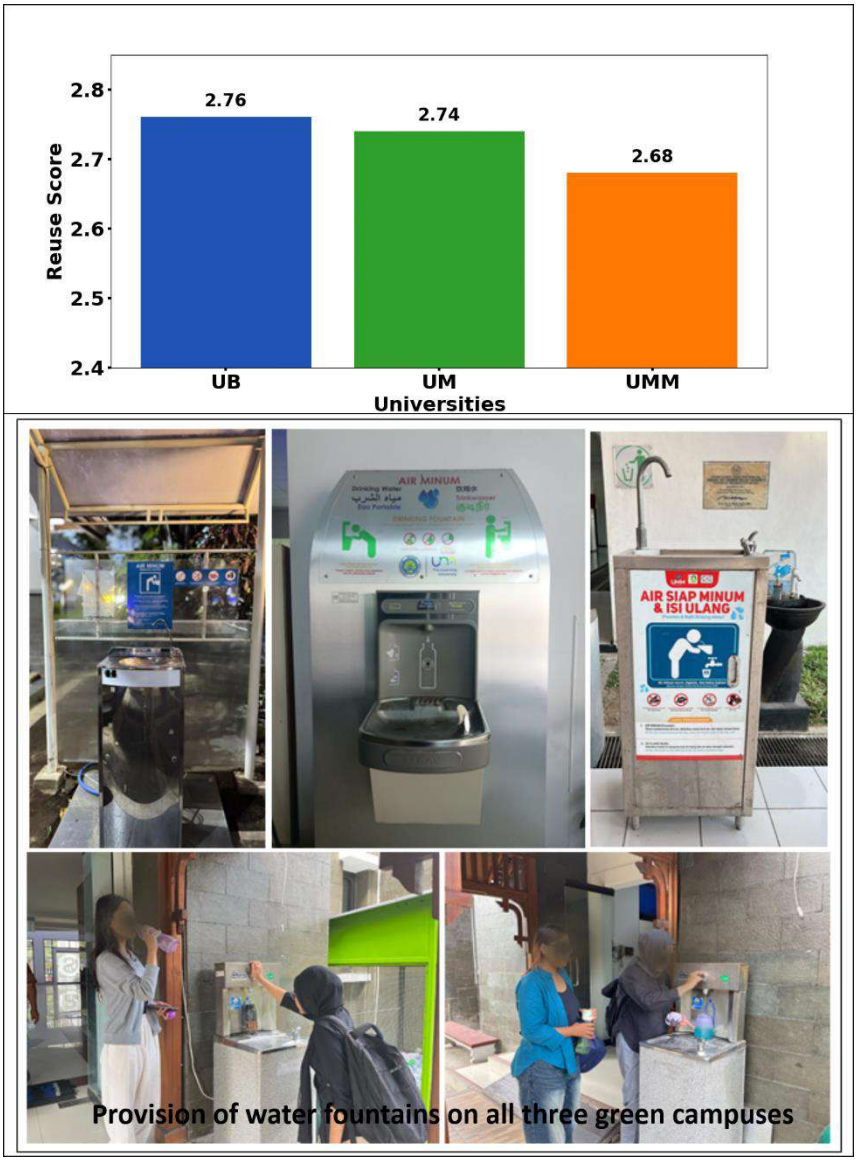


Fig. 7: Weighted mean score results of student reuse practices at three green campuses, highlighting the role of water fountain facilities on campus to support the use of reusable bottles

as the United Kingdom, which managed to reduce the distribution of single-use plastic bags and decrease their usage by 81% per capita per month between 2010 and 2012 (Thomas *et al*., 2016). The three campuses have also instituted environmental education through learning to perpetually foster students' self-initiative in adopting reuse concepts (Thomas *et al*., 2019). Significantly practiced reuse can reduce the burden of plastic waste at landfills and minimize the impact of plastic pollution, thereby preserving natural resources more effectively (Bonilla-Jurado *et al*., 2024; Douglas *et al*., 2024).

Waste recycle

The characteristic of plastics being difficult to decompose necessitates proper recycling after use (Alam *et al*., 2025). The practice of recycling

has gained importance as it supports the reuse of materials and provides greater energy savings than the production of raw materials, which in turn helps to reduce the volume of plastic waste accumulating in landfills (Maitlo *et al*., 2022; Pandey *et al*., 2023). Literature studies reveal that recycling can save between 40-100 MJ/kg of energy and minimize the depletion of fossil fuels (Prakash and Pathak, 2017). However, previous research states that recycling is actually the practice most frequently evaluated (Helm *et al*., 2023). Other studies also reveal that only about 1% of waste undergoes the recycling stage, largely due to a lack of participation (Mbama *et al*., 2023). According to research findings indicating that students' methods of managing plastic waste, particularly in recycling, are classified as "poor". University of Muhammadiyah Malang has an average of 2.30, while Brawijaya University has 2.26 and State University of Malang has 2.24 (Fig. 8). Based on the results of observations, the Student Executive Board of University of Muhammadiyah Malang has implemented several recycling programs that involve students in transforming plastic waste into high-value products, such as paving blocks (Fig. 8). Brawijaya University and State University of Malang also contribute and show commitment to recycling programs through collaboration with third parties and the provision of waste banks on campus (Fig. 8). Nevertheless, the effective execution of waste banks on campus significantly depends on student engagement to guarantee that the recycling initiative runs efficiently and sustainably. Based on observations, the recycling concept is still implemented manually by university staff after collection at the three campuses, with fewer than 10 workers and no direct student involvement. Furthermore, insufficient recycling infrastructure and the inconsistency of sorting bins contribute to the mixing of plastic waste downstream, resulting in students being unwilling to take part in recycling initiatives on campus. In this regard, upstream segregation and student involvement need to be maximized, specifically through public awareness programs, so that recycling practices can be properly implemented. The efforts made by the three campuses to educate students about the importance of the recycling concept imply that there is still a need for further integration in providing adequate facilities and information regarding the recycling programs initiated by the universities, so that students can participate directly in recycling activities. This corresponds with prior studies, which asserts that institutions that effectively embed environmental education and furnish appropriate facilities are likely to see increased student engagement in plastic waste recycling initiatives (Ralph and Stubbs, 2014; Sugiarto *et al*., 2022).

Waste disposal

One of the factors targeted in green campus policies to achieve the goals of waste reduction programs is by reducing littering behavior. On-campus disposal practices are associated with the manner in which students handle plastic waste. In terms of disposal practices in plastic waste management, University of Muhammadiyah Malang has a score of 2.55, and Brawijaya University has a score of 2.50, both categorized as “good,” while students at State University of Malang still tend to be lacking in this practice, with a score of 2.49 (Fig. 9). Reflecting on the observation results, each of the three campuses has provided waste disposal facilities that are categorized into three distinct types to assist in the recycling of plastic waste. The disposal practices at University of Muhammadiyah Malang and Brawijaya University are evident in the self-service culture implemented on campus, particularly in the canteen areas (Fig. 10). Meanwhile, although waste disposal facilities are adequate at State University of Malang, students still rely on cleaning staff, especially in the canteen and learning space areas, so the self-service culture has not yet been established among students (Fig. 10).

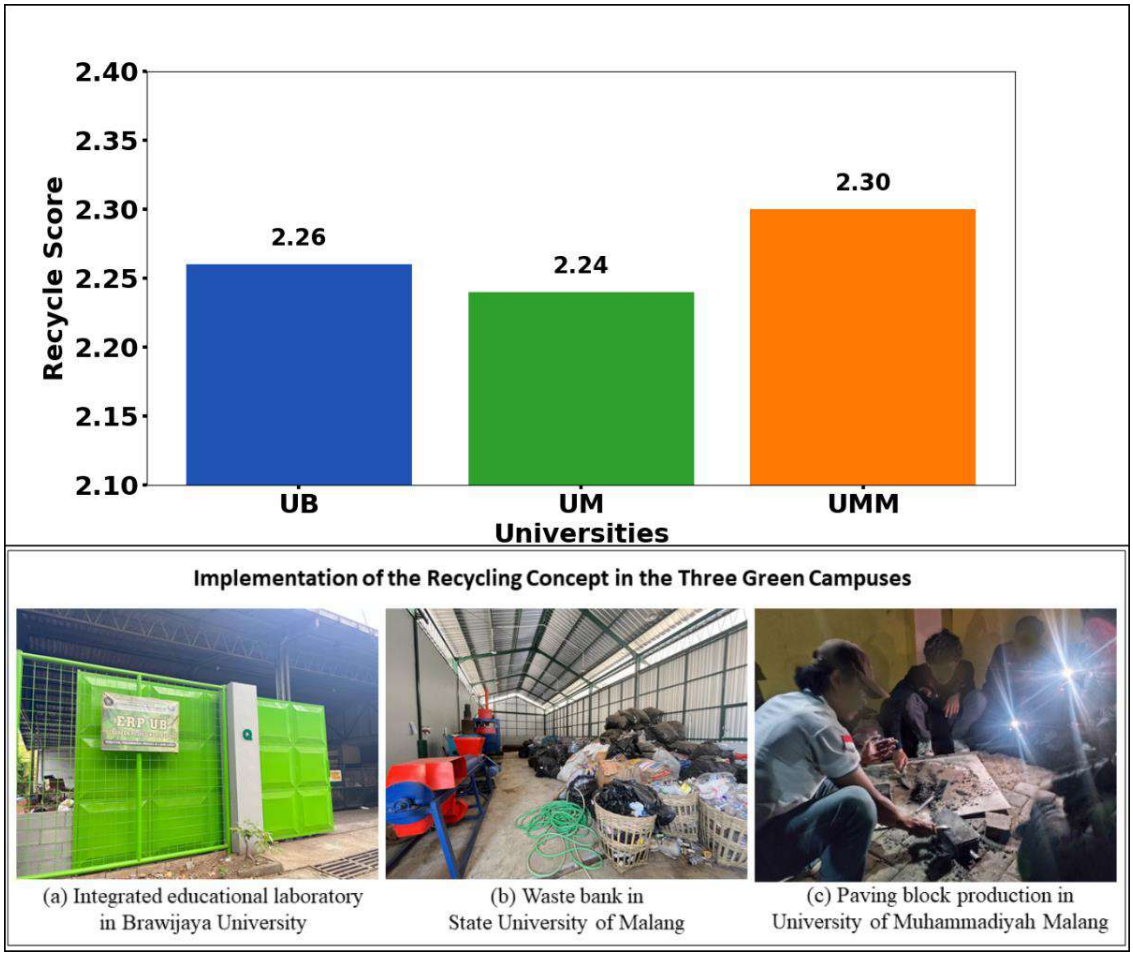


Fig. 8: The results of students' plastic waste recycling practices at three green campuses, based on a weighted mean score, supported by the availability of campus recycling facilities (such as integrated educational laboratories, waste banks, and paving block making workshops)

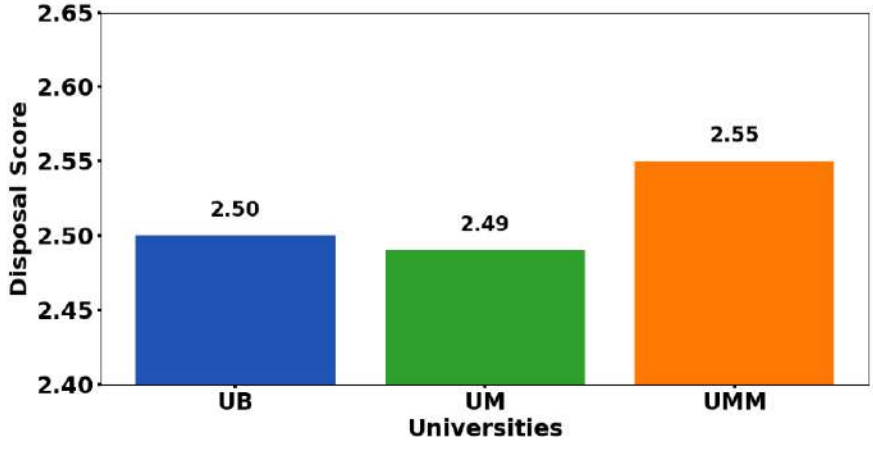


Fig. 9: The weighted mean scores for student practices related to the disposal aspect at the three green campuses

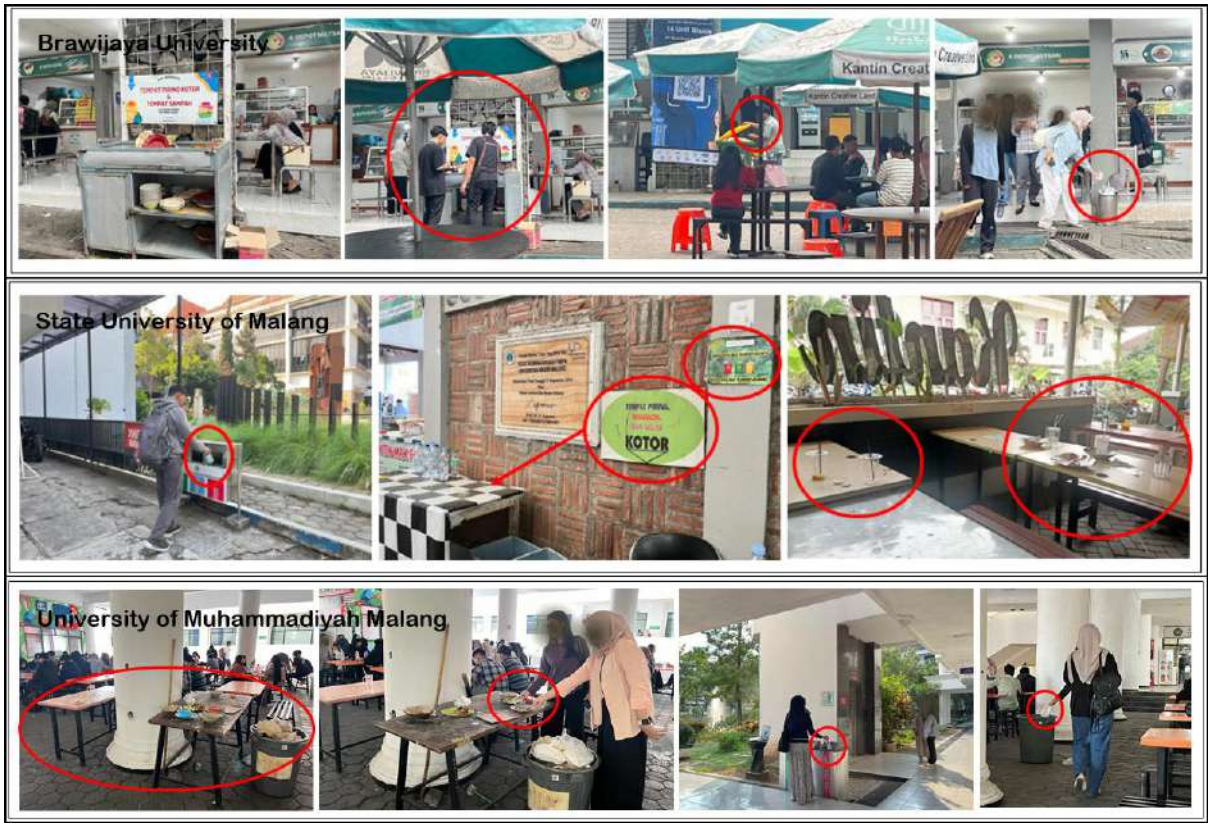


Fig. 10: The implementation of student waste management practices is demonstrated through the self-service culture on the three green campuses

This frequently happens because of inadequate socialization within each faculty, a lack of preventive measures, and the nonexistence of uniform penalties (Starovoytova and Namago, 2018). Therefore, the results of students' disposal practices become a complex area (Morris *et al*., 2024), due to poor disposal practices, such as a disposable mindset and dependence on sanitation staff, which can exacerbate the accumulation of plastic waste in landfills (Chae and An, 2018; Chen *et al*., 2021). These results underscore the significance of appropriate disposal methods for students in mitigating the effects of plastic waste buildup in campus settings. Personal involvement, such as a self-service culture, is needed to encourage individuals to take responsibility for the plastic waste they produce without relying on others to dispose of it (Ramakrishna and Ramasubramanian, 2024). Moreover, it is essential for campuses to supply waste bins that are not restricted to the classifications of organic, inorganic, and hazardous/toxic waste, but should also feature multiple categories designed to meet the specific needs of each campus. Research at Massey University (New Zealand) indicates that 83% of students are more likely to properly sort their waste if the campus provides more waste bins (Balkaya and Bilgin, 2019). In line with research at Rhodes University (South Africa), which revealed that recycling bins should be strategically placed and easily accessible (Mtutu and Thondhlana, 2016). These findings have significant implications for achieving green campus sustainability. The findings indicate that

while reuse and reduction practices tend to be stronger, recycling practices tend to be weaker. This indicates that initiatives for green campuses might be more effective in executing prevention-oriented practices compared to recovery-oriented practices. For green campuses, these findings suggest the need to improve operational transparency in recycling practices and ensure that plastic waste streams are not remixed downstream. The disparities in infrastructure present at the three green campuses imply that aligning recycling facilities with student behavior is necessary for each campus. Therefore, to achieve sustainable green campus initiatives, institutional frameworks need to be developed in accordance with student needs. This research contributes to the development of green campuses by providing insights into creating policies and initiatives to promote sustainable practices among students, particularly in plastic waste recycling practices. Students play a crucial role as effective agents who can bring about profound change (Mohamad *et al*., 2021; Murray, 2018), therefore, empowering and involving students in practices such as segregation, reducing, reusing, recycling, and disposing of plastic waste is important. The results indicate that the environmental culture present on campus, the accessibility of facilities and infrastructure for managing plastic waste, as well as ongoing campaigns, are linked to the practices of students in handling plastic waste. Well-implemented plastic waste management practices can make students' active participation in reducing the burden on on-campus waste collection points and strengthen the institution's image as a sustainable green campus. These findings also need to be interpreted within the broader context of Indonesia's plastic waste management system as a developing country. Recycling facilities are limited, and downstream processing capacity remains uneven, which could impact the achievement of sustainability initiatives on green campuses.

CONCLUSION

The practice of plastic waste management is recognized as a crucial component in addressing various sustainable development challenges. By implementing plastic waste management practices, students can be empowered to act as agents of change in addressing environmental issues. The research reveals that students at the three green campuses tend to be more active in engaging in reuse practices (68.17%), reduction (67.92%), segregation (64.17%), and disposal (62.83%), but still perform poorly in recycling practices (56.67%), indicating the need for further attention. This study reveals that the approach of managing plastic waste via reduction and reuse is more readily embraced by students, given that it is easier to implement both psychologically and structurally in a green campus environment. These findings imply that green campus initiatives may be better at implementing prevention-based practices than recovery-based ones. For green campuses, these findings highlight the need for increased operational transparency in recycling practices and ensuring that plastic waste streams are not remixed downstream. To successfully implement sustainable green campus initiatives, institutions must create frameworks that cater to the requirements of their students. Furthermore, the findings suggest that the environmental culture on campus, the ease of access to facilities and infrastructure for plastic waste management, and consistent campaigns are associated with students' practices in managing plastic waste. For the purpose of achieving a sustainable green campus, universities should focus on developing

students' skills, facilitating participation, and improving recycling practices through the curriculum and a range of programs that include environmental education, thereby ensuring lasting experiences. This study makes a theoretical contribution to the literature by conceptualizing plastic waste management as an integrated practice within the waste management hierarchy. It positions the five measured aspects as interrelated stages of practice in achieving green campus sustainability. However, this study has several limitations. First, this study uses a descriptive-quantitative research design and a lengthy questionnaire distributed to students, which may lead to inconsistent responses. Secondly, the scope of this research remains restricted to Malang City, Indonesia. Third, response bias might arise, and it is not possible to entirely eliminate non-response bias. Additionally, voluntary participation could result in volunteer bias, which may cause an overrepresentation of students. Therefore, these limitations may affect future research by obtaining more representative and comprehensive results, namely by conducting in-depth interviews with respondents during the survey, expanding the study to several green campuses across various regions or other countries, and conducting inferential statistical tests to analyze significant differences. Future studies are strongly encouraged to explore the subsequent aspects, particularly in order to realize a sustainable green campus: 1) exploring and analyzing the factors that hinder students in practicing plastic waste recycling; 2) incorporating a mixed-methods approach to avoid self-report bias and strengthen empirical validation; 3) using a longitudinal design to examine the temporal stability and evolution of plastic waste management practices on green campuses; 4) a comparative study across various green campuses in Indonesia to clarify best practices in plastic waste management among university students. Consequently, forthcoming studies may aid in the advancement and execution of a more sustainable green campus.

AUTHOR CONTRIBUTIONS

N. Shaherani conducted field observations, literature review, collected primary data, organized data, analyzed and interpreted data, and prepared the entire manuscript text, including editing. S. Utaya, the corresponding author, contributed by guiding the first author in drafting the research background, research objectives, methodology, and manuscript review. Sumarmi provided assistance in research design, content analysis, and manuscript review. S. Bachri prepared data visualization and interpreted the results, including reviewing the results and discussion. T. Matsumoto assisted with discussing the depth of novelty and the manuscript review. I. Rachman reviewed the manuscript and provided conclusions.

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CONFLICT OF INTEREST

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

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

ABBREVIATIONS

%	Percent
f_i	Frequency of responses
x_i	Assigned weight of each Likert scale category
$\sum f_i$	Total number of responses
dk	1, error level 1%, 5%, 10%
EU	European Union
EPA	Environmental Protection Agency
ISWA	International Solid Waste Association
MJ/kg	Megajoule per kilogram
MT	Million tons
N	Population size
P	Population
S	Sample
s	Number of simples
SDG	Sustainable development goals
t/d	Tons per day
UB	Brawijaya University
UM	State University of Malang
UMM	University of Muhammadiyah Malang
UNEP	United Nations Environment Programme
WM	Weighted mean
x^2	Chi square

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REVIEW PAPER

Emerging artificial intelligence and machine learning paradigms in environmental pollution control and abatement

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ABSTRACT

The growing complexity of environmental pollution, driven by rapid industrialisation and urbanisation, has highlighted the limitations of traditional approaches to environmental monitoring and control. In recent years, artificial intelligence (AI) and machine learning (ML) have emerged as powerful tools for environmental applications; however, most current implementations remain predominantly prediction-oriented, with limited interpretability, generalizability, and integration with underlying physical processes. This review provides a qualitative and critical synthesis of emerging AI paradigms, focusing on their applications, interconnections, and limitations in environmental pollution control. The review examines key paradigms, including physics-informed machine learning, explainable artificial intelligence, digital twin systems, edge intelligence, federated learning, and autonomous optimization approaches. These paradigms are analysed in terms of their capabilities to enhance model reliability, improve real-time decision-making, and support system-level integration. Applications across major environmental domains, including air quality management, water and wastewater treatment, soil remediation, and solid waste management, are discussed to highlight both advancements and domain-specific challenges. Unlike previous reviews that focus on individual techniques, this work integrates multiple emerging paradigms within a unified framework, emphasising their complementary roles and potential for hybrid implementation. Particular attention is given to critical challenges, including data scarcity and heterogeneity, model transferability, computational requirements, reproducibility, and regulatory acceptance. The review also highlights that many current studies remain limited to simulation-based or site-specific implementations, underscoring the need for broader real-world validation. Key research gaps and future directions are identified, including the development of hybrid modeling frameworks, standardized evaluation metrics, improved uncertainty quantification, and responsible and transparent AI deployment. Emerging trends, such as decentralized and adaptive AI systems, are also discussed in the context of sustainable environmental management. In addition, the integration of AI with domain knowledge and environmental processes is essential to ensure reliability, transparency, and practical applicability in real-world systems. Overall, emerging AI paradigms are positioned as enabling tools for transitioning from prediction-centric models to integrated, interpretable, and adaptive systems for effective and sustainable environmental pollution control.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
96	1	2

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INTRODUCTION

Environmental pollution remains a serious problem for the integrity of ecosystems, public health and sustainable development, both at the regional and at the global level. Rapid industrialization, urban growth, population, and intensifying anthropogenic activities have led to an increasing complexity in pollution profiles in air, water, soil, and solid waste systems. Despite decades of advancements in pollution monitoring, pollution treatment technologies, and pollution regulations, many environmental management strategies are reactive, site-specific, and limited in their ability to address dynamic and interconnected processes in pollution. Conventional methods for controlling pollution are grounded primarily in empiricism, mechanistic modeling, and rule-based decision-making methods. While these methods have been successful in controlled or well-characterized environments. They can often struggle with capturing nonlinear interactions, spatiotemporal variability, and uncertainty that are inherent in environmental systems of the real world. Furthermore, the growing data of environmental information generated by sensor networks, remote sensing platforms and smart infrastructure has outpaced the analytical capacity of traditional modeling techniques to cope with the increasing demand for more sophisticated data-driven tools (Sundas *et al.,* 2024; Volf *et al.,* 2024; Sridhar and Parimalarenganayaki, 2025; Hashir *et al.,* 2025). It is in this regard that artificial intelligence (AI) and machine learning (ML) have proven to be powerful enablers in controlling environmental pollution. During the last decade, different types of AI-based schemes have been extensively implemented in several applications for the forecasting of pollutant concentration, estimation of emissions, optimization of processes, and environmental risk assessment. Applications cover a wide range of areas such as air quality prediction, optimization of wastewater treatment processes, mapping of soil contamination or waste management logistics. These early implementations have demonstrated the potential of AI in aiding the extraction of meaningful patterns from complex datasets and improving the predictive performance of AI over traditional approaches. However, the first generation of AI applications in environmental pollution control has been mostly prediction-based, usually of the black box type based on historical data. Such approaches often have poor interpretability, poor generalizability to other sites and reduced robustness in changing environmental conditions. These limitations have constrained their practical deployment, particularly in regulatory and operational contexts where transparency, reliability, and physical consistency are paramount (Mathaba and Banza, 2023; Popescu *et al.,* 2024; Olawade *et al.,* 2024). The recent development of sensing technologies, computational capabilities and artificial intelligence methodologies has introduced a shift towards more sophisticated and integrated artificial intelligence frameworks. Emerging paradigms emphasize the combination of physical and chemical knowledge in learning processes, increased model output explainability, integration of real-time systems, and adaptive decision-making. Concepts like physics-informed machine learning, explainable artificial intelligence, digital twins, edge intelligence, federated learning, and autonomous optimization systems are a step away from isolated data analytics to intelligent environmental management systems. Against this background, a comprehensive and critical synthesis of these new emerging paradigms of AI and ML is timely and needed. While many studies have been done in certain areas of the environment, a cohesive evaluation of the contributions of next-generation AI frameworks to pollution control and abatement in several environmental media is scarce. Moreover, challenges such as data quality, scalability, energy consumption, infrastructure compatibility, and regulatory acceptance still influence the speed of

adoption in the real world (Sharma *et al.,* 2022; Rashid and Kausik, 2024; Miller *et al.,* 2025; Yan *et al.,* 2025). This review aims to critically analyze the development and new paradigms for AI and ML in the field of environmental pollution control and abatement. The review combines recent developments in AI methodologies, discusses their application to air quality management, water and wastewater treatment, soil remediation, and solid waste management (SWM), and helps identify challenges and research needs. By offering a structured and forward-looking assessment, this work seeks to clarify the role of AI of the next generation as an enabling tool for more effective, transparent, and sustainable environmental pollution control strategies. In this context, the present review aims to provide a critical and integrative assessment of emerging AI and ML paradigms for environmental pollution control and abatement. Unlike previous studies that focus on individual methodologies, this work synthesizes multiple paradigms within a unified framework, emphasizing their interconnections, strengths, and limitations. The review further examines their applications across major environmental domains, including air, water, soil, and solid waste systems, while critically evaluating challenges related to scalability, interpretability, data requirements, and regulatory acceptance. By bridging the gap between methodological development and practical implementation, this study offers a forward-looking perspective on the role of next-generation AI in enabling adaptive, transparent, and sustainable environmental management. This review focuses on recent developments in AI paradigms for environmental pollution control, primarily covering studies from the last decade. Conventional statistical models and purely empirical approaches are not considered in detail, as the emphasis is on next-generation AI frameworks that integrate physical knowledge, interpretability, and system-level intelligence.

Evolution of artificial intelligence and machine learning in environmental pollution control

The use of artificial intelligence and machine learning tools in environmental pollution control has grown and developed over the last two decades in response mostly to greater data availability and computational capacity. Early attempts have mostly been based on statistical modeling and rule-based expert systems for environmental monitoring and decision-making. While these approaches offered valuable insights under controlled conditions, they were limited in the ability to handle nonlinear relationships, high-dimensional datasets, and complex interactions between environmental variables (Rautela *et al.,* 2024; Ji *et al.,* 2025; Le Goff, 2025). The adoption of conventional machine learning methods such as artificial neural networks, support vector machines, decision trees and ensemble approaches came next, which represented a huge change towards data-driven environmental modeling. These techniques provided a means of better predicting the concentration of pollutants, treatment efficiencies and emission patterns of pollutants from air, water, and soil systems. In wastewater treatment and air quality forecasting, for example, ML-based models proved to be better predictive models than traditional empirical models. However, their effectiveness was often limited because of site-specific training data, limited interpretability, and sensitivity to data quality and variability (Ladi *et al.,* 2022; Supto, 2025; Anik *et al.,* 2025). With the explosive proliferation of environmental datasets produced by sensor networks, satellite-based observations, and smart infrastructure, deep learning methods (e.g., convolutional neural networks and recurrent neural networks) came to the forefront. These methods have been especially successful in the processing of spatiotemporal data, image-based pollution mapping and time-series forecasting. Despite their success, deep learning models posed new challenges concerning the black box behavior of their models, the high computational requirements, and the integration of domain

knowledge, thus limiting their acceptance in regulatory and operational settings. More recently, hybrid modeling approaches have emerged that combine both data-driven learning with process-based models and domain expertise. These approaches try to combine the strength of both physical modeling and machine learning to improve their robustness and lower the dependency on large datasets. At the same time, more focus has been put on model transparency, uncertainty quantification and real-time adaptability, which is also in line with the urgent need for trustworthy AI in environmental decision-making (Yuan *et al.,* 2020; Mukonza and Chiang, 2023; Lian *et al.,* 2025; Ekundayo and Ezugwu, 2025). In the context of environmental systems, interpretability extends beyond model transparency in a computational sense. It includes the ability to relate model outputs to physically meaningful variables, regulatory thresholds, and operational decisions. Unlike conventional machine learning contexts where interpretability may focus on feature importance or visualization, environmental applications require explanations that can support risk assessment, policy compliance, and process optimization. The lack of such domain-relevant interpretability has limited the adoption of many data-driven models in real-world environmental management. However, it is important to note that not all deep learning models are equally opaque. For instance, convolutional neural networks applied to satellite imagery and spatial pollution mapping can offer a degree of interpretability through activation maps and feature visualization techniques. Compared to earlier neural network models, such approaches can provide spatially explicit insights into pollution patterns. Nevertheless, these interpretations often remain qualitative and may not fully align with the quantitative and regulatory requirements of environmental decision-making, thereby limiting their practical adoption. The evolutionary path is characterized by a progressive movement from prediction-centric and isolated AI applications towards more integrated, interpretable, and system-oriented AI. Such developments have paved the way for the new generation of AI and ML paradigms that focus on physical consistency, explainability, scalability and operational relevance. These emerging paradigms discussed in the next section are a crucial step to the realization of the practical deployment of intelligent systems for effective environmental pollution control and abatement (Banad *et al.,* 2025). Fig. 1 represents a schematic representation of the evolution of artificial intelligence applied to environmental pollution control. Despite significant advancements, earlier machine learning and deep learning approaches in environmental pollution control have often exhibited limited generalizability across different environmental contexts and this is largely due to their dependence on site-specific datasets, sensitivity to data quality, and lack of integration with governing physical and chemical processes. In many cases, insufficient reporting of model architectures, training procedures, and validation strategies has also limited reproducibility and comparability across studies. These limitations highlight the need for more robust, interpretable, and physically consistent modeling frameworks, which have driven the development of emerging AI paradigms discussed in the following section.

Emerging AI and machine learning paradigms for environmental pollution control and abatement

The use of AI and ML in environmental pollution control has moved away from traditional predictive modeling methods and has become more adaptive, interpretable, and system-integrated. Early applications of ML were mostly in regression and classification-based prediction of pollutant concentrations or process performance. While effective in controlled conditions, such approaches can often struggle with non-stationary environmental systems, poor data transferability and poor integration with physical processes. In response, some new AI and ML paradigms are reshaping the way smart systems are designed

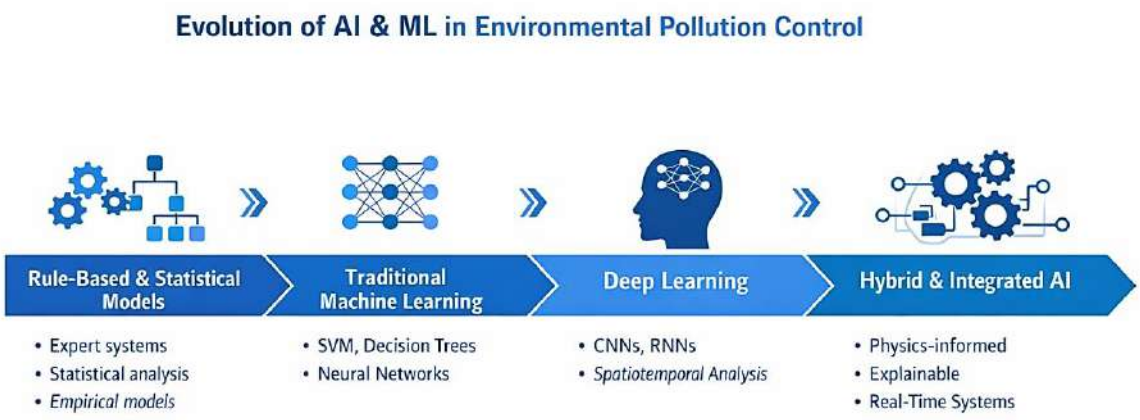

Fig. 1: Schematic representation of the evolution of artificial intelligence and machine learning methods applied to environmental pollution control

and implemented for pollution abatement (Peng *et al.,* 2024; Campos *et al.,* 2026; Rajesh *et al.,* 2025). One of the most important developments is the development of physics-informed machine learning (PIML). Unlike purely data-driven models, PIML injects the governing physical, chemical or biological constraints in the learning process. This paradigm in particular is relevant for environmental systems, where the mass balance, the reaction kinetics, the transport phenomena and the thermodynamic principles are established. By incorporating such constraints, PIML models can improve generalizability and physical consistency compared to purely data-driven approaches. However, while PIML can reduce reliance on large datasets by embedding domain knowledge, its performance remains sensitive to data quality, noise, and the accuracy of governing equations. In practice, physics-informed neural networks often require careful tuning and may exhibit convergence challenges, particularly in sparse or highly heterogeneous environmental systems (Zhi *et al.,* 2024; Sun *et al.,* 2024; Ghareeb *et al.,* 2025). Another crucial change is the increasing focus on explainable artificial intelligence (XAI). Conventional deep learning models are often "black boxes", which makes it hard for the models to be accepted in a regulatory and operational context. XAI techniques focus on enhancing the transparency of models by understanding the key input features, quantifying the uncertainty, and explaining the decision pathways. In pollution control applications, explainability is critical for regulatory compliance, risk assessment, and stakeholder trust, especially in air quality management, emission source apportionment and treatment process control (Hassija *et al.,* 2024; Liu *et al.,* 2025). The concept of digital twins has also gained momentum as a transformative AI-enabled paradigm. Digital twins combine real-time sensor data, process models and machine learning algorithms to produce dynamic virtual replicas of physical environmental systems. In the field of pollution abatement, digital twins facilitate scenario testing, predictive maintenance and adaptive control of treatment plants, air quality networks and waste management systems. Their ability to aid in real-time decision making is a shift from reactive to proactive environmental management (Zhang *et al.,* 2025; Venkateswarlu and Sathiyamoorthy, 2025). It is important to distinguish between digital twins and conventional simulation models. A true digital twin involves bidirectional data exchange between the physical system and its virtual

counterpart, enabling continuous updating and adaptive control. Many current implementations in environmental systems are still at the level of simulation-based or partially integrated models, rather than fully realized digital twins. In practice, digital twin architectures rely on real-time data acquisition from sensor networks, integration with process-based or data-driven models, and feedback mechanisms for system monitoring and control. The performance of such systems depends on sensor density, data quality, and computational infrastructure required for real-time data assimilation. Digital twins may also incorporate physics-informed models to ensure physical consistency, while reinforcement learning can be embedded within digital twin frameworks for adaptive control. Similarly, edge intelligence and federated learning can support the deployment of these systems in decentralized monitoring environments. These paradigms are therefore complementary rather than competing approaches. Advances in sensing technologies and distributed monitoring have also further incentivized the implementation of edge AI and federated learning frameworks. Traditional centralized AI models require a lot of data transfer and computational resources, which may not be feasible in the large-scale environmental monitoring case. Edge AI enables localized data processing at sensor or device levels, and federated learning, which enables models to be trained together without sharing raw data. These paradigms show significant potential for decentralized environmental monitoring, particularly in applications such as distributed air quality sensing and smart water networks. Recent studies have explored the use of federated learning for multi-location air quality prediction and edge AI for real-time on-device inference in sensor networks, demonstrating reduced data transmission requirements and improved scalability. However, the number of fully implemented environmental applications remains limited, and further validation in real-world systems is required to establish their broader applicability (Brecko *et al.,* 2022; Sah *et al.,* 2025). There is a gradual move towards autonomous and self-optimizing AI systems for pollution control. These systems take a combined approach of reinforcement learning, real-time feedback, and adaptive control strategies to optimise operational parameters with minimal human intervention continuously. Applications include intelligent aeration control in wastewater treatment, adaptive emission control strategies and autonomous remediation systems. While still in an early stage of deployment, such approaches represent a trend towards closed-loop, AI-controlled environmental control systems. Collectively, these emerging paradigms represent a broader trend from prediction-focused AI to integrated, interpretable, and adaptive AI as appropriate for the complexity of controlling environmental pollution. Their successful implementation, however, relies on careful integration into these systems, data quality assurance, and alignment with regulatory and sustainability goals (Parsoya *et al.,* 2025; Hocaoglu *et al.,* 2025; Zamfir *et al.,* 2025). In environmental applications, the term "self-optimizing" may refer to the optimization of different objectives, including energy consumption, effluent quality, chemical usage, or a combination of these factors. In reinforcement learning frameworks, such objectives are encoded through reward functions, which often involve multi-objective trade-offs. Designing stable and physically meaningful reward functions that balance operational efficiency and regulatory compliance remains a significant challenge. Recent developments of physics-informed and hybrid artificial intelligence frameworks have proven to hold great potential for enhancing the reliability and generalizability of environmental pollution models. For example, physics-constrained recurrent neural networks have been created to explicitly enforce mass-conservation principles in water quality and salinization modeling, which improved predictive

stability under unseen boundary conditions compared to conventional data-driven models (Raissi *et al.,* 2019). Similarly, physics-informed neural networks (PINNs) have been used in riverine pollutant transport problems by incorporating the advection-dispersion equations into the learning process to provide a way to correctly reconstruct contaminant concentration fields under sparse monitoring conditions (Di Bella *et al.,* 2026). These studies point to the benefits of incorporating physical laws in the architecture of AI to mitigate the limitations of data scarcity and to make models more robust in complex environmental systems. The growing use of digital twin systems is another significant paradigm shift in pollution control applications, especially in water and wastewater treatment systems. Recent implementations of wastewater treatment plant digital twins combine online sensor data, mechanistic process modeling and machine learning algorithms in modular software architectures to enable predictive maintenance, operational diagnostics and scenario analysis (Fuller *et al.,* 2020). Comprehensive reviews of digital twin deployments in wastewater systems further illustrate their potential for enhancing system understanding and operational resiliency, while highlighting challenges around sensor reliability, data integration, and standardization across facilities (Zhang *et al.,* 2025). These case studies suggest that digital twins are moving from the conceptual to the practical as decision support systems for pollution abatement. Autonomous optimization based on reinforcement learning is also of interest in environmental process control. In applications to wastewater treatment, reinforcement learning controllers trained in simulated environments have been shown to optimize the aeration and nutrient removal processes and reduce energy consumption compared to traditional control strategies (Bai *et al.,* 2026; Croll *et al.,* 2023b). Although these studies are mostly performed in simulation or pilot-scale systems, they show the feasibility of closed-loop and self-optimizing control strategies that are dynamic and adjust to the influent variability, presenting a way towards more intelligent and energy-efficient pollution control systems. Addressing issues of transparency and regulatory acceptance, explainable artificial intelligence (XAI) techniques have been increasingly coupled with air quality prediction models. Physics-informed models are typically suited for steady-state or slow-transient processes, whereas reinforcement learning and edge intelligence are more appropriate for real-time monitoring and control applications requiring rapid response. Studies employing explainable AI techniques such as Shapley additive explanations (SHAP) and local interpretable model-agnostic explanations (LIME) have demonstrated potential for identifying key drivers of air pollution and improving model transparency. However, many existing studies are limited in scope and vary in methodological rigor, highlighting the need for more standardized and high-quality evaluations in environmental applications (Sharma *et al.,* 2024; Yenkikar *et al.,* 2025). Such applications are just a few examples of how XAI can help bridge the gap between high-performance AI models and the need for transparent, policy-relevant environmental decision-making. Emerging paradigms centered on decentralized intelligence have further increased the scope of application of AI in environmental monitoring. Federated learning coupled with edge or multi-access computing has been suggested for air quality monitoring across distributed sensor networks, allowing the training of these models in a collaborative way without the need for centralized data sharing while maintaining the privacy of the data and alleviating the communication burdens (Syed *et al.,* 2023). Complementary research on edge AI architectures based on low-power sensor networks shows the feasibility of real-time on-device inference for air pollution monitoring, which greatly lowers the latency as well as the data transmission requirements in an urban

environment (Singh *et al.,* 2023). Together, these approaches underscore the increased role of privacy-preserving and resource-efficient artificial intelligence (AI) systems in controlling environmental pollution on a large scale. These case studies demonstrate a distinct shift from isolated, prediction-centric AI models to integrated, physically consistent, explainable, and adaptive intelligence frameworks. Such emerging paradigms, increasingly, are becoming capable of supporting real-world environmental pollution control and abatement by meeting complex data processing methodologies with the operational, regulatory, and sustainability requirements of the environmental systems. The role of AI and ML in pollution control is listed in Table 1. While each paradigm offers distinct advantages, they are not mutually exclusive and are increasingly being integrated into hybrid frameworks. For instance, digital twins can incorporate physics-informed models for improved physical consistency, while edge intelligence and federated learning can enable decentralized and scalable implementations. The suitability of each paradigm also depends on temporal and spatial scales, with some approaches better suited for real-time control and others for long-term system modeling. Therefore, future research should focus on integrative frameworks that leverage the complementary strengths of these paradigms. In addition, uncertainty quantification remains a critical aspect of PIML applications in environmental systems. Approaches such as Bayesian neural networks, ensemble modeling, and probabilistic physics-informed frameworks can be employed to estimate predictive uncertainty, particularly under sparse data conditions or in highly dynamic environments. Furthermore, hybrid formulations combining partial physical knowledge with data-driven components offer flexibility in adapting PIML models to emerging pollutants or complex reaction pathways where governing equations are not fully defined.

Applications of new AI and machine learning paradigms in environmental pollution control

The application of emerging artificial intelligence (AI) and machine learning (ML) paradigms has moved from isolated predictive tools to integrated and adaptive systems in major areas of environmental pollution. In recent research, it has been shown that when combining physical knowledge, interpretability, decentralization and real-time intelligence, more reliable and deployable solutions for the control of pollution are achieved (Karniadakis *et al.,* 2021; Wang *et al.,* 2024). This section provides a review of representative applications and case studies in the areas of air quality management, water and wastewater treatment, soil remediation, and SWM.

Air quality management and control of atmospheric pollution

Air quality management has been one of the most active application areas for AI-based environmental modeling, especially for particulate matter forecasting and gaseous pollutant prediction (Reichstein *et al.,* 2019). While deep learning models have shown high predictive performance, their limited interpretability has constrained their use in regulatory and policy-driven contexts (Samek *et al.,* 2021). Explainable artificial intelligence (XAI) techniques have thus been increasingly incorporated into air quality prediction models to identify dominant meteorological and emission factors. Studies using SHAP and LIME frameworks have shown that variables such as boundary layer height, wind speed, temperature, and emission intensity significantly influence fine particulate matter (PM2.5) and air quality index variability (Chakraborty *et al.,* 2024; Houdou *et al.,* 2024; Agbehadji and Obagbuwa, 2025). However, such interpretability methods may be sensitive to correlated input variables, which are common in air quality datasets, potentially affecting the robustness of feature attribution. Decentralized AI

Table 1: Emerging AL and ML paradigms for environmental pollution control and abatement

Emerging AI/ML paradigm	Core concept	Environmental relevance	Representative applications	Key advantages	Key limitations	Sources
Physics-informed machine learning (PIML)	Integration of governing physical, chemical, or biological laws into data-driven models	Improves physical consistency, generalizability, and robustness in complex environmental systems	Air dispersion modeling; wastewater treatment optimization; contaminant transport in soils and aquifers	Physically consistent predictions; improved extrapolation; reduced dependence on purely empirical data	Sensitivity to noisy and sparse data; difficulty in defining accurate governing equations for complex systems; convergence instability in PINNs; high computational cost; challenges in scaling to multi-component environmental systems	Karniadakis *et al.,* 2021
Explainable artificial intelligence (XAI)	Techniques for interpreting model predictions and identifying key influencing factors	Supports regulatory acceptance, risk assessment, and evidence-based environmental management	Emission source apportionment; air quality prediction; process diagnostics in treatment systems	Improved transparency; enhanced trust; supports policy and decision-making	Trade-off between interpretability and predictive accuracy; instability of attribution methods (e.g., SHAP) under correlated variables; lack of standardized interpretability metrics; limited direct actionability for operational decisions	Samek *et al.,* 2021
Digital twins	Dynamic virtual replicas of physical systems with bidirectional data exchange, integrating real-time data, models, and AI	Enables adaptive, predictive, and proactive environmental system management	Smart wastewater treatment plants, air quality monitoring networks, waste management systems	Real-time optimization; predictive maintenance; scenario analysis and decision support	High infrastructure and sensor requirements; challenges in real-time data integration and calibration; need for bidirectional coupling for true digital twin functionality; high computational and maintenance costs; lack of standardization	Sharma *et al.,* 2024; Syed *et al.,* 2024
Edge intelligence	On-device or near-sensor AI processing for decentralized data analysis	Enables real-time monitoring and decision-making in distributed environmental systems	Distributed air quality monitoring; smart water networks; remote sensing systems	Reduced data transmission; improved responsiveness; scalable decentralized monitoring	Limited computational and memory resources; model simplification may reduce accuracy; vulnerability to noisy or intermittent sensor data; challenges in coordination across distributed nodes	Ficili *et al.,* 2025
Federated learning	Collaborative model training across distributed nodes without sharing raw data	Enhances cross-regional learning and reduces reliance on centralized data systems	Multi-city air pollution modeling; regional water quality prediction; distributed monitoring networks	Improved generalization across heterogeneous datasets; reduced data transfer; enhanced scalability	Model heterogeneity affecting convergence; challenges with non-IID environmental data; communication overhead; potential performance reduction compared to centralized models	Alwabli, 2024
Autonomous optimization systems	AI-driven closed-loop control systems using reinforcement learning and feedback mechanisms	Enables adaptive and self-optimizing environmental control systems	Intelligent aeration control in wastewater treatment; adaptive emission control; automated remediation systems	Continuous optimization; reduced operational cost; adaptive response to dynamic conditions	Dependence on simulation-based training; limited real-world validation; difficulty in defining multi-objective reward functions; safety and regulatory concerns, and high data and computational requirements	Ojadi *et al.,* 2025

paradigms are also gaining attention. Federated learning methods for multi-station and multi-city air quality modeling have shown potential for improved generalization across diverse urban settings, while reducing reliance on centralized data storage (Alwabli, 2024). Complementary edge AI implementations based on low-power sensor networks and on-device inference have enabled near real-time monitoring while reducing data transmission and supporting deployment in resource-constrained environments (Singh *et al.,* 2023). While these approaches demonstrate significant potential, many studies remain limited to specific urban contexts or controlled datasets, highlighting the need for broader validation under real-world conditions.

Water and wastewater treatment systems

Water and wastewater treatment systems are one of the most subordinate fields for AI-powered pollution control because of well-instrumented infrastructure, as well as testing models of processes. Digital twin frameworks incorporating mechanistic models, real-time sensor data and ML modules have been developed to facilitate predictive maintenance, fault diagnosis and operational scenario analysis in wastewater treatment plants (Wang *et al.,* 2024; Rodriguez-Alonso *et al.,* 2024). These systems allow for virtual experimentation under different influent and operation conditions without interruption of plant operations. Autonomous optimization using reinforcement learning (RL) has also been widely studied with regard to wastewater process control. RL-based controllers based on benchmark simulation models have shown lower aeration energy use while ensuring regulatory effluent standards, outperforming traditional control strategies in simulation and pilot-scale studies (Hernandez-del-Olmo *et al.,* 2023; Croll *et al.,* 2023a; Alluhaidan *et al.,* 2026). Although most implementations still fall into a pre-industrial stage, these results show the feasibility of closed-loop, self-optimizing treatment systems. Physics-informed machine learning methods further improve the modeling of water pollution by incorporating mass balance equations and reaction kinetics into learning architectures. Applications of physics-informed neural networks (PINNs) for contaminant transport and fate modeling are more robust and to require less data in the context of sparse monitoring requirements (Biazar *et al.,* 2025). Collectively, these studies point to the potential of hybrid digital twin-physics-informed-RL frameworks for intelligent and energy-efficient water pollution control. It should be noted that many reinforcement studies in wastewater treatment are based on simulation environments with idealized influent conditions. In practice, wastewater systems are highly stochastic, with significant temporal variability in flow and pollutant load, which can affect model performance. The transfer of RL models from simulation to real-world systems therefore, remains a key challenge.

Soil pollution and contaminated site remediation

Soil pollution and subsurface contamination are serious problems because of high spatial heterogeneity, low sampling density, and complex physicochemical interactions in the processes of contaminant transport and transformation. Unlike air and water systems, where it is easier to constantly monitor the situation, soil systems are often prone to sparse and irregular datasets, making accurate prediction and remediation planning particularly difficult. Emerging AI paradigms have seen an incorporation into the problem of these challenges, with data-driven modeling of the problem coupled with information regarding the problem. Physics-informed machine learning (PIML) and hybrid modeling methods have proven especially promising in this regard. By incorporating governing equations, such as advection-dispersion transport, sorption kinetics and reaction mechanisms, into learning frameworks, these models can achieve better prediction accuracy under limited data conditions. For example, physics-informed neural networks have been used

for the reconstruction of contaminant distributions and estimation of transport parameters in heterogeneous subsurface environments and have shown better generalization than purely data-driven methods (Keçeci *et al.,* 2024; Ke *et al.,* 2025; Rabbi, 2025). However, the performance of these models is still sensitive to the quality of the data and the reliability of the underlying physical assumptions, especially for very heterogeneous soils or multi-contaminant systems. Hybrid AI approaches using geospatial data, remote sensing and machine learning have also been used to map soil contamination and measure ecological risks. Techniques like random forest, support vector machines and deep learning models have been developed to predict heavy metal distribution and identify pollution hotspots. While these approaches can be used to capture nonlinear relationships between environmental variables, their transferability across sites is limited because of variations in soil properties, climatic conditions and pollution sources (Minasny *et al.,* 2024). AI-driven decision support systems are also playing an increasing role in remediation planning and technology selection. By combining predictive models and optimization algorithms, these systems can examine remediation strategies based on various criteria, such as cost, efficiency, and environmental impact (Nie *et al.,* 2024). Such approaches have the potential for more adaptive and site-specific remediation planning. However, their practical implementation is limited by uncertainties in model predictions, limited access to high-quality training data, and difficulty validating model outputs under real-world conditions. Despite these advancements, the use of AI in managing soil pollution is seen to be less advanced than in air and water systems. Key challenges include scarcity of data, high spatial variability, and complexity of subsurface processes, which affect the reliability and scalability of models. Future studies should be focused on combining the physics-informed models with geospatial intelligence, enhancing the quantification of uncertainties, and developing standardized validation frameworks to facilitate the practical implementation of AI-driven soil remediation strategies.

Solid waste management and circular economy applications

SWM has also benefited greatly from progress in computer vision and deep learning, specifically in automated waste sorting and material recovery. Deep convolutional neural networks have proven to be powerful for the classification of municipal and industrial waste streams with high classification accuracy, resulting in improved recycling efficiency and reduced contamination in sorting facilities. Recent industrial-scale studies have shown that AI-driven sorting systems, particularly those based on computer vision and deep learning, have demonstrated high accuracy in waste classification, contributing to improved sorting efficiency and reduced contamination in recycling streams. However, quantitative improvements in throughput and large-scale operational performance remain less well documented and require further validation (Sirimewan *et al.,* 2024). Beyond sorting, AI-enabled optimization models and digital twins have been integrated in waste collection logistics and planning at the facility level to facilitate lessening fuel consumption, increased routing efficiency, and maximized resource recovery in line with circular economy goals (Niero *et al.,* 2021). Table 2 represents the application of AI and ML in pollution control. Despite these advances, challenges remain in the areas of waste heterogeneity, sensor reliability and economic feasibility, especially in developing regions. Nevertheless, existing supporting evidence suggests that AI-assisted waste management systems can make a meaningful contribution towards sustainable waste management, provided it is supported by the right policy and infrastructure. While these applications demonstrate the potential of AI in environmental

Table 2: Applications of emerging AI and machine learning paradigms across major environmental pollution domains

Application domain	Emerging AI/ML paradigm	Target pollution problem	Key outcomes and benefits	Sources
Air quality management	Physics-informed ML	Spatiotemporal prediction of $PM_{2.5}$, NO_2, O_3 under complex meteorology	Improved generalization; physically consistent forecasts	Ma *et al.,* 2023; Chen *et al.,* 2025
Air pollution control	Explainable AI	Emission source identification and policy-relevant attribution	Transparent decision support; regulatory trust	Jalali *et al.,* 2025
Distributed air monitoring	Edge AI & federated learning	Real-time urban air quality monitoring	Low latency; privacy-preserving learning	Quang and Doan, 2025; Abimannan *et al.,* 2023
Water and wastewater treatment	Digital twins	Process optimization and predictive maintenance in WWTPs	Energy savings; improved effluent quality	Rodríguez-Alonso *et al.,* 2024
Wastewater process control	Autonomous optimization (reinforcement learning)	Aeration and nutrient removal control	Continuous self-optimization; reduced operational cost	Aponte-Rengifo *et al.,* 2023
Surface and groundwater	Physics-informed ML	Contaminant transport and fate prediction	Reduced data demand; enhanced robustness	Meray *et al.,* 2024; Kaliraj *et al.,* 2026
Soil contamination	Hybrid ML models	Heavy metal distribution and risk assessment	Improved spatial prediction accuracy	Haruzi and Moreno, 2023
Remediation planning	AI-based decision support	Selection and optimization of remediation strategies	Cost-effective and adaptive remediation	Abrams *et al.,* 2024; Loganathan, 2026
SWM	Computer vision and ML	Waste sorting and material recovery	Improved recycling efficiency	Lakhouit, 2025; Soni *et al.,* 2025
Circular economy systems	Digital twins and system-level AI	Waste-to-resource optimization	Enhanced resource recovery and lifecycle efficiency	Agarwal *et al.,* 2025

WWTP: Wastewater treatment plant

systems, many reported studies are based on controlled datasets, simulation environments, or pilot-scale implementations. Further validation under real-world conditions is required to assess scalability, robustness, and long-term performance. Despite their potential, these emerging paradigms must be critically evaluated in terms of scalability, reproducibility, and real-world applicability. Differences in temporal and spatial scales, data availability, and system dynamics may influence the suitability of specific AI approaches across environmental domains. Therefore, integrated frameworks that combine multiple paradigms, such as physics-informed digital twins or edge-enabled federated systems, are likely to play a crucial role in advancing intelligent and adaptive pollution control strategies.

Challenges and research gaps in environmental pollution control using AI

Among these challenges, data quality and model generalizability represent the most critical barriers to large-scale deployment, while issues such as computational cost and regulatory integration are emerging but increasingly important considerations. Despite great progress in artificial intelligence and machine learning for environmental pollution control and abatement, there are still several technical, operational and institutional challenges that constrain the large-scale deployment of AI and machine learning.

Addressing these challenges is the key to moving promising methods based on AI from experimental studies to reliable real-world environmental applications (Li *et al.,* 2025; Morain *et al.,* 2025). One of the most persistent problems is the quality and availability of data. Environmental datasets are often heterogeneous, incomplete and subject to measurement uncertainty, sensor drift and spatial and temporal gaps. Many AI models require large and high-quality datasets for their training, which may not be available in developing regions or for emerging contaminants. This limitation works to limit the model transferability and raises the risk of biased or overfitted predictions (Koldasbayeva *et al.,* 2024). Model generalizability and scalability are important research bottlenecks. AI models created for certain sites/conditions often don't perform well when applied to different environmental conditions. Variations in climate, source of pollutants, operational practices and regulatory standards can have a strong impact on model reliability. Developing the scalable frameworks that can be adapted to different environmental settings without extensive retraining remains an open problem (Alnafrah, 2025; Ukoba *et al.,* 2025). The lack of interpretability and transparency in complex AI models is a major barrier to regulatory acceptance and trust for operations. Black-box models are often hard to validate, explain and justify in compliance-oriented environmental management. While explainable AI approaches provide promising solutions, there is currently little agreement on standardized measures of interpretability that can be used in environmental decision-making (Saeed and Oplin, 2023). Computational and energy requirements of advanced AI models are a new type of concern, especially in the sustainability context. Deep learning and real-time optimization frameworks may have significant computational resource needs that can lead to increased energy consumption and carbon footprints. Model complexity and environmental sustainability goals are still a major gap in research (Bolon-Canedo *et al.,* 2024; Ariyanti *et al.,* 2025). Integration of AI systems into the existing environmental infrastructure and governance frameworks is also challenging. Many pollution control facilities are based on legacy systems that are not designed for real-time data integration or for autonomous control. Furthermore, regulatory frameworks are often evolving more slowly than technological developments, which can lead to uncertainty about who is responsible for ensuring accountability, validation, and ethical deployment of AI-driven solutions (Koley *et al.,* 2025). Ethical, social and equity considerations require more attention for AI-enabled environmental management. Data-driven systems will inadvertently perpetuate environmental inequalities if implemented without caution for regional disparities and stakeholder involvement. Future research should focus on inclusive data practices, transparent decision-making and human-in-the-loop approaches to ensure responsible and equitable use of AI in pollution control (Santos and Carvalho, 2025). Another important consideration is the environmental footprint of AI systems themselves. The computational and energy requirements of advanced machine learning models can contribute to increased carbon emissions, raising concerns regarding the sustainability of AI-driven solutions. Emerging concepts such as "Green AI" emphasize the development of energy-efficient algorithms and model architectures to minimize environmental impact. Furthermore, AI has the potential to support rapid decision-making during extreme environmental events, such as chemical spills, floods, or wildfires, by enabling real-time

data assimilation and predictive analytics. The development of regulatory, ethical, and governance frameworks is essential to ensure the responsible, transparent, and equitable deployment of AI technologies in environmental management.

FUTURE DIRECTIONS AND OUTLOOK

The future of artificial intelligence and machine learning in environmental pollution management is anticipated to be driven by a gradual shift from isolated standalone applications that focus on prediction to integrated and adaptive systems, as well as decision-oriented. Rather than replacing conventional environmental engineering approaches, next-generation AI is likely to serve as an enabling layer to increase system understanding, operational efficiency and policy support (Santos and Carvalho, 2025). One important direction for the future is the further incorporation of domain knowledge and physical principles into the AI models. Physics-informed and hybrid modeling frameworks are likely to become more critical in determining how to improve the robustness, interpretability, and transferability of models in a range of environmental settings. Such approaches can help bridge the gap between data-oriented intelligence and process-oriented environmental science, especially in data-scarce or highly dynamic systems (Wu *et al.,* 2024). The ongoing development of explainable and trustworthy AI will be critical for broader regulatory acceptance and operational adoption. Future research efforts could focus on the standardized development of interpretability metrics, uncertainty quantification approaches, and validation protocols specific to environmental applications. These efforts are critical in fostering confidence among regulators, practitioners and stakeholders who are relying on AI-assisted decision-making (Nastoska *et al.,* 2025). Advances in sensing technologies, edge intelligence, and digital infrastructure are anticipated to provide system-level environmental management in real-time. Digital twins and decentralized AI frameworks may be useful for adaptive control of treatment plants, emission networks, and monitoring systems, enabling more proactive and resilient pollution abatement strategies. However, such systems should be designed with scalability, cybersecurity, and interoperability in mind (Afrazi *et al.,* 2025). From a governance perspective, the alignment of solutions driven by artificial intelligence with policy, regulatory and sustainability goals will become more important. Future frameworks should focus on transparency, accountability, and human oversight, and ensure that AI systems are used to complement, not replace, expert judgment. Integrating AI tools with environmental governance may also aid in more responsive and evidence-based policymaking (Cordeiro *et al.,* 2025). Overall, the successful implementation of new AI and ML paradigms for environmental pollution control is likely to rely on interdisciplinary partnerships among environmental scientists, engineers, data scientists, policy makers and stakeholders. By addressing current challenges and focusing on responsible innovation, AI-enabled systems have the potential to make a meaningful contribution to sustainable and resilient environmental pollution control strategies. From a practical perspective, the successful implementation of AI-driven pollution control systems requires a systematic approach that includes data acquisition and quality assurance, model selection and validation, integration with physical infrastructure, and continuous monitoring and updating. Pilot-scale studies and real-world case implementations are essential for evaluating system performance under dynamic

environmental conditions. In addition, standardized benchmarking frameworks and performance metrics are needed to assess the effectiveness, scalability, and sustainability of different AI paradigms across environmental applications.

CONCLUSION

The growing complexity of environmental pollution and the inadequacy of standard monitoring and control methods have accelerated the use of artificial intelligence and machine learning in environmental management. This review has reviewed the development of AI-based methods and identified the rise of the next generation paradigms, which go beyond prediction-oriented modeling and towards more integrated, interpretable and adaptive systems. Among the emerging paradigms, physics-informed and hybrid machine learning approaches show excellent potential to enhance model reliability and generalizability by incorporating domain knowledge into data-driven frameworks. Explainable artificial intelligence plays a role in the improvement of transparency and the acceptance of regulation, although its utility is based on the development of stable and actionable interpretation methods. Digital twin frameworks and autonomous optimization systems provide exciting opportunities for real-time monitoring and adaptive control of environmental processes. Still, their implementation on a large scale is limited by data availability, infrastructure needs, and system integration challenges. Similarly, edge intelligence and federated learning offer a scalable solution for decentralized environmental monitoring, but there are issues associated with model consistency, computational issues, and coordination in distributed systems that need to be addressed. Despite these advancements, there are still several critical challenges that are limiting the practical deployment of AI-driven solutions in the control of environmental pollution. These include data heterogeneity and scarcity, non-transferability of models between different environmental conditions, high computational and energy demands, and the absence of standardized validation and benchmarking frameworks. In addition, regulatory acceptance, reproducibility of results and integrating AI systems into existing environmental governance structures are still significant barriers. Tackling these challenges demands moving from prediction-focused, siloed models to integrative and system-level approaches that employ a mix of physical knowledge, data-driven intelligence and domain expertise. Future research should be focused on the development of hybrid and multi-scale frameworks combining physics-informed modeling, real-time data assimilation and adaptive optimization. Greater emphasis is required on uncertainty quantification, reproducibility, and the development of standardized evaluation metrics to allow meaningful comparison between studies. In addition, new technologies like generative artificial intelligence and large language models could offer new capabilities for knowledge integration, decision support and human-ai interaction in environmental systems, albeit their role is yet to be fully explored. Overall, AI and ML should not be considered as a replacement for the traditional practices of environmental engineering, but rather as a complementary tool that will improve the understanding of the system, assist in the decision-making process, and facilitate more adaptive and resilient approaches to pollution control. The smooth transition from research to actual implementation will rely on interdisciplinary cooperation, strong validation

and the creation of transparent, accountable and context-specific AI solutions that are compatible with environmental and societal objectives.

AUTHOR CONTRIBUTIONS

J. Aravind was responsible for searching the bibliography, selecting the relevant references, coding the references, writing the initial manuscript draft, synthesizing the manuscript, and revising the final manuscript version. J. Nouri was responsible for conceptualizing the draft, analyzing the 'references' coding, and reviewing the whole manuscript. S.M. Tehrani reviewed the manuscript draft and checked the references.

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CONFLICT OF INTEREST

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

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☑ Negative AI Statement

The author(s) declared that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
AI	Artificial Intelligence
LIME	Local interpretable model-agnostic explanations
ML	Machine learning
PIML	Physics-informed machine learning
PINNs	Physics-informed neural networks
$PM2_{.5}$	Fine particulate matter (2.5 micrometers or less in diameter)
RL	Reinforcement learning
SHAP	Shapley additive explanations
SWM	Solid waste management
WWTPs	Waste Water Treatment plants
XAI	Explainable artificial intelligence

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REVIEW PAPER

Linking environmental, social, and governance investment metrics to technology adoption and carbon reduction in global energy companies

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ABSTRACT

Environmental, Social, and Governance investment metrics have rapidly evolved from voluntary disclosure instruments into strategic determinants of capital allocation within the global energy sector. Yet their functional linkage to technological transformation and measurable carbon reduction remains conceptually fragmented, often mediated by inconsistent reporting architectures and uneven governance enforcement. The objectives of this study were to examine how environmental, social, and governance investment signals shape technology adoption pathways and to assess the extent to which these signals translate into verifiable decarbonization outcomes across energy firms operating in both fossil intensive and low carbon segments. Synthesising emerging interdisciplinary evidence, the review analyses three interlocking mechanisms. First, capital reallocation through environmental, social, and governance weighted financing structures reshapes firm level investment incentives, lowering the cost of capital for low emission technologies while constraining carbon intensive asset expansion. Second, governance driven innovation mandates, including board oversight, executive remuneration alignment, and transition risk disclosure, institutionalise technological upgrading and emissions accountability. Third, social license pressures, expressed through stakeholder activism, community risk exposure, and reputational valuation, shape corporate adoption of decarbonization technologies and operational transparency. The review further interrogates methodological tensions in environmental, social, and governance measurement, including rating divergence across agencies, disclosure asymmetry between firms, data opacity in private markets, and greenwashing risk, all of which complicate causal attribution between environmental, social, and governance performance and emissions outcomes. By integrating financial, technological, and environmental literatures, the paper proposes a systems pathway framework linking environmental, social, and governance metrics to decarbonization through technology diffusion, operational optimisation, asset portfolio restructuring, and innovation spillovers. The review concludes that environmental, social, and governance metrics are most effective when embedded within regulatory alignment, science-based targets, transition taxonomies, and verifiable technology deployment indicators rather than disclosure volume alone. This synthesis clarifies how environmental, social, and governance investment logic can accelerate or constrain energy transition pathways depending on metric design, governance credibility, policy coherence, and technological absorptive capacity.

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INTRODUCTION

Global energy systems sit at the centre of the climate mitigation challenge because they produce the largest share of human-generated greenhouse gas (GHG) emissions. Electricity generation (Allam *et al.*, 2013; Kabeyi and Olanrewaju, 2022; Yuan *et al.*, 2020), fossil fuel extraction (Bauer *et al.*, 2016; Sarwer *et al.*, 2022), refining (Miyagi Martire *et al.*, 2025), and industrial energy use (Nunes, 2023; Shi *et al.*, 2024) collectively shape the atmospheric carbon trajectory more than any other economic sector. For decades, decarbonization strategies within energy companies evolved slowly, shaped mainly by environmental regulation, fluctuations in oil and gas prices, and the declining cost of renewable technologies (Fadiga *et al.*, 2024; Pierce *et al.*, 2024; Wójcik-Jurkiewicz *et al.*, 2021). These drivers, while influential, operated unevenly across regions and firms, often producing incremental rather than systemic emissions reductions. As a result, technological transition in the energy sector has historically lagged climate policy ambition. In recent years, however, a parallel transition force has emerged from global financial markets through the rapid institutionalisation of ESG investment metrics (Erdoğdu *et al.*, 2025; Khamisu and Paluri, 2024). These metrics were initially developed to guide ethical investing and corporate transparency, but they have evolved into powerful valuation instruments that shape how capital is allocated. Investors now use sustainability performance indicators alongside traditional financial data to evaluate long-term risk exposure, transition readiness, and corporate resilience in a decarbonising economy (Bouteska *et al.*, 2025; Ponomareva Reshetnikova, 2025; Teixeira, 2026). This shift has repositioned sustainability from a peripheral reporting exercise to a central determinant of financial competitiveness. The financial implications are particularly profound for energy companies because their asset portfolios are predominantly carbon-intensive and constrained by existing infrastructure. Large-scale fossil fuel facilities, pipelines, and thermal power plants require long amortisation periods, making rapid technological substitution financially complex (Barasa Kabeyi and Olanrewaju, 2022; Farnoosh, 2022). Under these conditions, sustainability performance increasingly determines access to affordable transition capital. Firms with stronger environmental and governance records often secure preferential lending rates, expanded investor bases, and inclusion in sustainability-aligned market indices (Chau *et al.*, 2025; Shmelev and Gilardi, 2025). Conversely, weak sustainability performance can elevate borrowing costs, restrict insurance coverage, and trigger shareholder activism demanding transition restructuring. Despite this financial transformation, a critical analytical gap persists. It remains unclear whether sustainability investment metrics function primarily as reputational disclosure or as significant drivers of technological adoption and measurable emissions reduction (Seera *et al.*, 2025; Silva *et al.*, 2025). High sustainability scores do not automatically translate into low-carbon infrastructure deployment. Some firms improve ratings through reporting transparency or operational efficiencies without fundamentally altering fossil-dependent production models. This ambiguity complicates efforts to evaluate whether financial sustainability frameworks are accelerating genuine energy system decarbonization or simply reshaping corporate signalling practices. This review addresses that gap by synthesising emerging evidence on how sustainability investment frameworks interact with technology deployment decisions across global energy firms. Rather than treating sustainability metrics as passive reporting tools, the review conceptualises them as techno-financial governance instruments capable of influencing innovation strategy, capital expenditure allocation, and infrastructure development timelines. By synthesizing insights from sustainable finance, studies on energy

transition, and research on corporate innovation, this review elucidates the mechanisms by which investment metrics can facilitate, limit, or redirect decarbonization pathways (Jørgensen and Ma, 2025). Additionally, it emphasizes the existing knowledge gaps that influence future research and policy design. This study aims to synthesise emerging evidence on how ESG investment metrics influence technology adoption and carbon reduction pathways in global energy companies and has been carried out in Kazakhstan in 2025.

METHODOLOGY

This study used a structured integrative review to examine how ESG investment metrics influence technological transformation and carbon mitigation in the global energy sector. The approach synthesized conceptual mechanisms and institutional pathways rather than aggregating effect sizes, with analysis organized around transmission channels linking ESG evaluation to firm level technology decisions, particularly through financial costs, governance incentives, and legitimacy pressures. Literature searches were conducted across major multidisciplinary databases and publisher repositories using clustered ESG and decarbonization keywords covering 2005–2025. Peer reviewed articles formed the core evidence base, supplemented by high quality reviews and policy reports, with staged screening and reference snowballing applied. Data extraction and coding captured study characteristics, methods, technological domains, and emissions outcomes alongside mechanism categories such as finance, governance, disclosure, innovation, and regulatory pathways. Evidence synthesis followed convergent thematic integration to develop an inductive ESG–decarbonization framework centered on capital allocation, governance accountability, and socio institutional legitimacy. Key limitations included heterogeneity in ESG metrics, reliance on observational evidence, geographical concentration of studies, and potential publication bias, though critical and null findings were incorporated to strengthen analytical balance.

Financial materiality of ESG metrics in energy capital allocation

ESG as a cost-of-capital modifier

The literature increasingly positions Environmental, Social, and Governance investment metrics as influential signals within the capital allocation architectures that shape technological transition pathways in energy firms. Rather than functioning as deterministic financing levers, ESG evaluations appear to operate through risk perception recalibration, disclosure transparency, and long-horizon resilience signalling, which collectively influence lender confidence and investor portfolio weighting. Empirical evidence suggests that firms with stronger ESG profiles often experience comparatively favourable financing conditions, particularly where external capital dependence is high. For instance, Gong *et al*. (2025) report that higher ESG ratings are associated with improvements in green total factor productivity, with financing constraint alleviation emerging as the primary transmission channel. This relationship indicates that ESG performance may expand financial flexibility for sustainability-linked capital expenditure, although the directionality of this association remains mediated by firm capability and regulatory context. However, the cost-of-capital thesis is neither uniform nor frictionless. Devalle *et al*. (2017) demonstrate that credit rating sensitivity is more strongly linked to social and governance indicators than to environmental performance. This asymmetry suggests that capital providers may prioritise governance reliability and social risk exposure as more immediate determinants of financial stability, while environmental metrics, particularly those tied to long-term transition risk, exert weaker short-term credit influence. This differentiation creates a structural bottleneck

where investments focused on ecology, which have longer payback periods, may not obtain corresponding financing benefits, even though they are highly relevant for decarbonization. Methodological advances in ESG evaluation attempt to address this allocation distortion. Zatonatska *et al*. (2025) develop structured interdependency frameworks that quantify cross-pillar ESG interactions within energy project assessment. Their modelling identifies renewable integration capacity and transition risk management as dominant investment decision nodes, illustrating how increasingly granular ESG scoring architectures may recalibrate capital flows toward technologically substantive decarbonization assets rather than disclosure-weighted performance indicators alone. Even so, capital market interpretation of ESG signals remains sensitive to informational volatility. Alofaysan *et al*. (2026) show that ESG-related uncertainty can exert negative valuation effects, particularly within renewable energy equities exposed to policy instability and subsidy fluctuation. Under such conditions, the financing advantages associated with strong ESG positioning may weaken or reverse, indicating that stable regulatory environments condition the persistence of ESG-linked capital benefits. At the technological interface, access to lower financing costs appears to facilitate deployment of operational monitoring and mitigation systems that would otherwise remain cost prohibitive. Methane detection infrastructures illustrate this transmission mechanism. Studies examining low-cost sensor networks and drone-based tunable diode laser absorption spectroscopy deployment (Cho *et al*., 2022; Wang and Wei, 2021) indicate that firms with stronger sustainability financing access are better positioned to invest in advanced emissions surveillance technologies. These systems enable real-time leakage detection and targeted mitigation, linking financial signalling to measurable operational carbon management practices. Yet aggregated ESG performance improvements do not uniformly translate into emissions decline (Fig. 1).

Portfolio rebalancing and asset stranding

ESG-informed portfolio rebalancing is increasingly interpreted as a capital reallocation process with material implications for fossil asset valuation and long-term investment viability. Rather than triggering automatic divestment, ESG screening interacts with climate policy expectations, regulatory signals, and investor risk modelling to reshape capital exposure to emissions-intensive infrastructure. Quantitative scenario modelling illustrates the scale of potential impairment. Chevallier et al. (2021), using a stochastic framework with stopping times across major fossil firms, link tightening climate policy to accelerated asset devaluation risk, while COALMOD-World modelling projects substantial excess coal capacity and up to USD 150 billion in stranded mining assets. Though inferential, such projections shape investor expectations and financing risk assessments. Project-level evidence reinforces this repositioning. Qualitative comparative analysis of Canadian oil sands pipelines identifies social mobilization and regulatory barriers, amplified by ESG scrutiny, as necessary conditions for cancellation (Janzwood, 2020), with legitimacy asymmetries further shaping infrastructure viability (Brunner and Axsen, 2020). Yet vulnerability is uneven. Firm-level transition risk analysis shows that impairment exposure varies by diversification, capital resilience, and adaptive capacity, suggesting exclusion screens may lack precision. Contestation is pronounced for natural gas. Transition models frequently categorize gas as a high-risk resource; however, systems analyses regard it as a transitional fuel and emphasize the potential for repurposing infrastructure (Gielen and Bazilian, 2021; Bugaje et al., 2022). Market

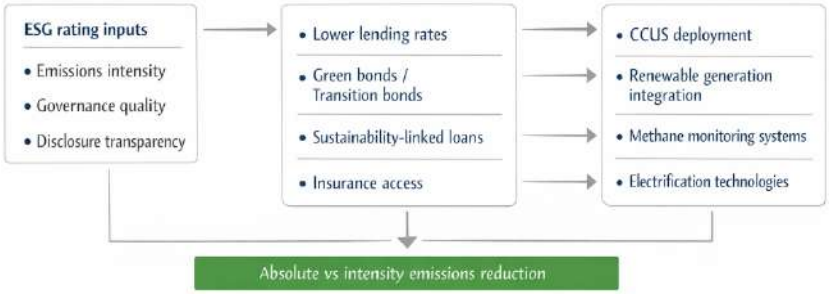

Fig. 1: ESG metrics as a cost-of-capital transmission mechanism



Fig. 2: Portfolio rebalancing and asset stranding dynamics

behavior nonetheless reflects ESG sensitivity, with rating downgrades driving divestment and stock price pressure (Galema and Gerritsen, 2025). However, structural lags persist between investor repositioning and project development, sustaining forward stranding exposure despite declining asset desirability (Fig. 2).

Governance metrics as innovation catalysts

Board oversight and climate technology mandates

Governance quality is widely positioned as the institutional interface through which ESG commitments translate into technological investment priorities and operational decarbonization strategies. Rather than exerting direct causal control over emissions, board oversight structures operate through mandate formation, executive accountability alignment, and innovation prioritization that shape organizational resource allocation. Empirical evidence supports this mediated pathway. A global study of 13,376 energy firms applying Baron and Kenny's mediation model finds strengthened climate governance reduces emissions primarily through expanded eco-innovation participation (Liêu et al., 2024), indicating governance influence is indirect and technology driven. Executive incentive alignment forms a complementary channel. Ritz (2022) shows that embedding climate metrics within executive compensation links remuneration to transition milestones, integrating long-horizon decarbonization goals into managerial decision systems, though effectiveness depends on monitoring and disclosure verification. Governance mandates also shape digital optimization deployment. Instrumental variable panel analysis finds artificial intelligence adoption reduces corporate energy consumption, energy intensity, and carbon emission intensity by about 2.0 percent, 1.8 percent, and 2.3 percent respectively (Zhou and Bu, 2026), mediated through green innovation and operational efficiency (Wang et al., 2025). Institutional absorptive capacity moderates these gains. A panel threshold model shows digital economy expansion yields non-linear carbon reduction benefits that decline beyond infrastructure maturity thresholds

(Yan et al., 2025). This complicates the assumptions regarding continuous proportional mitigation.

Disclosure, transparency, and innovation signalling

Governance architecture within ESG systems is widely interpreted as disclosure-enabling structures through which firms communicate technological transition strategies, investment pathways, and decarbonization commitments to external stakeholders (Xiong et al., 2025). Beyond compliance reporting, these disclosures function as strategic innovation signals shaping partnerships, subsidy access, and collaborative technology development, though their credibility depends on governance quality, institutional trust, and the verifiability of transition claims. Empirical evidence indicates that governance-enabled transparency can catalyze innovation collaboration. Wei *et al*. (2025) show that strategic alliances enhance green total factor productivity by strengthening senior management green cognition and supporting localized sustainability standards, positioning disclosure as a coordination mechanism aligning organizational learning with external technological ecosystems. Governance design moderates this signaling effect. Lakhwani (2025), examining clean energy startups in emerging economies, finds Public Private Partnership structures balance stakeholder alignment with scaling flexibility, enhancing transparency while preserving innovation agility, whereas overly centralized or fragmented systems weaken decision flow and signaling credibility. Disclosure signaling also extends into participatory transition governance. Coenen *et al.* (2025), through the Mission Oriented Transition Assessment framework, argue that credible roadmaps require anticipatory, scenario-based governance incorporating stakeholder deliberation and long-term systems modelling, embedding disclosure within iterative validation processes. Technical verification further shapes signal interpretation. Mianes *et al.* (2025) highlight voluntary conformity assessment infrastructures, including certification and audit regimes, as mechanisms translating narrative commitments into measurable investment propositions. Incentive environments introduce additional moderation. Zhao *et al*. (2025) and Xu *et al.* (2025) link ESG performance to green innovation and corporate value, though effects weaken under high R&D burdens or financial constraints, while policy tools such as guarantees and tax subsidies strengthen disclosure-innovation conversion. Jiao (2024) identifies a U-shaped subsidy relationship with ESG performance. Chen *et al*. (2024) further show ESG strength enhances innovation novelty and sophistication under policy uncertainty and digital transformation pressure (Fig. 3).

Environmental metrics and technology deployment pathways

Operational decarbonization technologies

Environmental performance metrics are frequently interpreted as investment signals that may encourage firms to pursue operational decarbonization technologies, including electrified extraction systems, hydrogen blending within gas networks, and renewable-powered refining configurations. However, the translation of environmental scoring pressure into technological deployment appears mediated by regulatory exposure, infrastructural readiness, techno-economic feasibility, and sector-specific transition risk. Rather than producing uniform adoption responses, environmental ratings function within broader institutional and market ecosystems that shape both the pace and direction of operational transformation. Firm heterogeneity constitutes an initial conditioning layer. Empirical analysis by Hmouda *et al*. (2024) demonstrates that environmental performance outcomes are significantly associated with geographic location and firm size, indicating that regulatory stringency, capital access, and institutional enforcement capacity influence the likelihood of clean technology adoption. Larger companies functioning within established

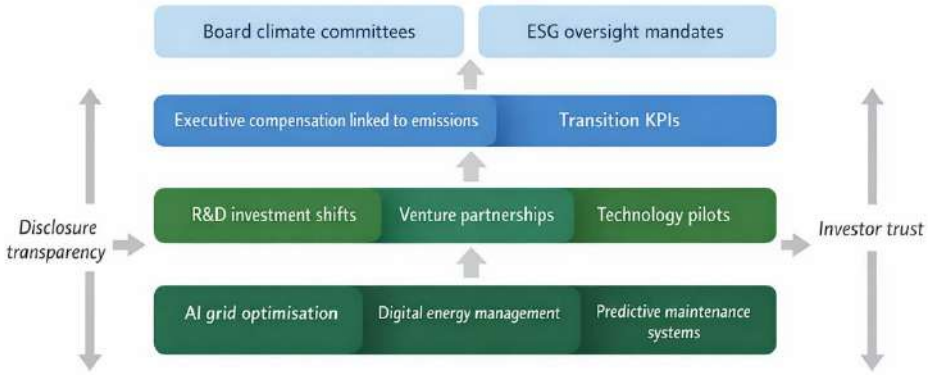

Fig. 3: Governance architecture and innovation diffusion model

regulatory frameworks seem to be more capable of managing the capital and operational expenses linked to decarbonization infrastructure. In contrast, smaller entities or those situated in jurisdictions with less stringent regulations may encounter structural barriers to adoption, even in the face of pressure from ESG evaluations. Hydrogen blending illustrates the technological promise and infrastructural complexity embedded within operational decarbonization pathways. A comprehensive technical review identifies blending hydrogen into existing natural gas systems as a potentially significant emissions mitigation strategy. By leveraging legacy pipeline networks, hydrogen integration may reduce combustion-related carbon intensity without requiring immediate full system replacement. Yet the review also documents critical materials science and safety constraints. Hydrogen embrittlement within pipeline steels, leakage risks, and compatibility limitations with legacy compressors and storage systems present substantial engineering barriers. These constraints necessitate updated safety standards, material retrofitting, and regulatory code revision, thereby slowing the conversion of environmental performance incentives into scalable infrastructure deployment. Decarbonization within refining systems similarly requires systemic technological reconfiguration rather than incremental operational adjustment. Alcocer García *et al*. (2025) analyse circular and decentralised refinery models that incorporate process intensification, electrification, and digital optimisation. However, long-horizon decarbonization within refining remains structurally dependent on the availability of low-carbon hydrogen feedstocks. Integrated modelling conducted by Shi *et al*. (2024), combining refinery linear programming optimisation with life cycle assessment, indicates that fossil-based hydrogen currently retains cost advantages. Renewable hydrogen pathways are projected to achieve cost competitiveness only under extended timeframes, potentially before 2060, with carbon taxation regimes acting as decisive economic tipping mechanisms. This temporal divergence introduces investment tension between near-term environmental scorecard expectations and the long-term capital recovery cycles required for hydrogen infrastructure transformation. The effectiveness of operational decarbonization technologies is further conditioned by interaction with macro-policy instruments. Advanced econometric modelling using the Panel Quantile Autoregressive Distributed Lag framework by Radulescu *et al*. (2025) demonstrates that emissions trading systems and environmental taxation policies produce uneven mitigation outcomes across distributional emissions quantiles. While regulatory pricing mechanisms contribute to emissions reduction in certain firm clusters, their influence weakens in others, particularly where technological substitution

options remain constrained. Across quantiles, however, green technology innovation emerges as a consistently robust driver of environmental performance improvement. Implementation complexity is amplified by site-specific environmental and ecological considerations. Environmental weighting matrix analysis within oil and gas operational contexts conducted by Guerrero Martin *et al*. (2023) categorises land alteration and ecosystem disruption as high-risk impact dimensions associated with infrastructure deployment.

Monitoring, measurement, and verification (MMV) systems

The expansion of advanced Monitoring, Measurement, and Verification (MMV) systems marks a critical infrastructural shift in operationalizing ESG accountability, enabling firms to move from periodic disclosure toward continuous environmental performance observation. Beyond reporting tools, MMV architectures function as data verification ecosystems supporting emissions attribution, transition monitoring, and regulatory compliance, closely tied to the digitalization of environmental governance through remote sensing, distributed sensors, and secure data systems. A central transformation is the shift from self-reported inventories to independent observational verification. Satellite-based methane detection illustrates this evolution by enabling atmospheric monitoring across dispersed assets and supporting baseline emissions datasets, leakage detection, and storage integrity validation within carbon capture systems (Jenkins *et al*., 2015). However, satellite resolution constraints limit facility-level attribution, creating reliance on complementary ground-based systems. Internet of Things networks and blockchain-integrated ledgers address this gap by enabling tamper-resistant carbon accounting and automated verification across supply chains (Jessica Obianuju Ojadi *et al*., 2025). Engineering advances reinforce feasibility, with optimized IoT detection hardware reducing transmission energy use by over 94 percent during non-event monitoring periods (Fay *et al*., 2023). Despite technological progress, structural barriers persist. Monitoring across fragmented production systems remains costly, with agricultural MRV deployment constrained by expensive farm-level data collection and validation (Perosa *et al*., 2023), raising incentive and participation challenges. Organizational readiness further conditions MMV effectiveness. Real-time data systems enhance ESG performance through efficiency and transparency gains (Tumpa *et al*., 2025), yet impacts are mediated by innovation capacity and service-oriented model adaptation (Chen and Wang, 2024). Standardization platforms such as Sustainable Enterprise Resource Planning systems improve reporting integration but face interoperability and taxonomy fragmentation constraints (Pizzi *et al.*, 2024). MMV systems thus function as enabling infrastructures translating disclosure into auditable metrics, though large-scale deployment remains limited by governance, cost, data ownership, and regulatory harmonization bottleneck (Fig. 4).

Social metrics and the technology social license

Community acceptance of transition infrastructure

Social acceptance emerges as a critical mediator for the deployment of low-carbon infrastructure, influencing whether projects such as wind farms, transmission corridors, and carbon storage reservoirs progress according to planned timelines. Empirical research suggests that opposition seldom arises solely from communication failures; instead, it is indicative of the structural and contextual factors in which project siting, governance arrangements, and economic incentives interact. Macro-level climate benefits often contrast with localized social and environmental costs, producing systemic bottlenecks that shape capital allocation, risk assessment, and investor confidence. Sanchez Nieminen and Laitinen (2025), in a systematic review of renewable energy opposition in Nordic countries, find that conflicts are multifaceted,



Fig. 4: Environmental metrics and operational technology stack

driven by visual disruption, procedural distrust, insufficient compensation, and threats to cultural heritage. These socio-cultural dimensions highlight that public resistance is deeply linked to perceptions of fairness, identity, and participatory legitimacy, rather than technological deficiency. Quantitative infrastructure optimisation models illustrate the operational consequences of social constraints. Bennett *et al*. (2023) demonstrate that when wind power siting incorporates environmental justice and social factors, transmission requirements expand nonlinearly to deliver equivalent energy capacity. This adjustment substantially alters project economics and introduces temporal delays, with potential implications for achieving national climate targets under existing planning paradigms. Beyond visual and procedural factors, ecological and distributive equity considerations further mediate project feasibility. Geospatial analyses by Yin *et al*. (2025) indicate that power transmission expansion can fragment habitats and disrupt species migration corridors, demonstrating that environmental externalities and social values intersect to affect project acceptance. Economic analyses similarly reveal spatial mismatches between infrastructure

burdens and benefits. Jo *et al*. (2026) find that regions hosting generation and transmission assets bear disproportionate land use and visual costs, while distant demand centers accrue employment and economic gains, generating perceptions of regional inequity that intensify local opposition. In the case of subsurface carbon storage initiatives, the factors influencing social license vary but remain pivotal. Bishop and English (2025) highlight that European case studies demonstrate the necessity of proactive engagement strategies alongside robust policy and financial frameworks. Förster *et al.* (2022) extend this analysis by emphasizing that public trust, equitable risk distribution, and participatory decision-making are as consequential as technical feasibility in determining project viability. Ciotta *et al.* (2025) further identify continuous stakeholder engagement as a non-negotiable component of project assessment, ensuring that social acceptance is treated with equivalent rigor to technical integrity considerations. At a global scale, Temper *et al*. (2020) quantify that over a quarter of energy projects, both fossil and low-carbon, facing social resistance are cancelled, suspended, or delayed, with some conflicts escalating to repression or violence.

Workforce transition technologies

Workforce transition technologies, including digital training simulators, remote operations safety systems, and robotics, are increasingly deployed at the intersection of ESG social metrics and operational decarbonization strategies. These systems enable firms to sustain productivity while supporting labor reskilling and safety improvements, though outcomes depend heavily on governance quality and implementation context. At the macro level, robust ESG investment is associated with measurable emissions reduction and ecological performance gains in the energy sector (Zhang *et al*., 2024). Digital transformation further mediates this linkage by enabling green innovation and strengthening overall ESG performance through organizational and managerial channels (Liu et al., 2025). In heavy industry, automation, electrification, and digitalization improve efficiency and worker protection, with robotics and remote operations reducing emissions while enhancing occupational safety (Tadros *et al*., 2026). However, critical perspectives warn that fragmented ESG systems can facilitate superficial compliance or "pseudo-social responsibility," where technology signals progress without resolving structural labor inequities (Qiao, 2025). Place-based analyses show that evaluating just transitions requires context-sensitive indicators and participatory governance frameworks incorporating skills, wellbeing, and community agency (Shapovalova *et al*., 2025). Capacity constraints also matter, as limited interdisciplinary expertise can hinder integration of reskilling technologies with decarbonization planning (Chopra *et al*., 2024). Effective transition therefore requires governance systems linking workforce technologies to verifiable social and environmental outcomes (Fig. 5).

Metric fragmentation and methodological constraints

ESG rating divergence

The assumption that ESG ratings consistently channel capital toward firms achieving substantive decarbonization is weakened by extensive metric fragmentation and methodological inconsistency across rating providers. Evidence from emissions intensive sectors indicates that ESG environmental scores frequently fail to align with observed carbon outcomes. An examination of 75 leading producers in the steel industry reveals a lack of significant correlation between environmental or emissions ratings and both total greenhouse gas emissions and emissions intensity, as well as with variations in these metrics over time. Firms receiving favourable scores could not be distinguished based on disclosed emissions data or investment patterns, suggesting that rating outcomes were driven by factors not directly linked to carbon performance

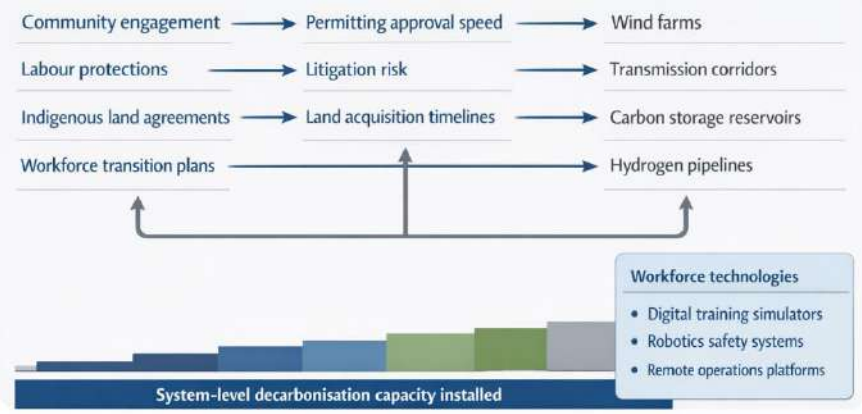

Fig. 5: Social license and infrastructure deployment interface

(Cregan *et al*., 2024a). Comparable results emerge in the aviation industry, where emissions scores for 57 carriers neither captured reported emissions levels nor demonstrated predictive validity, while divergence across rating agencies remained substantial (Cregan *et al*., 2024b). This divergence introduces opacity into ESG signalling. Firms may achieve strong aggregate ESG profiles through governance practices or environmental management processes while remaining highly carbon intensive in operational terms. As a result, ESG ratings may become decoupled from the specific objective of emissions reduction. The underlying limitation is systemic rather than firm specific, arising from discretionary weighting schemes, reliance on non-standardised qualitative indicators, and limited transparency regarding score construction. These features generate conflicting market signals that can distort capital allocation and incentivise optimisation toward score improvement rather than toward material reductions in greenhouse gas emissions (Table 1).

Disclosure versus performance paradox

A further constraint emerges from the observed divergence between ESG disclosure quality and realised environmental performance. Although disclosure may lead to better outcomes in specific circumstances, the mere intensity of reporting does not ensure operational transformation. Evidence from Chinese A share listed firms suggests that ESG disclosure may correlate with improved environmental performance through mediating mechanisms such as green innovation and increased media scrutiny (Wu *et al*., 2025). However, this relationship is conditional rather than automatic. Cross country analysis across 28 jurisdictions demonstrates that the effectiveness of emission reduction policies is significantly moderated by corporate governance quality, with stronger governance structures reducing greenwashing risks and strengthening the association between disclosed commitments and lower emissions intensity (AlHares, 2025). In the absence of robust governance, firms may expand reporting infrastructure without undertaking corresponding technological change. Research on Industry 5.0 highlights how digitalisation and advanced reporting frameworks can be deployed to enhance transparency and responsiveness (Yadav *et al*., 2025), yet these tools can also function symbolically when not embedded within binding decision making processes. This disclosure performance gap reflects misaligned incentives in which market and regulatory pressures reward reporting sophistication itself, sometimes independently of substantive emissions outcomes. Companies may thus become intensive in their disclosures while still being limited in their ability to transform.

Table 1: ESG rating construction, sources of divergence, and implications for emissions assessment

Rating dimension	Typical methodological approach	Source of divergence or bias	Implications for emissions measurement	Risk for capital allocation and interpretation	Sources
Indicator selection	Combination of environmental policies, management systems, targets, disclosure practices, and selected outcome indicators such as emissions intensity	Absence of a standardised indicator set and differing interpretations of materiality across sectors and regions	Environmental scores may not systematically correspond to absolute emissions levels or changes in emissions intensity	Capital may be directed toward firms with extensive ESG policies and disclosures rather than those achieving lower operational emissions	(Lindgren *et al.*, 2025)
Weighting of ESG components	Aggregation of environmental, social, and governance indicators using proprietary weighting schemes	Discretionary and non-transparent weighting, with varying emphasis on governance or social dimensions relative to environmental outcomes	Carbon intensive firms may receive high overall ESG scores despite limited emissions reductions	Comparability across firms and regions is reduced, weakening the reliability of ESG signals in investment decisions	(Ali *et al.*, 2025)
Reliance on disclosed data	Predominant use of self-reported corporate disclosures supplemented by public filings and third-party information	Disclosure asymmetry, selective reporting, and uneven verification across jurisdictions	Reported performance may reflect reporting capacity rather than realised emissions outcomes	Increased exposure to greenwashing and overestimation of transition progress	(Chen *et al.*, 2025)
Treatment of absolute versus intensity metrics	Greater emphasis on emissions intensity and relative performance metrics than on absolute emissions	Intensity metrics can improve through output growth or structural changes without reducing total emissions	Reductions in intensity may coexist with rising aggregate emissions	Investors may infer decarbonization progress where system level emissions remain unchanged or increase	(Dutta *et al.*, 2025)
Temporal alignment	Use of contemporaneous or short lag indicators relative to rating publication cycles	Limited incorporation of long-term emissions trajectories and delayed effects of capital investment	Ratings may fail to capture lagged impacts of technology deployment on emissions	Short term ESG improvements may be prioritised over long horizon mitigation strategies	(Zhang and Cheng, 2025)
Sectoral adjustment practices	Application of sector specific benchmarks and peer comparisons	Inconsistent sector classifications and benchmark definitions across rating methodologies	Emissions performance may appear favourable relative to peers despite high absolute carbon intensity	Capital allocation may reinforce sectoral norms rather than absolute decarbonization objectives	(Bendig *et al.*, 2025)
Verification and assurance	Partial use of externally assured data alongside unaudited disclosures	Uneven assurance standards and limited coverage of scope 3 emissions	Measurement uncertainty persists for value chain emissions and indirect impacts	Risk of mispricing transition exposure and underestimating stranded asset risk	(Borchardt *et al.*, 2025)

Greenwashing and technology symbolism

The disclosure performance gap is frequently exploited through greenwashing strategies that emphasize selective technological signals while obscuring continued dependence on carbon intensive core activities. A scoping review of sustainable finance identifies multiple greenwashing practices, including ambiguous claims, selective disclosure, and emphasis on immaterial initiatives, all of which erode stakeholder trust and undermine the informational value of ESG metrics (Dempere *et al.*, 2024). Evidence from the public sector similarly indicates that symbolic compliance is prevalent, with ESG disclosure quality often weakly connected to actual sustainability outcomes and organizational efficiency (Efthalitsidou *et al.*, 2025). Within energy and industrial firms, technology symbolism often takes the form of highlighting pilot projects, minority renewable investments, or demonstration scale carbon capture initiatives while simultaneously expanding fossil-based production. Such practices create an appearance of transition without proportional structural change. Critiques of corporate pseudo social responsibility describe this pattern as green hypocrisy, whereby symbolic alignment with sustainability narratives weakens the inferred link between ESG oriented capital flows and real-world emissions mitigation. In

these contexts, ESG metrics may reflect communicative effectiveness rather than technological or operational transformation.

Integrative pathway framework from metrics to mitigation

The integrative framework linking ESG metrics to decarbonization outcomes is conceptual in nature and is intended as an analytical heuristic rather than a tested causal model. It identifies three interrelated pathways through which ESG signals may shape technological trajectories and emissions outcomes, subject to institutional, regulatory, and technological constraints. The capital pathway describes how ESG assessments can influence financing conditions rather than directly causing emissions reductions. Empirical studies indicate that stronger ESG profiles are associated with preferential access to green bonds, sustainability linked loans, and climate aligned equity instruments, often featuring lower financing costs or performance indexed terms (Rodrigues Loiola *et al*., 2025). Enhanced access to capital could increase companies' ability to invest in renewable energy generation, carbon capture technologies, grid enhancements, hydrogen infrastructure, and electrified operations (Long *et al*., 2024). However, the emissions implications of such investments depend on ass*et al*location choices. Where capital supports substitution toward low carbon assets, reductions in absolute emissions are more likely. Where financing is used to refinance or marginally optimize existing fossil-based assets, mitigation effects remain limited (Ji *et al*., 2025) (Table 2). The governance pathway captures organizational mechanisms that condition how ESG expectations are translated into strategic decisions. Board level sustainability oversight, climate risk disclosure, and investor engagement have been associated with the integration of emissions related indicators into executive compensation and long-term incentive structures (Morrison *et al*., 2025). Such alignment may reorient innovation priorities toward low carbon research and development, pilot deployment, and partnership strategies (Zhang and Huang, 2024). Governance integration can reduce internal resistance from incumbent fossil-oriented divisions and facilitate reallocation toward emerging technologies such as green hydrogen, advanced storage, and digitally enabled efficiency systems (Grasso and Delatin Rodrigues, 2025). Where governance mechanisms remain weak, ESG compliance is more likely to remain symbolic, limiting technological diffusion. The legitimacy pathway operates through external stakeholder relations rather than internal decision making. Strong ESG performance can enhance social acceptance by signaling environmental responsibility, labor protections, and community engagement. Consequently, this may lessen resistance to the implementation of renewable energy systems, the development of transmission infrastructure, carbon sequestration initiatives, and essential mineral supply chains (Rachmawati *et al*., 2025). Reduced resistance can shorten permitting timelines and lower litigation risk, enabling earlier deployment and faster displacement of carbon intensive capacity. Conversely, firms with contested social or environmental records often face delays or cancellations of low carbon projects despite access to capital. In this sense, legitimacy functions as an enabling condition rather than a direct driver of emissions reduction (Hansen *et al*., 2024). Across all three pathways, outcomes are mediated by structural context. Carbon pricing strengthens financial incentives within the capital pathway (Ibishova *et al*., 2024). Transition taxonomies and disclosure mandates reinforce governance accountability. Regulatory stability influences the speed at which legitimacy translates into deployment (Sunanda *et al*., 2025). Technology maturity further conditions temporal

Table 2: ESG mechanisms, technology adoption pathways, moderating conditions, and reported decarbonization outcomes

ESG pathway mechanism	Dominant ESG dimension	Technology categories influenced	Nature of empirical evidence	Reported emissions outcome indicators	Key moderating constraints	Sources
Capital access and financing conditions	Environmental, Governance	Renewables, electrification, CCUS, grid modernisation	Predominantly correlational; limited mediation evidence	Emissions intensity, renewable capacity, capital expenditure allocation	Carbon pricing, technology maturity, asset substitution versus refinancing	(Calcaterra *et al.*, 2024)
Governance alignment and incentives	Governance	Low carbon R and D, hydrogen, storage, digital optimisation	Associational and qualitative process evidence	Innovation output, transition milestones, emissions intensity trends	Board authority, legacy asset lock in, incentive design	(Yan *et al.*, 2025)
Social legitimacy and stakeholder acceptance	Social	Renewable parks, transmission infrastructure, carbon storage	Qualitative and case based evidence	Project timelines, deployment scale	Community opposition, regulatory stability, land access	(Witte, 2021)

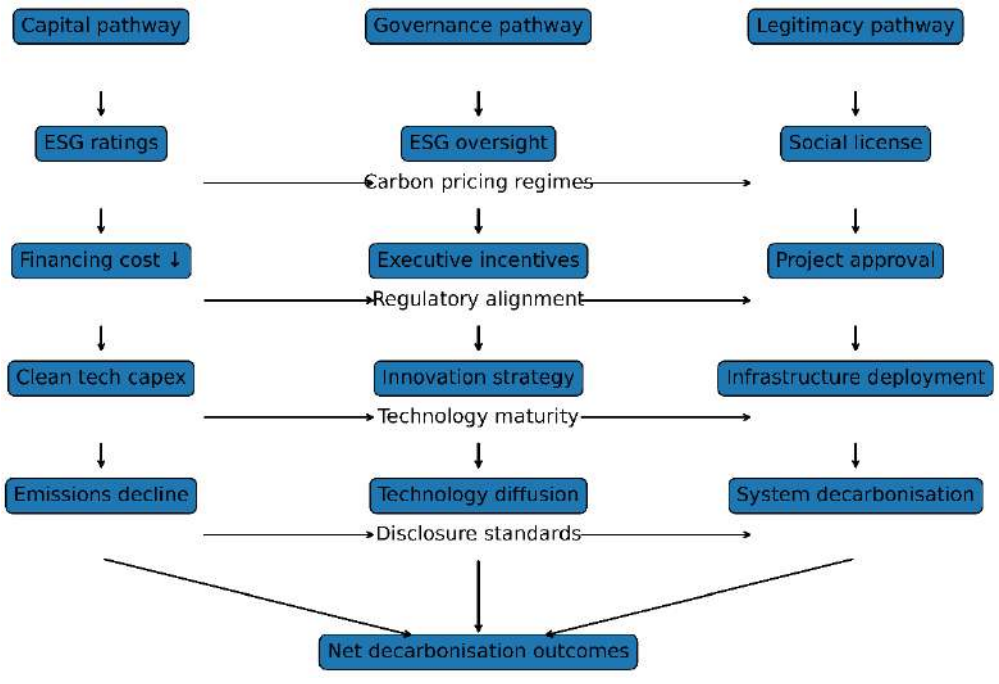

Fig. 6: Integrative ESG-to-decarbonization pathway framework

dynamics, as commercially established renewables scale more rapidly, while nascent systems such as green hydrogen or direct air capture exhibit longer lag times between ESG signaling and measurable mitigation (Masoumilari *et al.*, 2026) (Fig. 6).

RECOMMENDATION

This review has two primary implications for theory and practice. First, it provides integrative insights by clarifying causal linkages between sustainability investment metrics, governance structures, and clean technology adoption in driving carbon reduction across global energy companies. The proposed integrative pathway framework highlights the importance of financing access, executive incentive alignment, and social license conditions in accelerating decarbonization. Second, the findings suggest that sustainability investment systems should incorporate

technology-specific indicators, such as renewable capacity deployment, carbon capture operationalization, and real-time emissions monitoring, which remain under emphasized in existing scoring models. Future research may focus on empirically testing the framework across regional energy markets, particularly in emerging economies. This review is beneficial for institutional investors, regulators, and energy policymakers seeking to refine sustainability finance mechanisms that directly link investment flows to measurable decarbonization outcomes.

CONCLUSION

This study has examined how Environmental, Social, and Governance (ESG) metrics are associated with technology adoption and carbon mitigation trajectories in global energy companies. Rather than treating ESG scores as direct determinants of decarbonization, the analysis has synthesized evidence indicating that ESG signals operate through conditional and mediated pathways. Across the literature, relationships between ESG performance, financing conditions, governance structures, and infrastructure deployment are predominantly correlational, with limited causal identification. The contribution of this review therefore lies not in asserting deterministic effects, but in clarifying the mechanisms through which ESG metrics may influence technological transition under specific institutional and regulatory contexts. The integrative framework proposed in this study outlines three interrelated pathways: access to capital, alignment of governance, and social legitimacy. The framework is intended as an analytical heuristic that organizes existing empirical findings rather than as a tested causal model. Evidence indicates that stronger ESG profiles are often associated with preferential access to sustainability-linked finance and portfolio reallocation toward lower-emissions assets. However, the emissions consequences of such financial shifts depend on whether capital is directed toward asset substitution and deployment of low-carbon capacity rather than refinancing or incremental efficiency improvements. Financial mechanisms consequently influence the range of opportunities for transition; however, they do not independently ensure a quantifiable emissions decline. Governance structures further mediate outcomes. Board oversight, executive remuneration linked to climate indicators, and disclosure of transition risks are associated with greater integration of decarbonization considerations into strategic planning and research portfolios. However, literature primarily records associations instead of impacts that have been experimentally verified. Firms operating under similar ESG pressures frequently exhibit divergent technological responses, reflecting differences in organizational capabilities, legacy asset structures, ownership models, and regulatory environments. These moderating factors limit the generalizability of ESG effects across jurisdictions and firm types. Social and legitimacy dimensions constitute an additional enabling condition. Community acceptance, stakeholder engagement, and regulatory credibility influence whether renewable energy installations, transmission infrastructure, and carbon storage facilities are deployed at scale. Empirical studies suggest that social performance can affect project timelines and permitting processes. However, the strength and direction of these effects vary across regions, particularly between OECD economies and emerging or resource-exporting contexts. Much of the available evidence is concentrated in Europe and China, indicating a geographical bias in the

current knowledge base. Caution is therefore required in extrapolating conclusions to underrepresented regions, including parts of Africa, Latin America, and Central Asia. The review also highlights structural limitations in ESG measurement. Rating divergence, non-standardized indicator selection, discretionary weighting, and heavy reliance on self-reported disclosure weaken the alignment between ESG scores and operational emissions outcomes. The disclosure–performance gap and the risk of symbolic compliance complicate attempts to interpret ESG improvements as evidence of substantive decarbonization. Distinguishing operational emissions reductions from accounting adjustments, offsets, or narrative repositioning remains a persistent challenge. These measurement limitations restrict the accuracy with which ESG metrics can be associated with atmospheric outcomes. Theoretically, this review adds value by synthesizing disparate elements of literature concerning sustainable finance, corporate governance, and energy transition into a coherent pathway model that clearly delineates moderating conditions. By distinguishing association, mediation, and enabling conditions, the analysis responds to calls for greater conceptual clarity in ESG–technology–decarbonization research. Practically, the findings suggest that managers and policymakers should avoid treating ESG scores as sufficient indicators of transition performance. Aligning ESG metrics with verifiable deployment indicators, such as installed renewable capacity, capital expenditure reallocation toward low-carbon assets, emissions intensity trajectories, and lifecycle accounting standards, would strengthen credibility. Regulatory harmonization, clearer transition taxonomies, and improved monitoring, measurement, and verification systems may reduce rating divergence and enhance comparability. Several limitations remain. The synthesis is constrained by the predominance of observational studies, short time horizons, and heterogeneous measurement approaches. Attribution challenges persist in isolating the independent effect of ESG signals from concurrent policy instruments such as carbon pricing, subsidies, and disclosure mandates. Time lags between investment decisions, technology deployment, and measurable emissions outcomes are insufficiently captured in existing datasets. Future research would benefit from longitudinal designs, quasi-experimental approaches, and firm-level case studies that track capital allocation, technology adoption, and verified emissions trajectories over extended periods. Improved integration of scope 3 emissions data and independent assurance mechanisms would further strengthen causal inference.

AUTHOR CONTRIBUTIONS

N.S. Mamytova conceptualized the review, coordinated the research process, synthesized the manuscript, and drafted the initial version; G.A. Sarbassova performed the literature search, selected relevant references, and coded the materials; M. Omarbekova performed the literature search, selected relevant references, and coded the materials; K.A. Mukanova interpreted the data, organized thematic structures, and drafted specific sections; L.A. Alzhanova interpreted the data, organized thematic structures, and drafted specific sections; S.S. Shamshedenova supported methodological design, analyzed references, and edited the manuscript; A. Talgatbekova supported methodological design, analyzed references, and edited the manuscript; Y.R. Rustemova validated the literature, conducted analytical synthesis, and reviewed the manuscript; U.K. Raimbekova validated the literature, conducted analytical

synthesis, and reviewed the manuscript; F.K. Zhanseit prepared the work plan, refined the conceptual framework, and critically reviewed the manuscript; Y. Pangaliyev prepared the work plan, refined the conceptual framework, and critically reviewed the manuscript; and T. Mkilima supervised the overall study, finalized the conceptual framework, reviewed the full manuscript, and approved the submitted version.

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CONFLICT OF INTEREST

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

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

ABBREVIATIONS

%	Percent
AI	Artificial intelligence
CO_2	Carbon dioxide
COALMOD-World	Global coal market model
E-7	Emerging seven economies
ERP/ ERPs	Emission reduction policy / policies
ESG	Environmental, Social, and Governance
Fig.	Figure
IoT	Internet of things
MMQREG	Method of moments quantile regression
MMV	Monitoring, measurement, and verification
MRV	Monitoring, reporting, and verification
R&D	Research and development
SMEs	Small and medium-sized enterprises
TDLAS	Tunable diode laser absorption spectroscopy
USD	United states dollar

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REVIEW PAPER

Integrated pest control and environmental risk management for sustainable chili pepper production

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ABSTRACT

Chili (Capsicum spp.) is a high-value crop in Indonesia constrained by a diverse insect pest complex, fragmented smallholder systems and intensive use of synthetic insecticides that cause environmental contamination, non-target impacts and resistance. This study synthesizes ecological and socio-economic evidence to 1) identify and quantify major pest constraints; 2) evaluate environmental and health costs of pesticide-centric management; and 3) assess eco-friendly Integrated Pest Management strategies and scale-up options. A systematic literature synthesis of peer-reviewed articles and grey literature published between 2010 and 2025 were investigated. Searches were run in Scopus, Web of Science, PubMed, AGRICOLA and Google Scholar and supplemented by Indonesian repositories and conference proceedings. Queries combined crop descriptors (chili, Capsicum), pest taxa (Bactrocera, Helicoverpa, Spodoptera, Bemisia tabaci, thrips, aphids, Liriomyza) and intervention types (biocontrol, biopesticide, botanical, Integrated Pest Management, nano-delivery). Preferred reporting items for systematic reviews and meta-analyses style screening, assessed study quality, extracted quantitative metrics on yield loss, application, non-target effects, and adoption rates were extracted. Furthermore, results were synthesized in both narrative form and as tabulated evidence by pest and intervention. The dominant pest complex comprises fruit flies (Bactrocera spp.), lepidopteran borers (Helicoverpa, Spodoptera), Bemisia tabaci, thrips, aphids and leafminers. Yield losses average 30 percent under poor management and exceed 70 percent in severe outbreaks. Utilizing insecticides on a calendar basis encourages resistance, diminishes beneficial insect populations, leads to pesticide residues, and causes water contamination. Integrated strategies—such as sanitation, resistant varieties, biological control, biopesticides, and selective pesticides—minimize inputs while maintaining yields. Emerging precision tools (AI detection, IoT traps, mass trapping, ribonucleic acid interference, nano-formulations) improve targeting but need regulation, lower costs, and field validation. The adoption of new practices is constrained by inadequate extension systems, concerns regarding product quality, disjointed supply chains, and the risk aversion exhibited by farmers. A four-pillar roadmap is proposed: ecological monitoring with thresholds, validated bio/botanical tools, farmer training with incentives, and supportive policy frameworks.

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INTRODUCTION

Chili (*Capsicum* spp.) holds a pivotal position in Indonesian agriculture, deeply embedded in the country's food culture, nutrition, and rural livelihoods. It acts as a vital commodity not only in the national food framework but also as a major factor affecting food security and inflation trends. Indonesia's chili sector accounted for approximately 32 percent (%) of the global spice output in 2020, producing over 2.7 million tons (Mt), with an average per capita consumption exceeding 5 kilograms (kg) annually, predominantly in fresh form (Saptana *et al.,* 2022). Although chili production holds considerable economic and nutritional value, it is confronted with substantial challenges that can frequently diminish yields by 20–30% or greater during intense pest outbreaks (Ahmad *et al.,* 2024; Sari *et al.,* 2023). Yield losses are largely driven by pest infestations, further compounded by fragmented landholdings, suboptimal agronomic practices, and climate variability, threatening the resilience of chili farming systems in Indonesia. Major pests include fruit flies (*Bactrocera* spp.), chili fruit borers (*Helicoverpa armigera*), whiteflies (*Bemisia tabaci*), thrips (*Scirtothrips* spp.), leaf miners (*Liriomyza* spp.), and cutworms (*Spodoptera*/*Agrotis* spp.) (De Costa *et al.,* 2021). These pests cause direct feeding damage that adversely affects fruit quality and yield. Furthermore, many of these pests transmit viral and bacterial pathogens, which exacerbate economic losses. The interactions between pests and viruses adds further complexity to chili production, especially in climatic conditions that are conducive to pest outbreaks (Suryanto, 2018a; Tasmin *et al.,* 2018). Historically, Indonesian farmers have relied heavily on broad-spectrum insecticides to control pests. However, this practice has promoted resistance, environmental contamination, residue accumulation in soil and produce, and harmful impacts on beneficial arthropods and pollinators (Shim *et al.,* 2023; Punniyakotti *et al.,* 2024). The consequences emphasize the importance of sustainable, regionally adapted integrated pest management (IPM) strategies that strike harmonize between pest control and ecological safety. IPM incorporates biological control, selective insecticides, cultural practices (including, intercropping, crop rotation), and physical barriers to develop resilient systems that protect natural enemies and reduce chemical dependence (Bottrell and Schoenly, 2018). Internet of things (IoT) sensor networks and AI-based detection tools are improving IPM precision through real-time pest monitoring and targeted interventions, reducing pesticide use and environmental impacts (Li and Wang, 2024; Agustian *et al.,* 2023). These technologies facilitate prompt decision-making for smallholder chili farmers in Indonesia. Nonetheless, the adoption of IPM is inconsistent, primarily due to insufficient extension services, gaps in training, financial limitations, and fragmented land ownership that obstructs coordinated pest management (Erdiansyah and Putri, 2020; Abbey, 2023). Addressing these barriers requires IPM frameworks that are context-appropriate, affordable, and accessible to smallholders across diverse agroecological zones. Ecological approaches such as biopesticides (botanical extracts and microbial agents) and repellent intercropping have shown promise for controlling major chili pests with low environmental risk (Adom *et al.,* 2024; Istianto *et al.,* 2025; Wiratno *et al.,* 2025; Bashyala *et al.,* 2022; Singh *et al.,* 2023). Nevertheless, broader incorporation into extensive IPM programs necessitates methodical validation and regionally tailored guidelines. The heavy application of pesticides in chili cultivation has led to soil and water pollution, a decline in biodiversity, and a reduction in ecosystem services, jeopardizing the sustainability of agriculture in the long run (Shim *et al.,* 2023). Climate change intensifies chili pest problems by altering pest lifecycles and increasing outbreak risks, requiring adaptive IPM strategies. This study synthesizes evidence up to 2025 on major insect pests affecting chili (*Capsicum* spp.), including their biology, damage, and detection

methods. It reviews the management strategies pertaining to, biological, cultural, and technological elements, as well as their ecological and economic repercussions. The review highlights the limitations of pesticide-intensive practices and the potential of eco-friendly alternatives. These methods encompass biological control, the use of botanicals, the development of resistant cultivars, and the enhancement of cultural practices. Emerging tools such as AI and IoT are also examined for precision monitoring and decision support in smallholder systems. An integrated framework is proposed to enhance productivity, resilience, and environmental sustainability of chili production in Indonesia. The application of botanical insecticides for pest management is a crucial element that must be adopted. Utilizing insecticides on rice plants serves a dual purpose: it effectively curtails pest attacks while simultaneously enhancing the vegetative growth of the plants, leading to a potential production rise of as much as 16% (Wiratno *et al.,* 2025). Morover, in cocoa pest management, botanical insecticides help control pests while preserving natural enemies (Trisawa *et al.,* 2026). Drawing from this synthesis, it is recommended that sustainable management strategies be developed in accordance with national agricultural priorities, environmental conservation efforts, and international phytosanitary standards. The aim of this review is to synthesise evidence on IPM for chili (*Capsicum* spp.) while explicitly integrating environmental risk assessment. The objectives of this research are 1) to provide a summary of the pest complexes associated with chili and the IPM strategies; 2) to evaluate the environmental effects of IPM in comparison to traditional pesticide methods utilizing standard metrics (for instance, field-use environmental impact quotient (EIQ); 3) assess monitoring, predictive and digital tools for pest and environmental risk management; 4) identify socioeconomic, policy and landscape drivers influencing IPM adoption and environmental outcomes. The study was conducted in Indonesia using secondary data compiled from Indonesian and international scientific literature, policy documents, technical reports, and environmental monitoring records published up to 2025.

METHODOLOGY

This study adopted a comprehensive, systematic approach to identify, appraise and synthesize evidence on insect pest constraints and environmentally sound management options for chili (*Capsicum* spp.), with an emphasis on the Indonesian context and comparable tropical smallholder systems. Systematic review methodologies facilitate the clear gathering and assessment of various evidence sources, assist in pinpointing areas lacking knowledge and areas of agreement, and guide policy and practice (Moher *et al.,* 2009).

Scope and objectives

The study targeted literature published through 2025 and addressed five core objectives: 1) document pest bioecology and incidence in Indonesian chili systems; 2) quantify agronomic and economic impacts; 3) evaluate environmental and ecological risks connected to pest management, which encompass residues, effects on non-target organisms, pollinator and soil health, water contamination); 4) assess efficacy, cost-effectiveness and scalability of eco-friendly tactics (biological control, botanicals, cultural practices, microbial products, precision tools); and 5) Determine the socio-economic and institutional limitations affecting adoption and the policy tools available for expansion.

Search strategy and information sources

A structured search protocol was implemented across international bibliographic databases (Scopus, Web of Science, PubMed, AGRICOLA), Google Scholar, Indonesian institutional repositories and relevant government and non-governmental organization (NGO) technical report collections. Search terms combined crop and pest descriptors (such as, chili, Capsicum, *Bactrocera,*

Helicoverpa, Bemisia), intervention types ("biocontrol", biopesticide, botanical, mass trapping, RNAi, nano-formulation), and environmental-risk terms (pesticide residue, pollinator, soil health, ecotoxicology, water contamination). Citation chaining along with focused searches of conference proceedings and policy documents enhanced database queries.

Inclusion and exclusion criteria

Included records comprised peer-reviewed field or semi-field studies, multi-season trials, reviews, and high-quality reports relevant to tropical smallholder systems. Priority was given to studies reporting agronomic outcomes, environmental indicators, or socio-economic metrics. Laboratory studies were employed exclusively to clarify mechanisms, not as the main evidence for management recommendations.

Screening, quality appraisal and data management

A preferred reporting items for systematic reviews and meta-analyses (PRISMA)-style screening workflow was applied to document identification, screening, eligibility and inclusion (Moher *et al.,* 2009). Records were filtered through title, abstract, and full text in accordance with specified inclusion criteria. The quality of the studies was assessed using standardized checklists, which encompassed randomization, replication, controls, sample size, reporting. Risk-of-bias informed evidence weighting. The review followed PRISMA 2020 procedures with database queries, record counts, and a 0–3 quality scoring protocol (Page *et al.,* 2021). Pest-specific descriptions were condensed into comparative synthesis tables summarizing intervention types, validation level (laboratory, greenhouse, field), and environmental indicators. This arrangement enables a more distinct comparison of pest management results, as well as the recognition of trends, discrepancies, and research voids. Focus ing on comparative synthesis rather than narrative description strengthens the systematic evaluation of environmentally responsible chili pest management. It also improves transparency and reproducibility, consistent with systematic review guidelines. (Page *et al.,* 2021). This approach helps assess how IPM strategies perform across different agroecological conditions and highlights remaining knowledge gaps for future research.

The study process

The review used a systematic literature search across international databases, Indonesian repositories, and grey literature. Studies were screened for relevance and quality. The extracted key data encompassed aspects such as pest biology, detection technologies, control methods, environmental impacts, and the factors that affect the adoption of chili IPM systems (Li and Wang, 2024). The findings were synthesized in a narrative format, highlighting results that have been validated in the field and those from multi-season trials. Citation chaining and expert consultation revealed further local studies. Priority was given to validated interventions and environmentally sustainable IPM strategies (Erdiansyah and Putri, 2020; Ferrari, 2015), Using transparent search criteria and standardized data extraction, studies reporting environmental indicators (residues, non-target effects, soil or water quality) were prioritized. This approach supports reliable synthesis and policy-relevant recommendations for sustainable chili pest management in Indonesia. The framework is summarized in Table 1.

Problem framing and opportunity

Chili (*Capsicum* spp.) serves as a fundamental dietary component and a lucrative cash crop for smallholder farmers in Indonesia; however, its production is consistently hindered by a variety of pest issues and structural obstacles to the implementation of sustainable practices (Suryanto, 2018b). Contemporary pests inflict both direct losses (fruit boring, sap extraction, defoliation) and indirect losses (virus transmission

Table 1: Environmental risk–oriented framework for sustainable chili pest management in Indonesia

Step	Core focus	Key outputs	Main actions
1. Evidence synthesis	Literature (2010–2025), national reports, residue records, biodiversity and climate data	Database linking pests, yield loss, pesticide use, and environmental impacts	Identify high-risk pests and chemicals; define knowledge gaps
2. Monitoring system	Sentinel traps, field scouting, residue testing, beneficial insect surveys	Early-warning indicators (trap thresholds, residue limits, predator:pest ratios)	Implement threshold-based interventions instead of calendar spraying
3. Environmental risk evaluation	Residue persistence, pollinator impact, soil and water contamination, ecotoxicology data	Risk ranking of active ingredients (high–medium–low)	Phase down high-risk pesticides; promote validated low-risk alternatives
4. Eco-friendly intervention portfolio	Biological control, botanicals, cultural practices, resistant varieties, selective products	Ranked eco-friendly tactics with efficacy and cost–benefit performance	Deploy integrated packages prioritizing biological and cultural measures
5. Resistance stewardship	Bioassays, spray history, mode-of-action analysis	Resistance monitoring maps and rotation guidelines	Enforce mode-of-action rotation and reduce chemical dependency
6. Adoption and policy integration	Farmer surveys, extension capacity, supply chain analysis	Identification of adoption barriers and leverage points	Strengthen extension, quality control of biopesticides, and policy incentives
8. Long-term sustainability monitoring	Ongoing residue, biodiversity and resistance surveillance (RS)	National environmental performance indicators	Institutionalize eco-friendly integrated pest management within regulatory frameworks

and market rejection for blemished fruit), producing field-level impacts that average 20–30% and occasionally exceed 50% during outbreaks (Ahmad *et al.,* 2024). These combined biophysical and socioeconomic limitations necessitate a review that merges pest ecology, detection, control technologies and adoption pathways into a unified and practical IPM agenda for Indonesia (Erdiansyah and Putri, 2020; Adom *et al.,* 2024).

The pest complex: composition, damage pathways and spatial heterogeneity

Chili production in Indonesia is constrained by a consistent pest complex: chili fruit borer (*Helicoverpa armigera*), whitefly (*Bemisia tabaci*), tephritid fruit flies (*Bactrocera* spp.), thrips (*Scirtothrips dorsalis*), leaf miners (*Liriomyza* spp.) and polyphagous defoliators (for instance., *Spodoptera* spp.). Distinct damage is caused by each group—internal fruit boring (*Helicoverpa*, *Bactrocera*) that reduces marketability; phloem-sap removal and virus transmission by whiteflies and thrips that adversely affect yield and quality; and foliage loss from miners and defoliators that compromise plant integrity (Hamidson *et al.,* 2024; De Costa *et al.,* 2021). According to field studies, there are regular yield declines of 20% to 30%, and during intense outbreaks, losses can be significantly higher, often exceeding 50% (Ahmad *et al.,* 2024; Prabaningrum *et al.,* 2022). Spatial and temporal heterogeneity—seasonality, cropping intensity, host mosaics and microclimate—determines which pest dominates at a given time, which is why calendar sprays often fail; monitoring- and phenology-based interventions are more effective (Suryanto, 2018a). Rising temperatures are modifying pest demographics: *Bemisia* thrives at thermal optima in the high 20s to low 30s degrees Celsius (°C), which is likely to result in an increase in generations, while Bactrocera's phenology is evolving towards earlier and more compact flight intervals (Xue *et al.,* 2022; Kriticos *et al.,* 2020; Cai *et al.,* 2023). These trends underscore the need for climate-resilient, weather-informed IPM. Landscape context and natural-enemy supply mediate control: conservation biological control (refugia, floral resources) reduces pest pressure where habitat quality and connectivity are sufficient (Tscharntke *et al.,* 2007). Indonesian trials show companion plants (kenikir, zinnia) lower whitefly incidence (Jasmi and Nasution, 2023; Rondonuwu *et al.,* 2014), but fragmented landscapes erode biocontrol services, so

interventions must be embedded in landscape planning and farmer coordination. In practice, IPM ought to employ spatially explicit monitoring techniques such as trap networks and degree-day or sentinel plots, utilize resistant or protected seedlings, implement conservation biocontrol methods suitable for smallholders, and incorporate climate-aware early-warning systems along with selective biopesticides (Latifah *et al.,* 2021; Rajapaksha *et al.,* 2023; Kriticos *et al.*, 2020). Scaling requires landscape-nested, multi-site trials that jointly measure pest demography, enemy spillover, yields and farmer costs to ensure robust, adoptable recommendations (Nugroho *et al.,* 2019; Prabaningrum *et al.,* 2022).

Detection and monitoring: from scouts to smart sensors

Early detection remains the cornerstone of successful suppression. Low-cost methods, farmer scouting, yellow/blue sticky traps, pheromone lures and routine field inspections, still provide the bulk of operational monitoring because they are affordable, interpretable and actionable for smallholders (De Costa *et al.,* 2021; Fening *et al.,* 2020). Concurrently, IoT sensor networks along with AI-based image recognition are developing into effective field tools that facilitate continuous monitoring, automated counting, and proactive warnings (Li and Wang, 2024; Agustian *et al.,* 2023). Prototype deployments combining multispectral sensors with trap counters have demonstrated pesticide reductions without yield loss in pilot studies (Li and Wang, 2024). Nonetheless, practical challenges to adoption persist, including costs, connectivity, and digital literacy, which limit uptake. Furthermore, AI models generally need local retraining or larger local image datasets to preserve accuracy across various environments (Abbey, 2023; Agustian *et al.,* 2023). Consequently, hybrid systems, community scouting augmented by smartphone or low-bandwidth AI tools and extension support, represent the most pragmatic near-term pathway (Abbey, 2023; Li and Wang, 2024).

IPM: evidence, trade-offs and scaling challenges

Fig. 1 illustrates the conceptual decision-support framework for eco-friendly IPM in chili. IPM combines cultural tactics (sanitation, crop rotation, intercropping), Natural control includes biological control (entomopathogens, parasitoids) and Botanicai insecticide, selective chemistries (IGRs, spinosyns) and physical methods (mass trapping, reflective mulches) under monitoring-based thresholds. Regional studies indicate IPM packages reduce pest loads and pesticide reliance while conserving beneficial arthropods (Bottrell and Schoenly, 2018; Adom *et al.,* 2024). Entomopathogens such as *Beauveria bassiana* and *Metarhizium* spp., microbial products like *Bacillus thuringiensis*, and validated botanical extracts (neem, garlic, citronella) have all shown efficacy in trials when integrated with sanitation and monitoring (Lahati and Haryanto, 2020). Nonetheless, the expansion of IPM is hindered by operational limitations: variability in product quality for biopesticides and botanicals, limited capacity for extension services to communicate protocols to farmers, upfront costs associated with biological releases or mass-trapping, and the continual threat of resistance arising from poor stewardship (Erdiansyah and Putri, 2020; Adom *et al.,* 2024).

Technical control options for priority pests Helicoverpa armigera (chili fruit borer)

Helicoverpa armigera is a major fruit-feeding pest in chili that damages flowers and developing fruits. Effective management combines selective insecticides (indoxacarb, pyridalyl, spinosad), *Bacillus thuringiensis* (Bt) formulations, and pheromone-based monitoring timed to larval phenology; entomopathogenic fungi may further improve control under suitable microclimates (De Costa *et al.,* 2021; Lahati and Haryanto, 2020). Selective insecticides paired with pheromone traps can effectively lower fruit borer populations, especially if foliar sprays are utilized in the early larval stages while maintaining consistent

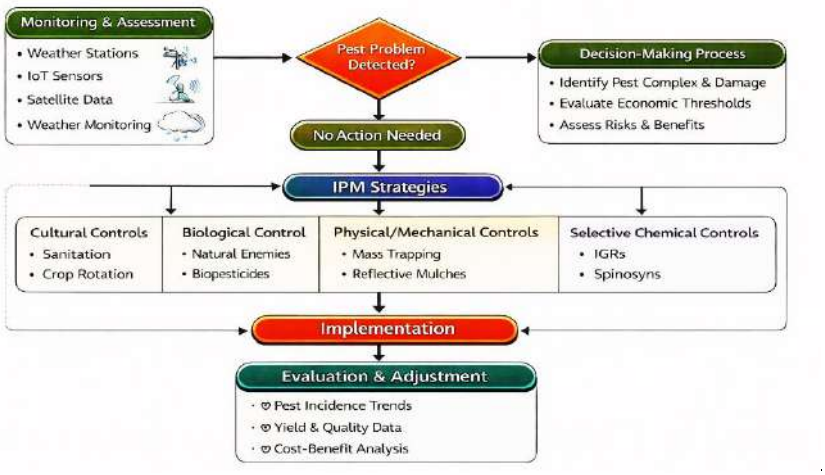

Fig. 1: Conceptual decision-support framework for eco-friendly IPM in chili based on pest monitoring, economic thresholds, and integrated control tactics

monitoring (De Costa *et al.,* 2021; Hadi *et al.*, 2025). However, resistance development and non-target risks require rotation of active ingredients and integration with biological control. Severe infestations may cause 30–70% yield losses (Abid *et al.,* 2020). Employing integrated approaches, including the use of pheromone traps and barrier crops like maize or marigold, can diminish infestations and enhance yields by as much as 36% in comparison to traditional methods (Kranthi *et al.,* 2002). Despite these advances, pest distribution variability, climatic influences, and resistance risks remain challenges, highlighting the need for integrated, multi-season studies and improved decision-support systems for optimized pest management.

Spodoptera spp. and *cutworms*

Recent advancements in chemistry and the use of botanicals play a crucial role in controlling *Spodoptera spp*. in chili (Capsicum spp.). Selective insecticides like indoxacarb, cyantraniliprole, and spinosad are effective in managing early larvae when applied in accordance with pest development and complemented by diligent scouting and sanitation practices (Mishra, 2017). Garlic (*Allium sativum*) extracts and essential oils show strong larvicidal and feeding-deterrent effects. Garlic oil nanoemulsions further improve efficacy and persistence, highlighting potential for sustainable pest management (Firmansyah, 2023; Giuliano *et al.,* 2024). Biological control agents such as entomopathogenic nematodes (*Steinernema* spp., *Heterorhabditis* spp.) and fungi (*B. bassiana*, *Metarhizium anisopliae*) also cause high larval mortality and are compatible with selective insecticides, enabling flexible IPM programs that conserve natural enemies (Thakur *et al.,* 2022).

Fruit flies (*Bactrocera* spp.)

The combination of protein bait sprays, mass trapping, and augmentative parasitoids (such as, *Fopius arisanus*) mitigates infestation when paired with sanitation efforts (Suryanto, 2018a). Fruit fly infestations can reduce marketable yield by 60–100% in severe cases (Hadi *et al.,* 2025). Protein bait sprays combined with attractants reduce populations by over 65% (De Costa *et al.,* 2021). Mass trapping in tropical orchards can reduce infestation by up to 70% (Suryanto, 2018b). Comprehensive IPM packages, including bait sprays, pheromone traps, and biological control methods, have enhanced chili production. Challenges in scaling involve optimizing attractants, managing mass-rearing logistics, and maintaining coordination among farmers.

Whitefly (Bemisia tabaci) and virus management

Whitefly suppression benefits from IGRs (buprofezin, novaluron), reflective mulches, and parasitoid conservation. Integrated virus management additionally requires host resistance and rogueing to reduce begomovirus spread (Nasruddin *et al.,* 2023). The diversity of biotypes and their sensitivity to temperature could restrict the applicability of strategies, highlighting the necessity for local calibration (De Costa *et al.,* 2021; Hadi *et al.*, 2025). IGRs can reduce whitefly density by up to 80% (De Costa *et al.,* 2021). Parasitoids such as *Encarsia formosa* offer strong biological suppression (Suryanto, 2018b).

Leaf miners (*Liriomyza* spp.)

Because leaf miner larvae feed internally, timing is critical: selective products (spinosad), sanitation, and sticky-trap–guided thresholds are the proven pathway (De Costa *et al.,* 2021). Field trials demonstrate that targeted applications can lead to as much as a 70% decrease in activity. Neem and other botanical products provide additional control. Sanitation and yellow sticky traps enhance early detection, while integrated strategies combining selective chemicals, botanicals, and cultural methods reduce infestation by over 60% and increase yields across Southeast Asia (Suryanto, 2018a).

Thrips (Scirtothrips dorsalis)

Managing thrips effectively involves utilizing insecticidal soaps, eliminating infested plant materials, and employing yellow sticky traps for early detection. Furthermore, good sanitation and appropriate irrigation are essential in preventing reinfestation (Suryanto, 2018b; Fening *et al.,* 2020). Integrated programs prioritize prevention and rapid intervention rather than repeated broad-spectrum insecticide use. Across major chili pests, effective control combines cultural practices, biological control, selective insecticides, and regular monitoring. Tools such as pheromone traps, botanicals, biopesticides, IGRs, and selective chemistries improve pest suppression, increase yields, and reduce environmental impacts. However, challenges remain, including pesticide resistance, climate variability, and the need for multi-location validation. Studies conducted in India, Pakistan, and Australia were part of the review due to their examination of similar pest complexes impacting *Capsicum* crops. These regions report significant losses from pests such as *Helicoverpa armigera*, *Thrips palmi*, *Bemisia tabaci,* and aphids, often managed using IPM approaches. Although such studies provide useful comparative evidence, differences in climate, cropping intensity, and farm management require cautious application to Indonesian systems (FAO, 2023; Pretty and Bharucha, 2015).

Biologicals and botanicals

Microbial agents such as *Beauveria*, *Metarhizium* and *Bacillus* spp. have shown consistent suppression in trials (Lahati and Haryanto, 2020; Nurdebyandaru *et al.,* 2010). Botanical essential oils such as *Cymbopogon nardus*, neem, and garlic, have shown the ability to deter oviposition, exhibit ovicidal effects, and possess larvicidal properties in both controlled experiments and certain field trials. Yet quality control, shelf-stability and standard dosing of locally produced formulations are weak, constraining broad adoption; regulatory guidance and certification schemes are needed to support scale-up (Adom *et al.,* 2024; de Oliveira *et al.,* 2021).

Technological frontiers: AI, IoT and nano-enabled delivery

Machine-vision models, e.g., you only look once (YOLO) family, and smartphone implementations are showing >90% detection accuracy for some pests in pilot studies, enabling near-real-time ID for farmer groups when linked to extension flows (Agustian *et al.,* 2023; Li and Wang, 2024). Affordable IoT sensor nodes (including trap counters and microclimate devices) deliver continuous data for forecasting based on weather

conditions and targeted interventions in prototypes (Li and Wang, 2024). Nano-formulations promise improved persistence and targeted delivery of biologicals and botanicals but require rigorous ecotoxicological and human-safety testing before broad adoption (de Oliveira *et al.,* 2021). For all three technology streams, co-design with users, offline functionality and sustainable maintenance/business models are prerequisites for uptake by smallholder communities (Abbey, 2023; Li and Wang, 2024). Current monitoring in numerous smallholder systems is inconsistent; implementing a tiered strategy (which includes farmer scouting, periodic residue testing, and local weather analysis) enhances decision support and resilience in IPM. Integrating trap counts with local weather and simple environmental indicators enables early warnings; prototypes exist but require local validation and extension support (Miller, 2025). Low-cost smartphone AI pest ID and shared IoT traps are practical tools for smallholder IPM. Adoption requires training, local-language interfaces, and cooperative models. Precision tools (AI, IoT, nano) have the potential to mitigate environmental hazards, but require evaluation of costs and connectivity. Basic technologies along with robust extension support are essential for successful implementation.

Emerging technologies and regulation

Novel interventions (biopesticides, RNAi, nano-formulations) show promise but need explicit environmental fate, non-target testing and regulatory pathways before widescale use (De Schutter *et al.,* 2022). Regulatory frameworks for RNAi and nano-formulations are still evolving; risk assessment guidance and local regulatory clarity are required before scale-up.

Host-plant resistance and participatory breeding

Cultivating plants for resistance to pests and viruses decreases reliance on pesticides and enhances the resilience of chili plants. Studies in Indonesia have discovered genotypes that exhibit fewer symptoms of whitefly-virus and reduced aphid colonization. Marker-assisted selection and participatory breeding can accelerate development of resistant varieties with acceptable market traits. Integrating vector ecology and virus epidemiology strengthens long-term resilience (Nasruddin *et al.,* 2023). Resistance develops in response to ongoing selection pressure; IPM that minimizes spray frequency, rotates modes of action, and maintains refugia and natural enemies can postpone the emergence of resistance (Georghiou, 1990). Lowering chemical selection pressure via IPM and diversifying control tactics (biological, cultural, chemical rotation) reduces selection intensity and slows resistance.

Socioeconomic determinants of adoption

Technical efficacy alone does not drive widespread adoption. Socioeconomic studies identify capital constraints, land fragmentation, weak extension and fragmented input chains as principal barriers to IPM uptake (Erdiansyah and Putri, 2020; Lukas *et al.,* 2024). Interventions that combine participatory training (farmer field schools), cooperative financing for shared infrastructure (mass-rearing and trap networks), and locally tuned advisory delivered through low-bandwidth digital channels demonstrate higher uptake in pilot studies (Singh *et al.,* 2023; Abbey, 2023). Integrating detailed cost-benefit assessments and labor/input accounting into trials is necessary to provide clear evidence of returns for farmers (Erdiansyah and Putri, 2020). Integrated monitoring should combine farmer scouting, residue and biodiversity checks, and socio-economic indicators (labour, costs, income) to guide IPM adoption. Adoption is shaped by risk perception, local norms, and extension quality, while Farmer Field Schools improve uptake. Studies should report disaggregated adoption data (gender, age, education, farm size). The combination of training and incentives—including biopesticide subsidies, cooperative purchasing, and market linkages—fosters greater adoption

than relying solely on incentives (Pretty and Bharucha, 2015).

Research gaps and priorities

Synthesis of the literature highlights immediate priorities: 1) multi-season, multi-location validation trials for biopesticides and integrated packages across Indonesian agroecologies (Adom *et al.,* 2024; Lahati and Haryanto, 2020); 2) longitudinal RS networks for *Helicoverpa, Bemisia* and *Bactrocera* using bioassays and molecular markers (De Costa *et al.,* 2021; Gul *et al.,* 2023); 3) participatory co-design and randomized trials for AI/IoT tools (Li and Wang, 2024; Agustian *et al.,* 2023); 4) ecotoxicology and lifecycle assessment for nano-formulations prior to scale (de Oliveira *et al.,* 2021); 5) breeding pipelines that combine resistance, yield and quality using marker-assisted and participatory strategies. These priorities correspond with institutional strengthening requirements for cooperatives and quality assurance to convert pilots into resilient landscapes (Lukas *et al.,* 2024; Adom *et al.,* 2024).

A context-sensitive IPM roadmap for scale-up

From the evidence, a practical Indonesian roadmap includes: (a) sentinel community trap networks and sentinel plots to generate local thresholds (De Costa *et al.,* 2021); (b) an offline smartphone-based ID tool for farmer groups tied to short advisory messages and extension callbacks (Agustian *et al.,* 2023; Li and Wang, 2024); (c) a tactic framework that emphasizes cultural and biological approaches initially, and only escalates to selective chemistries when certain thresholds are exceeded (Bottrell and Schoenly, 2018; Adom *et al.,* 2024); (d) local certification and minimal standards for microbial and botanical products; and (e) cooperative mechanisms for mass-rearing, shared trap procurement and IoT maintenance (Lukas *et al.,* 2024; de Oliveira *et al.,* 2021). Incorporating both economic and non-target endpoints into each field trials will bridge evidence practice gaps and bolster trust among farmer (Erdiansyah and Putri, 2020; Adom *et al.,* 2024). Multi-year evidence indicates IPM can stabilise yields and reduce cumulative pesticide use, but conclusions require replicated multi-season trials and residue monitoring (Pretty and Bharucha, 2015). Through the reduction of both the frequency and quantity of synthetic pesticide applications, IPM is projected to diminish long-term accumulation and ecological risks, however, data on residues over multiple seasons are required for validation.

Chili (Capsicum) varietal resistance to pests

Chili (*Capsicum annuum*) resistance research has advanced from phenotypic screens to genetic and metabolomic analyses: QTL fine-mapping has repeatedly identified loci for thrips resistance (van Haperen, 2021; Maharijaya *et al.,* 2015), while metabolomic and transcriptomic work implicates terpenoid and diterpene-glycoside pathways (including capsianosides) in induced defence (Zhang *et al.,* 2020; Zhang *et al.,* 2023). Capsaicinoids can be insecticidal or deterrent but may be detoxified by generalist herbivores (Claros-Cuadrado *et al.,* 2019; Zhu *et al.,* 2020). Large screens now designed to combat whitefly, aphids, mites, fruit borers and pepper weevil, with certain accessions demonstrating partial or environment-specific resistance (Li *et al.,* 2023; Rini *et al.,* 2025); pepper weevil is an emerging concern (Adeleye *et al.,* 2024). Resistance against mites and lepidopteran borers is frequently insufficient, thus it is advisable to integrate genomics-enabled breeding (such as QTL pyramiding, marker-assisted selection) with metabolite markers, microbiome-based enhancements and IPM strategies to attain sustainable, regionally tailored control (El-Kasser, 2023; Tanpure *et al.,* 2017; Lozada *et al.,* 2022; Sam-on *et al.,* 2024; Jakubowska *et al.,* 2022; Bulle *et al.,* 2023). Tables 2–7 summarize key control methods by pest (type, dose, target stage, test environment, recommendations).

Table 2 describes the integrated control methods used for the effective management of chili fruit borer (*Helicoverpa* spp.) infestation in chili cultivation. Table 3 outlines various cultural, biological, mechanical, and chemical control methods adopted for managing cotton leafworm (*Spodoptera litura*) in agricultural crops. Table 4 presents different integrated pest management strategies used for the control of fruit fly (*Bactrocera* spp.) infestation in fruit and vegetable crops. Table 5 highlights commonly adopted control methods for the effective management of whitefly (*Bemisia tabaci*) populations in crop production systems. Table 6 summarizes integrated control strategies used for the management of leaf miner (*Liriomyza* spp.) infestation affecting vegetable and horticultural crops. Finally, Table 7 describes various management practices used for controlling aphid (*Aphis gossypii*) infestation and reducing its impact on crop growth and yield.

Climate and landscape influences

IPM's reduced input use often lowers greenhouse-gas externalities and improves farmer health and livelihoods, representing co-benefits beyond pest control. Local climate, rainfall, and landscape characteristics significantly influence pest life cycles and the population of natural enemies; thus, IPM thresholds and timing must be adjusted according to local climate and landscape data (Pretty and Bharucha 2015). Landscape measures (semi-natural habitats, rotation, area-wide coordination) enhance ecosystem services (natural enemies, pollination) and reduce pest spillover, supporting landscape-scale sustainability (Table 2, Table 3). Anticipated increases in temperature and changes in precipitation patterns will affect pest life cycles and could broaden their geographical distribution; therefore, adaptive monitoring and revised thresholds are needed for chili IPM (Pretty and Bharucha, 2015).

Environmental risks (soil and water)

The frequent application of broad-spectrum pesticides leads to greater contamination of soil and water, negatively affecting soil organisms. In contrast, IPM techniques, including reduced or strategically timed spraying and the use of biological control, can mitigate these adverse effects (Table 4, Table 5, Table 6). Multi-season residue monitoring in soil and surface water, along with indicator-taxa surveys, is needed to evaluate cumulative ecological effects (Aktar *et al.,* 2009). When IPM reduces pesticide applications, monitoring should also assess declines in persistence and bioaccumulation of active ingredients. This review uses the Field-Use Environmental Impact Quotient (EIQ) to compare relative environmental risks when data on active ingredients and application rates are available. The EIQ serves as a useful metric for evaluating the effects of pesticides across various management strategies. Although it has limitations, combining EIQ with residue monitoring and biodiversity indicators enables a more comprehensive evaluation of environmental risks in chili pest management systems (Kovach *et al.,* 1992).

Economics/ Cost-effectiveness

Data from smallholder IPM initiatives indicates lower pesticide expenses and frequently stable or enhanced yields (Table 7). Therefore, cost-effectiveness ought to be expressed as net income per ha, along with adjustments in labor and inputs. Market and value-chain influences; Market incentives (price premiums, certification, supply-chain linkages) increase willingness to adopt eco-friendly pest management; reporting market access variables is recommended (Pretty and Bharucha 2015). Provide an overview of the value-chain context (market distance, premiums, contracts) since market access plays a crucial role in determining the financial feasibility of sustainable pest management practices. Quantify short-term opportunity costs (labour reallocation, temporary yield risk) and report net income over 1–3 seasons to assess financial risk of switching to IPM.

Table 2: Control methods for chili fruit borer (*Helicoverpa* spp.)

Control method	Dose	Test environment	Key finding	Sources
Nucleopolyhedrovirus (HaNPV) alone and HaNPV + spinetoram/ emamectin benzoate	HaNPV and labeled rates of spinetoram or emamectin were used in combination trials for larval control.	Field trials on crops infested by *H. armigera*.	HaNPV combined with spinetoram or emamectin benzoate provided greater larval suppression than single treatments.	(Abid *et al.,* 2020)
Field efficacy of multiple HaNPV isolates (isolate-dependent responses)	HaNPV isolates applied at reported POB/ha rates (e.g., 1.5–3.0 × 10^{12} POB/ha.	Field trials on cotton and chickpea.	Certain HaNPV isolates (e.g., CBE I, NEG) significantly reduced larval counts and increased yield; isolate-dependent efficacy observed.	(Jeyarani *et al.,* 2010)
Comparative bio-efficacy: NPV vs Spinosad (field comparison)	Authors used NPV and spinosad at the study's field rates.	Field comparisons on bollworm/*Helicoverpa* populations.	Spinosad showed strong immediate knockdown; NPV provided slower but persistent mortality.	(Nawaz *et al.,* 2019)
Screening of Vip3A (Bt) proteins-laboratory toxicity against *H. armigera*	Laboratory bioassays at the concentrations tested in the paper	Lab bioassays against multiple lepidopteran species including *H. armigera*.	Several Vip3A proteins demonstrated high activity against *H. armigera* in laboratory bioassays.	(de Escudero *et al.,* 2014)
Flubendiamide/ cyantraniliprole / diamides — field efficacy reports	In the field trials, manufacturer's recommended label dose was used	Field trials on tomato/chickpea/cotton; comparative insecticide trials.	Diamide insecticides (flubendiamide, cyantraniliprole, chlorantraniliprole) provided strong larval control in field trials.	(Patel Gajraj *et al.,* 2016)
Pheromone traps-trap type and monitoring (trap-based management/ monitoring)	Trap type (funnel, delta) and lure formulations evaluated as per methods.	Field monitoring studies and trap-standardization trials.	Funnel trap design and pheromone lure choice significantly affect male capture and are recommended for monitoring and spray timing.	(Fite *et al.,* 2020)

Table 3: Control methods for cotton leafworm (*Spodoptera litura*)

Control method	Dose	Test environment	Key finding	Sources
Flubendiamide, spinosad, indoxacarb-comparative field trials	Authors used commercial label rates in field trials	Field experiments on vegetable crops (capsicum/cabbage/tomato).	Flubendiamide and spinosad consistently achieved the highest larval suppression in field trials	(Karuppaiah *et al.,* 2019)
Bacillus thuringiensis (NPV/Bt)-biorational options and field use	NPV and Bt formulations applied at study rates (authors report field doses).	Field/polyhouse trials.	NPV and Bt sprays reduced larval populations and damage and are recommended as biorational IPM options.	(Maqsood *et al.,* 2028)
Resistance monitoring and diamide susceptibility	Field populations tested against diamide insecticides (bioassays as described).	Field sampling and laboratory bioassays.	Regional differences and emerging resistance to diamides and other chemistries noted; monitoring recommended as part of resistance management.	(Che *et al.,* 2024)
Synergy/ compatibility studies: reduced-dose mixtures with bioagents	Lab synergy assays and semi-field tests (methods report ratios tested).	Lab and semi-field assays.	Certain reduced-rate combinations (chemical + biopesticide) provided additive or synergistic mortality.	(Khan *et al.,* 2021)
Nanoparticle formulations (experimental)-enhanced efficacy	Nanoparticle concentrations and characterization reported in experimental work.	Laboratory and small-scale field tests.	Nanoparticle formulations increased larval mortality and persistence vs conventional formulations in several experimental studies.	(Miranti *et al.,* 2025)

Table 4: Control methods for fruit fly (*Bactrocera* spp.)

Control method	Dose	Test environment	Key finding	Sources
Male Annihilation Technique (MAT) methyl eugenol/ cue-lure based	Standard MAT dispensers (methyl eugenol with insecticide or toxicant) per program guidelines.	Area-wide trials, monitoring/operational projects.	Methyl eugenol (MAT) effectively suppresses male populations of responsive *Bactrocera* spp. and is recommended for suppression and early containment.	(Zhou *et al.,* 2024)
Kaolin particle film (Surround®) and protective netting	Kaolin applied as particle film per trial methods; netting mesh sizes.	Field trials on capsicum/chili (project level trials).	Kaolin film and exclusion netting reduced oviposition and fruit infestation but require reapplication after rain	(Ali, 2016)
Lure+kill/ lure mixtures in baited traps (species-specific attraction)	Lure and bait formulations tested per study (various mixtures described).	Field baited trap trials across host crops.	Lure mixtures and species-specific baits improve trap attraction and optimize trapping-based suppression strategies.	(Ahmad *et al.,* 2023)
Area-wide integrated approaches and monitoring	Program descriptions, trap densities and integrated tactics.	Area-wide programs and synthesis reports.	Area-wide tactics (MAT, baiting, sanitation, exclusion) provide the most effective suppression, supported by monitoring and recommended trap densities.	(Shelly *et al.,* 2022)

Table 5: Control methods for whitefly (*Bemisia tabaci*)

Control method	Dose	Test environment	Key finding	Sources
Insect growth regulators (IGRs): Pyriproxyfen, buprofezin), biorational options	Authors report commercial label rates and IGR application frequencies used in trials.	Field and greenhouse studies on vegetable crops.	IGRs (pyriproxyfen, buprofezin) effectively suppress populations and are relatively selective to parasitoids, supporting IPM use.	(Gogi *et al.,* 2021)
Reflective (silver) mulch-vector suppression	Reflective mulch types, installation and trial details in methods.	Field trials on tomato, atermelon and other cucurbits/vegetables.	Reflective mulch reduced whitefly landing, eggs, nymphs and virus incidence; recommended as a cultural control tactic.	(Nasruddin *et al.,* 2020)
B. bassiana and other EPF (entomopathogenic fungi)	Spore suspensions and commercial formulations tested (e.g., 10^7–10^8 conidia/mL in greenhouse/lab trials).	Greenhouse and field/greenhouse trials on eggplant/tomato.	EPF (*B. bassiana*, *Cordyceps javanica*) reduced eggs, nymphs, and adults in greenhouse trials; efficacy depends on humidity and application method.	(Cabrera-Mireles *et al.,* 2025)
Botanical extracts and plant-derived compounds	Plant extract concentrations and methods reported	Lab/greenhouse bioassays and small-scale field trials.	Plant extracts (e.g., Datura stramonium, garlic, capsicum) caused significant adult mortality in lab and greenhouse assays.	(Jasman *et al.,*2026)
Area-wide IPM and natural enemy conservation	Program descriptions and recommendations reported.	Area-wide and protected cultivation contexts.	Conservation of NE, selective IGRs, and cultural tactics (reflective mulch, trap crops) are key to sustainable whitefly management.	(Stansly and Natwick, 2010)

Table 6: Control methods for leaf miner (*Liriomyza* spp.)

Control method	Dose	Test environment	Key finding	Sources
Azadirachtin/ neem products- biorational option (reviews and trials)	Commercial azadirachtin formulations and trial concentrations reported in studies and reviews.	Greenhouse and field experiments (various crops).	Azadirachtin reduces feeding and larval survival and is compatible with some biocontrol approaches.	(Chaudhary *et al.,* 2017)
Abamectin-efficacy and non-target considerations	Abamectin rates and parasitoid compatibility discussed.	Field/lab compatibility studies.	Abamectin effectively controls leafminer larvae but may harm parasitoids (*Diglyphus isaea*), requiring compatibility caution.	(Kaspi, and Parrella, 2005)
Diglyphus isaea-augmentative parasitoid releases	Release methods and rates reported in applied trials.	Greenhouse / protected cultivation releases.	Releases of *Diglyphus isaea* reduced leafminer populations in protected-crop trials.	(Ridland *et al.,* 2020)

Table 7: Control methods for Aphid (*Aphis gossypii*)

Control method	Dose	Test environment	Key finding (as reported)	Sources
Clove oil nanoparticles (CO-NPs)-contact spray	Lethal concentration 50 (LC_{50}) = 0.32% (48 h); LT_{50} = 3 h at 1.2%; progeny reduction 95.01% at 1.2%.	Lab / greenhouse / on-plant chili tests.	CO-NPs produced strong contact toxicity and large reduction in progeny;	(Ikawati *et al.,* 2024)
Chromolaena odorata leaf extract-toxicity and compatibility tests	Plant extracts (10–40% w/v) caused dose-dependent mortality, with 40% most effective; extracts also inhibited Lecanicillium lecanii in vitro.	Lab (PDA) + pot/greenhouse trials on chili.	40% extract produced very high aphid mortality; also found incompatibility with *L. lecanii*.	(Nurhayati *et al.,* 2022)
Aphidius colemani (parasitoid)-banker plants and releases	Review summarizes release systems, banker plants and stressors that influence efficacy.	Greenhouse / protected cropping systems.	*A. colemani* widely used in greenhouse production; efficacy depends on climate, plant/host interactions and insecticide regimes.	(Prado *et al.,* 2015)
Azadirachtin/ neem products-review and synthesis	Review and trial summaries report typical product concentrations and modes of action (IGR/antifeedant).	Lab/greenhouse/field trials across crops.	Neem/azadirachtin reduces survivorship and fecundity of aphids; photodegradation and slower action noted.	(Chaudhary *et al.,* 2017)
Plant resistance/ host plant effects (review)	Plant resistance mechanisms and implications for aphid population development described.	Review/meta-analysis of plant resistance literature.	Host plant resistance can reduce aphid performance, suggested as a component of IPM.	(Gebretsadik *et al.,* 2025)
Citronella oil (*Cymbopogon nardus*) application	Laboratory: citronella oil tested at various concentrations compared to control.	Laboratory bioassay and Field trial	Citronella oil showed strong toxicity (89.1%) and reduced Aphis gossypii populations by 91% in field trials.	(Istianto *et al.,* 2025)

Pest pressure is the primary biophysical constraint on Indonesian chili, reducing yield via direct feeding, blemishing and virus transmission (De Costa *et al.,* 2021). Chili pest problems are a mosaic—lepidopteran borers, polyphagous defoliators, mobile fruit flies, sap-feeding whiteflies and cryptic leaf miners—each with different life histories and damage patterns. Consequently, using a single tactic like calendar spraying results in only short-lived benefits while

fostering resistance and affecting non-target organisms (Hadi *et al.,* 2025; Suryanto, 2018b). Consequently, monitoring- and phenology-based interventions (pheromone/sticky traps plus scouting) that translate observations into threshold-guided actions should form the backbone of IPM (Fening *et al.,* 2020; De Costa *et al.,* 2021). Reduced pesticide use in IPM benefits pollinators, predators and soil biota; nevertheless, localized non-target monitoring is recommended to confirm net benefits (Aktar *et al.,* 2009). The incorporation or enhancement of natural enemies can lead to effective pest control, but it is essential to conduct a pre-release ecological risk assessment to mitigate any negative consequences for native biodiversity (Pretty and Bharucha, 2015). Field evidence supports prioritizing low-risk botanicals and microbial products (e.g., neem, *Metarhizium*, *Beauveria*) alongside cultural measures; selective chemistries are reserved for threshold exceedances to conserve beneficials and slow resistance (Rajapaksha *et al.,* 2023; Lahati and Haryanto, 2020; Nurdebyandaru *et al.,* 2010; Adom *et al.,* 2024). Emerging tools (infrared imaging, e-nose, AI classifiers, IoT traps) offer earlier detection and precision targeting but perform best when embedded in farmer-centric, hybrid systems combining local scouting, offline ID tools and extension support (Sinha *et al.,* 2023; Agustian *et al.,* 2023; Li and Wang, 2024; Abbey, 2023). Evaluating environmental risks should occur simultaneously with efficacy assessments: the frequent use of broad-spectrum insecticides leads to a decline in natural enemies and pollinators, as well as changes in soil and aquatic environments (de Oliveira *et al.,* 2021; Adom *et al.,* 2024). Eco-friendly options vary in formulation and field performance, and newer delivery systems (e.g., nanoparticles) carry additional ecotoxicological uncertainty (Rajapaksha *et al.,* 2023; Deka *et al.,* 2021). Resistance dynamics link agronomy and environment—overreliance on narrow modes of action accelerates resistance and environmental load—so stewardship (mode-of-action rotation, refugia, area-wide surveillance) is essential (De Costa *et al.,* 2021; Gul *et al.,* 2023). Adoption depends on socioeconomic and institutional supports—profitability, labor, credit, extension and input quality drive farmer choices—so scalable bundles (such as, seed + site-specific fertilization + border cropping) and cooperatives for shared infrastructure can improve uptake but require finance and coordination (Miranda *et al.,* 2023; Tobing *et al.,* 2021; Jasmi and Nasution, 2023). Breeding complements IPM: QTL mapping and metabolomics link thrips and other resistances to terpenoid/diterpene pathways, while capsaicinoids could discourage some pests but are susceptible to detoxification by generalists (van Haperen, 2021; Maharijaya *et al.,* 2015; Zhang *et al.,* 2023; Claros-Cuadrado *et al.,* 2019; Zhu *et al.,* 2020). Large screens show partial, environment-specific resistance to whitefly, aphids, mites and others (Li *et al.,* 2023; Rini *et al.,* 2025), and emergent pests (pepper weevil) need targeted breeding and tactics (Adeleye *et al.,* 2024). Often, resistance against chewing pests and borers is not entirely sufficient, which is why it is recommended to implement genomics-enabled breeding methods like QTL pyramiding and marker-assisted selection, as well as metabolite markers, microbiome boosters, and the incorporation of IPM (El-Kasser, 2023; Tanpure *et al.,* 2017; Caarls *et al.,* 2025; Lozada *et al.,* 2022; Javan *et al.,* 2024; Sam-on *et al.,* 2024; Jakubowska *et al.,* 2022; Bulle *et al.,* 2023). In practice, pragmatic agronomy (protected nurseries, Trichoderma-amended compost, PGPR, microclimate and irrigation management) reduces susceptibility and lowers input needs (Latifah *et al.,* 2021; Ahmad *et al.,* 2024). Nonetheless, trade-offs and operational obstacles (such as inconsistent biopesticide quality and coordination expenses for area-wide strategies) continue to exist (Adom *et al.,* 2024; Lukas *et al.,* 2024). Priority actions are standardized multi-site validation of biopesticides/bundles with

environmental and socioeconomic endpoints, and co-design/scale-up of affordable, offline monitoring (smartphone ID, community IoT traps) plus resistance surveillance for *Helicoverpa*, *Bemisia* and *Bactrocera* to underpin stewardship and scalable adoption (Rajapaksha *et al.,* 2023; Li and Wang, 2024; Agustian *et al.,* 2023; De Costa *et al.,* 2021; Gul *et al.,* 2023). Participatory varietal selection and breeding are key to lowering in-season inputs and synchronizing resistance with market traits (Daryanto *et al.,* 2023; Latifah *et al.,* 2021).

RECOMMENDATION

Chili pest management in Indonesia should shift to monitoring-based IPM using traps, field scouting, and action thresholds instead of routine spraying. Cultural, biological, and botanical controls should be prioritized as the first line of defense. Chemical pesticides ought to be applied solely when thresholds have been surpassed, accompanied by diligent resistance management. National programs should support multi-site validation of eco-friendly technologies and monitor environmental impacts such as non-target effects and residues. Funding is needed to enhance the development of pest-resistant chili varieties through marker-assisted breeding and participatory testing. Ultimately, the successful adoption of sustainable practices necessitates robust extension services, farmer field schools, cooperative monitoring networks, financing support, and clear regulatory standards.

CONCLUSION

The existing body of research emphasizes the considerable and increasing influence of insect pest complexes on chili (Capsicum spp.) cultivation, especially in tropical areas like Indonesia. Major pest groups; including Helicoverpa armigera, Spodoptera spp., fruit flies (Bactrocera spp.), whiteflies (Bemisia tabaci), thrips, aphids, and leaf miners (Liriomyza spp.); cause substantial yield losses, often exceeding 30–70% in severe infestations. An analysis of these pests and their control strategies indicates that no individual control method is adequate to maintain production. Instead, a coordinated and integrated pest management framework is essential. This framework integrates biological control agents, botanical insecticides, and selective chemical inputs with digital monitoring technologies, early-warning systems, and predictive pest modeling. Cultural practices like sanitation, intercropping, trap cropping, and employing resistant varieties are significant as well. Furthermore, institutional mechanisms, including farmer cooperatives, input quality assurance systems, participatory extension, and certification schemes—are essential for facilitating the transition of technologies from trials to actual implementation in farmers' fields. To attain large-scale sustainable pest management, it is essential that research and implementation prioritize the integration of pest control strategies with socio-economic and ecological factors. Priority areas include long-term monitoring of pest resistance and population dynamics, standardization of botanical formulations, validation of biocontrol agents, and adoption of precision agriculture tools.

AUTHOR CONTRIBUTIONS

Affandi contributed to conceptualization, project coordination, and final content review. K.D. Sutanto contributed to conceptualization, methodology design, and manuscript drafting. M. Istianto contributed in Data collection and bibliography compilation; contributed perspectives to the discussion; review of the final manuscript. Wiratno contributed to Literature review, analysis of integrated pest management strategies, and critical revision of the manuscript. R. Murtiningsih assisted in Data interpretation, manuscript editing and overall draft review. A. Meilin contributed in Manuscript formatting, organization of research flow and presentation.

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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
°C	Degree Celsius
AI	Artificial intelligence
Bt	*Bacillus thuringiensis*
B. tabaci	*Bemisia tabaci*
B. bassiana	*Beauveria bassiana*
Capsicum spp. / spp.	Capsicum (species); spp. = species (plural)
CO-NPs	Clove oil nanoparticles
EIQ	Environmental impact quotient
EPF	Entomopathogenic fungi
ETc	Crop evapotranspiration
HaNPV	*Helicoverpa* nucleopolyhedrovirus (*H. armigera* NPV)
IGR / IGRs	Insect growth regulator(s)
H. armigera	*Helicoverpa armigera*
IoT	Internet of Things
IPM	Integrated pest management

kg	Kilogram
LC_{50}	Lethal concentration 50
LT_{50}	Lethal time 50
MAT	Male annihilation technique
Mt	Million tons
NE	Natural enemies
NGO	Non-governmental organization
NPV	Nucleopolyhedrovirus
PDA	Potato dextrose agar
PGPR	Plant growth-promoting rhizobacteria
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
QTL	Quantitative trait locus
RNAi	RNA interference
RS	Resistance surveillance
sp.	Species (singular)
YOLO / YOLOv5	"You only look once"

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