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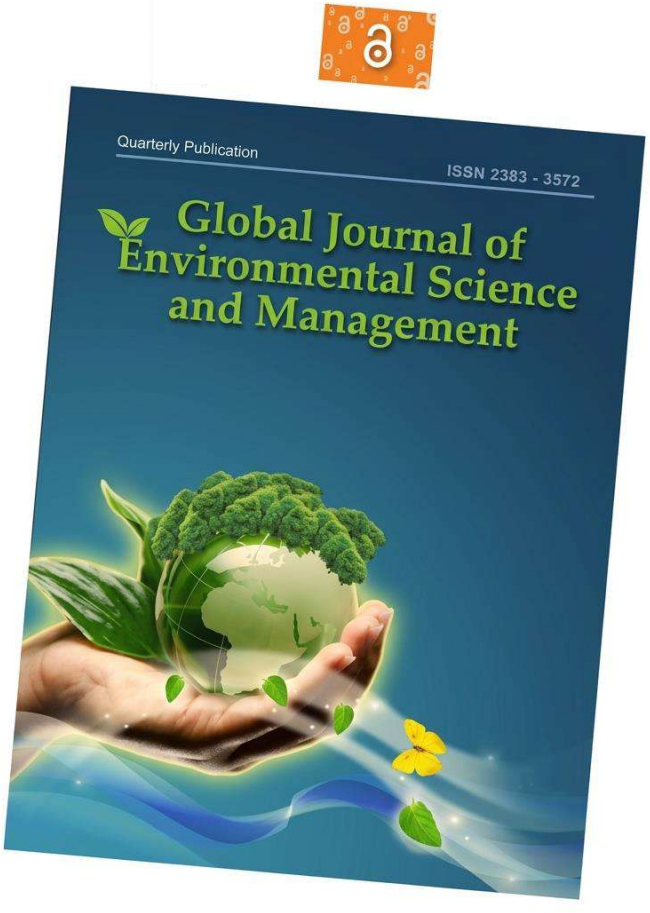

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ORIGINAL RESEARCH PAPER

Biodiversity-oriented criteria for measuring the effectiveness of mangrove ecosystem rehabilitation success

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ABSTRACT

BACKGROUND AND OBJECTIVES: The area of Indonesia's mangrove ecosystem is approaching 3.5 million hectares. Approximately 52 percent of the area has been damaged and requires rehabilitation. The objectives of this study were to evaluate the extent of ecosystem recovery following mangrove rehabilitation by analyzing the natural occurrence and diversity of the resident biota.

METHODS: This study was conducted in Segarajaya Village, Tarumajaya District, Bekasi Regency, Indonesia, from April to November 2024. The obtained data were flora diversity data (represented by vascular plants) and fauna diversity data (represented by taxa of birds, reptiles, benthic crustaceans, mollusks, and fish). Data on flora and vegetation were collected from 5 meters x 5 meters sampled plots for seedlings and saplings (21 plots) and 10 meters x 10 meters sampled plots for trees with stem diameter ≥ 10 centimeters (17 plots), placed concentrically. Sampling plots were established systematically along a linear transect extending from land to sea, with a consistent inter-plot distance of 50 meters. Avian community data were collected using the point count method within fixed-radius circular plots (25 diameter), with a sampling duration of 20 minutes per plot. Data analysis includes Importance Value Index for vegetation, Shannon-Wiener Diversity Index, Sørensen Community Similarity Index, Chi-square Test of Independence, Mann-Whitney U Test.

FINDINGS: The results reveal that the diversity of mangroves in the rehabilitation areas is extremely low (consisting of 1–3 species; Shannon-Wiener Diversity Index of 0–0.36). No natural recruitment of associated mangrove flora was recorded within the rehabilitation areas until the stands reached ten years of age. The establishment of new habitats through this restoration planting has facilitated the colonization of both terrestrial and aquatic faunal communities. The Sørensen Community Similarity Index for terrestrial fauna in rehabilitation areas compared with natural areas only ranges between 37 percent and 58 percent, indicating a relatively low level of community similarity.

CONCLUSION: A decade of *Rhizophora stylosa* monoculture mangrove forest rehabilitation has produced structurally mature stands but has failed to restore floral and faunal to levels comparable to natural forests.

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INTRODUCTION

The mangrove ecosystem is crucial and unique in coastal areas (Yuliana *et al.*, 2019; Yuliana *et al.*, 2020; Hewindati *et al.*, 2023). Mangrove ecosystems function as highly effective sediment sinks, trapping terrigenous mud, organic debris, and anthropogenic litter transported by riverine and oceanic currents (Sari *et al.,* 2022). Because of its fertility, mangrove serves as a habitat for a wide range of biota (Yuliana *et al.*, 2019) as well as a nursery, feeding, and spawning ground (Hewindati *et al.,* 2023). The mangrove vegetation also serves as a critical habitat, attracting juvenile fish and small-sized teleosts (Sari *et al.,* 2022; Yuliana *et al.,* 2022). However, mangrove is also a vulnerable, extreme, and highly dynamic ecosystem. Human activities that may harm the mangrove ecosystem also pose a serious threat to its sustainability (Retnaningdyah *et al.,* 2022). Consequently, this degradation reduces the provisioning of ecosystem services to local communities (Yuliana *et al.*, 2026), particularly those derived from mangrove ecosystems (Yuliana *et al.* 2019; Rohila *et al.*, 2017). Indonesia is one of the countries with the largest area of mangrove forest in the world. With a coastline length of about 95,181 kilometers (km), Indonesia's recorded mangrove ecosystem is approximately 3,489,140.68 hectares (ha) wide, or equal to 23 percent (%) of the world's mangrove ecosystem (Metkono *et al.*, 2022; Kotijah and Ventyrina, 2019). Nevertheless, about 1,817,999.93 ha of this mangrove area (52.1% of the total area) has been damaged (Metkono *et al.,* 2022; Kotijah and Ventyrina, 2019). Given the urgency of habitat degradation, various mangrove restoration and rehabilitation efforts have become essential. In this context, targeted replanting initiatives are deployed to counteract forest loss and expedite ecosystem recuperation (Wirabuana *et al.*, 2025). The commitment of the Indonesian government to rehabilitate damaged mangrove areas has been demonstrated in the establishment of a special institution, namely the Peatland and Mangrove Restoration Agency, formed through Presidential Regulation Number 120 of 2020 (Kinasih and Harmawan, 2025). The Indonesian government has also prepared the National Mangrove Rehabilitation Roadmap 2021–2030 (Nurhati and Murdiyarso, 2023; Kinasih and Harmawan, 2025), with a target of mangrove rehabilitation of 600,000 ha (Sasmito et al., 2023). As a national level, a large-scale mangrove restoration initiative was implemented in 2020, utilizing a labor-intensive program to plant 17,641 ha across 34 provinces (Arifanti *et al.*, 2022). In 2021, the successfully planted mangrove areas increased to 80,000 ha. The successful implementation of this mangrove rehabilitation program, however, needs further monitoring, particularly in terms of whether the new plants can grow well to form mangrove forests and develop mangrove ecosystems. Current metrics for assessing the success of mangrove rehabilitation remain overly broad, often focusing on initial planting targets rather than long-term ecological functionality. As stated in Appendix VIII of the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia (MEF-RI) Number 23 of 2021 on the Implementation of Forest and Land Rehabilitation, this benchmark is limited to the success of plant growth through the assessment of the area of successful growth and the percentage of plant growth and average height. Alternative indicators of successful mangrove ecosystem restoration include the natural recruitment and colonization of characteristic flora and fauna indigenous to the regional baseline. The success of the restoration is reflected in the increased diversity of the mangrove vegetation, the improved physical and chemical quality of the environment, and the diversity of macrozoobenthos—such as crustaceans and gastropods—living in the mangrove forests as bioindicators (Retnaningdyah *et al.,* 2022). The return of faunal communities, particularly fish, crustaceans, and macroinvertebrates, is an important benchmark for evaluating the functional recovery of rehabilitated mangrove ecosystems (Bosire *et al.,* 2008). Kamali and Hashim (2011) found that the

vegetation structure and species composition of replanted mangroves in Malaysia gradually recovered over time. A study conducted by Alongi (2002) in Indonesia highlights that mangrove rehabilitation success is frequently evaluated solely through the lens of seedling survival rates and canopy closure, thereby overlooking the broader dimensions of biodiversity recovery. Replanted monoculture stands of *Rhizophora* spp. have shown a limited capacity to support faunal diversity compared to naturally mixed-species mangroves. Spontaneous colonization of flora and fauna serves as a reliable bioindicator of ecosystem recovery (Damastuti *et al.,* 2022). Furthermore, biodiversity assessments are rarely integrated into official monitoring frameworks for mangrove rehabilitation (Wirabuana *et al.,* 2025). In Indonesia, the current regulatory framework, as stipulated in the Minister of Environment and Forestry Regulation No. 23 of 2021, restricts success metrics primarily to plant growth rates and canopy cover, with no provisions for biodiversity-based indicators. This disparity between empirical scientific knowledge and policy execution constitutes a major impediment to the rigorous evaluation of large-scale national rehabilitation initiatives. Biodiversity integrates the cumulative outcomes of all ecological processes into measurable indices (Magurran, 1988; Nagelkerken *et al.*, 2008). As such, biodiversity indices provide a holistic, multi-trophic signal of ecosystem recovery that single-metric, growth-based assessments fundamentally cannot capture (Bosire *et al.*, 2008; Gilman *et al.*, 2008). Moreover, chronosequence studies analyzing faunal and floral recovery across stands of varying ages within a single rehabilitation site remain exceptionally scarce in Indonesia, thereby limiting the understanding of post-intervention ecological trajectories. This study makes three novel contributions to mangrove rehabilitation assessment. First, it simultaneously evaluates flora, terrestrial fauna, and aquatic fauna diversity across a single rehabilitation chronosequence in the Segarajaya mangrove area, Bekasi Regency. Second, it applies the Sørensen Community Similarity Index to quantitatively benchmark rehabilitated against natural mangrove communities. Third, this study makes a novel contribution within the Indonesian policy context by proposing quantitative, multi-taxa biodiversity indicators designed to be integrated directly into national-level frameworks for auditing mangrove rehabilitation success. Based on this rationale, this study identified two components that most sensitively reflect rehabilitation effectiveness: 1) Mangrove diversity (Shannon-Wiener Diversity Index (H') and species richness); 2) Bird species richness and community composition, which respond rapidly to habitat structure changes and are observable without destructive sampling. Based on the objectives, this study has the following hypotheses (H):

H_1: Flora diversity in mangrove rehabilitation areas increases progressively with stand age, but remains significantly lower than that of the natural reference forest.

H_2: Fauna diversity in mangrove rehabilitation areas increases with stand age.

H_3: The spontaneous presence and diversity of biotic communities across rehabilitation stands of different ages can serve as empirically valid, multi-taxa indicators for evaluating and standardizing mangrove ecosystem rehabilitation success.

The objective of the present study is to evaluate the efficacy of mangrove rehabilitation in ecosystem restoration, utilizing the natural recolonization and recruitment of resident biota as key ecological indicators of success. This study has been carried out in Segarajaya mangrove area, part of Jakarta Bay from 2024 to 2025.

MATERIALS AND METHODS

Study area

The research locations covered well-preserved mangrove rehabilitation and mangrove forest areas in Segarajaya Village, Tarumajaya District, Bekasi Regency, Indonesia (Fig. 1). To capture

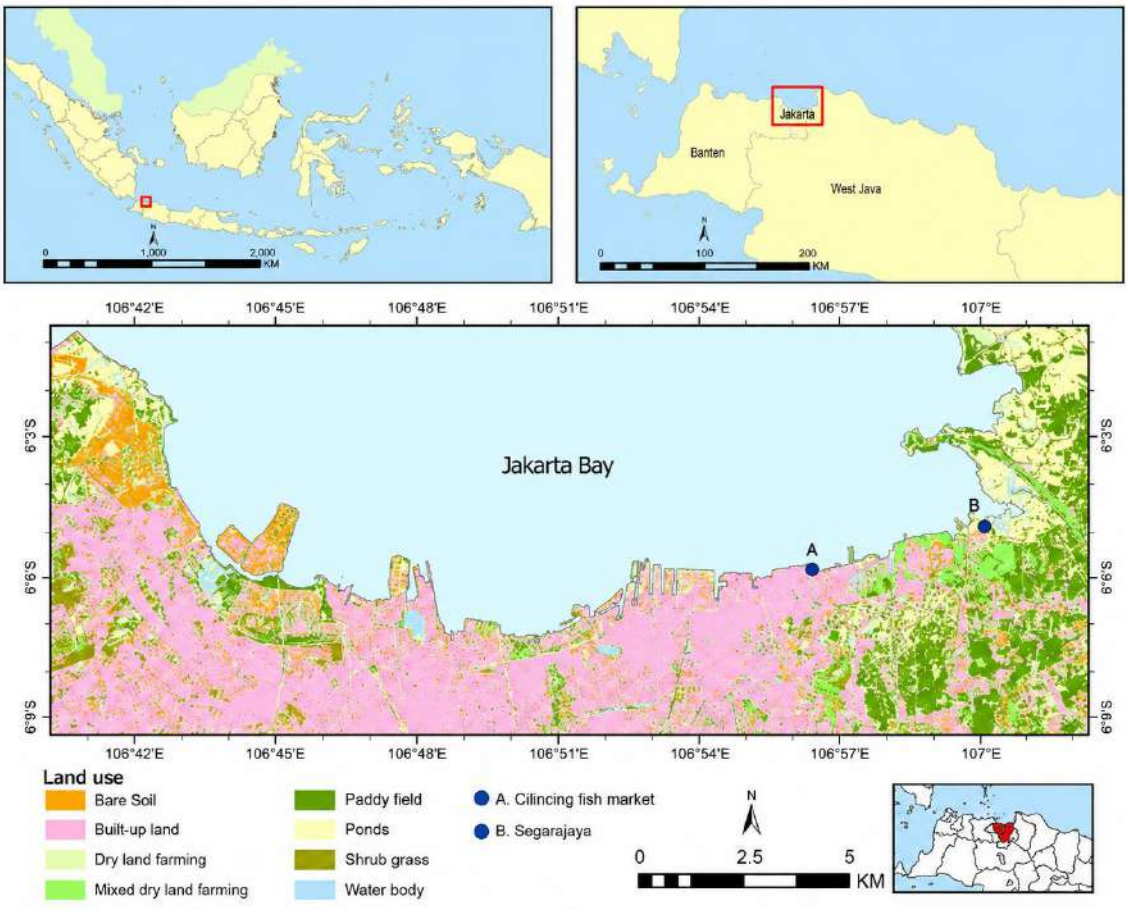

Fig. 1: Geographical location of the study area in Segarajaya Village, part of Jakarta Bay, Indonesia (Yuliana *et al*., 2026)

post-restoration environmental dynamics, sampling was conducted across a chronosequence of mangrove rehabilitation areas characterized by distinct planting years. According to the availability in the field, the 2024 rehabilitation area (representing the 0-year-old stand), the 2019 rehabilitation area (the 5-year-old stand), and the 2014 rehabilitation area (the 10-year-old stand) were selected as the research locations. In addition, the closest remaining natural mangrove forest area was also selected for comparison.

Data collection

The collected data comprised floral diversity, represented by vascular plants, and faunal diversity, represented by five key taxonomic groups: birds, reptiles, benthic crustaceans, mollusks, and fish. Data on flora and vegetation were collected from 5 meters (m) x 5 m sampled plots (for seedlings and saplings) and 10 m x 10 m sampled plots, for trees with stem diameter ≥ 10 centimeters (cm), placed concentrically. These plots were systematically sampled in a straight line from land to sea, with a distance between plots of 50 m. Due to spatial constraints within the mangrove rehabilitation zones, the number of sampling plots allocated for floral and vegetation data collection was unevenly distributed across the different plot sizes. A total of 21 plots measuring 5 m × 5 m were established, distributed as follows: 2 plots in the 2024 area, 2 plots in the 2019 area, 8 plots in the 2014 area, and 9 plots in

the natural forest area. Additionally, 17 plots measuring 10 m × 10 m were established, comprising 8 plots in the 2014 area and 9 plots in the natural forest area. While this sampling imbalance represents a limitation of the present study, future research should implement an expanded sampling design with uniform replication across all plot sizes. Data on birds were gathered using the point count method (Ralph *et al*., 1995; Bibby *et al*., 2000), by making sampled plots in the form of a virtual circle with a diameter of 25 m and a counting time of 20 minutes in each plot. The plots were sampled systematically, with a distance between plots of 50–100 m, the placement of which was determined later in the field. With a minimum of three replicates established per rehabilitation zone, a total of 46 avian sampling sheets were compiled. Reptile data were collected using visual encounter surveys across the four designated study areas. All reptiles observed in the locations were recorded in terms of their species, numbers of individuals (ind), and microhabitats in which they were found. Data on crustaceans were acquired by setting 3 m x 3 m sampled plots. The observation was made at low tide. To maximize sampling efficiency, all benthic crustaceans within the designated plots—including both infaunal individuals in the substrate and epifaunal individuals associated with mangrove roots—were collected manually or via hand nets for subsequent recording. In a 1 m x 1 m area in the middle of the sampled plots, the mud was dug 20–30 cm deep to catch the crustaceans hiding in holes and mud sediment. The mud was then filtered using a mesh (mesh size 1 millimeters (mm)), and the crustaceans were collected, kept in plastic bags, and preserved with 70% alcohol. In permanently waterlogged zones where substrate excavation was highly constrained, crustacean sampling was supplemented by deploying crab traps and dragon traps at designated monitoring locations. This passive sampling effort yielded a total of 65 trap-nights for the crab traps and 26 trap-nights for the dragon traps. In addition to the crustacean data obtained, some data were also obtained on fish accidentally entered into the two types of traps. Other fish data were collected from fishermen's catches at the studied locations. Birds are the most reliable biological indicator for measuring the effectiveness of mangrove ecosystem rehabilitation. Birds are easily detected, highly sensitive to habitat structure, and offer extensive ecological literature for comparison. Assessments of additional faunal groups serve as complementary indicators, providing a more comprehensive evaluation of overall ecosystem recovery. A significant limitation of this study are: 1) the use of presence/absence rather than count-based data for diversity analysis; 2) the lack of seasonal consideration; 3) the absence of systematic abiotic measurements, including sediment texture, organic carbon content, redox potential, salinity, dissolved oxygen, and tidal inundation frequency. These parameters are known to exert a profound influence on both floral and faunal diversity within mangrove ecosystems (Feller *et al.*, 2010; Gilman *et al.*, 2008); consequently, their omission limits the mechanistic depth of the resulting ecological interpretations. Future studies are therefore recommended to employ count-based data collection and paired wet/dry season surveys and include all the parameters that are now limitations.

Data analysis

The obtained data were analyzed using the following formulas.

a. Density (D) (ind/ha or ind/m²)

D = Number of a species / Total area sampled (1)

b. Relative density (RD)

RD = Density of a species / Total density of all species × 100% (2)

c. Frequency (F)

F = Number of plots in which a species is found / Total area sampled (3)

d. Relative frequency (RF)

RF = Frequency of a species / Total frequency of all species × 100% (4)

e. Importance Value Index (IVI)

IVI = RD + RF (5)

For the mangrove trees, the processed data were added to those of tree dominance:

f. Dominance of a species (Do) (m^2/ha)

Do = Basal area (BA) of a species / Total area sampled (6)

g. Relative dominance (RDo)

RDo = Dominance of a species / Total dominance of all species × 100% (7)

h. Importance Value Index (IVI)

IVI = RD + RF + RDo (8)

Data were processed to obtain the Shannon-Wiener Diversity Index (H'), Sørensen Community Similarity Index (S_s), Chi-square Test of Independence (χ^2), and Mann-Whitney U Test (U), using some equation on Table 1. The use of H' as a standalone metric introduces key interpretive constraints. (1) it conflates species richness and evenness, meaning that a community containing five evenly distributed species can yield an identical H' value to a community of ten species dominated heavily by a single taxon; (2) It requires abundance data, not just presence/absence, so H' there reflects only species richness; (3) It does not capture functional diversity, trophic structure, or community composition similarity with natural reference forests. H' was complemented with species richness, and S_s to produce a more robust multi-metric assessment.

RESULTS AND DISCUSSION

Flora and vegetation

The selected study locations represent a chronosequence of mangrove rehabilitation areas, spanning different planting cohorts to capture post-restoration ecological dynamics. Each block was planted as part of a mangrove planting project carried out by certain institutions, either private or public. The seedlings and planting areas were prepared by the locals through a mangrove conservation community. Therefore, the diversity of mangroves in the rehabilitation areas is determined primarily by the species planted (Bosire *et al.*, 2008). Mangrove species planted in the locations is mainly the spotted mangrove (*Rhizophora stylosa*). According to local accounts, this species is selected due to the high availability of wild seedlings, which develop directly from its viviparous propagules. In addition, the size of its seedling is big, and it is easy to handle until planting time. Ecologically, *R. stylosa* is well-adapted to muddy substrates and high salinity, making it a preferred species for mangrove rehabilitation programs across the Indo-Pacific region (Primavera and Esteban, 2008; Tomlinson, 1986). Besides *R. stylosa*, there are various other species of mangrove flora around Segarajaya Village. Despite dense human settlement and extensive land conversion for residential use, aquaculture, and industrial infrastructure including factories, a crematorium, and a combined-cycle power plant (PLTGU), diverse mangrove species persist within interstitial spaces between households, fish farms, and marginal abandoned lands (Table 2). A total of 16 mangrove flora species were recorded, comprising 10 tree species, 5 herbs, and 1 shrub. The most abundant species in these locations are grey mangrove (*Avicennia marina*), white mangrove

Table 1: Equations used to calculate the parameters of flora and fauna communities

Equation	Note
Shannon-Wiener Diversity Index (Magurran, 1988):	
$H' = -\sum_{i=1}^{s} \left(\frac{n_i}{N}\right) ln \left(\frac{n_i}{N}\right)$	H' = Shannon-Wiener Diversity Index n_i = number of ind per species N = total number of all ind
Sørensen Community Similarity Index (Sørensen, 1948):	
$S_s = \frac{2a}{2a+b+c}$	S_s = Sørensen Community Similarity Index a = total species in both communities b = number of species in community A c = number of species in community B
Chi-square Test of Independence (Zar, 2010): $\chi^2 = \Sigma [(O - E)^2 / E]$	χ^2 = Chi-square Test of Independence O = frequency of species presences or absences E = expected frequency under the null hypothesis of independence
Mann-Whitney U Test (Zar, 2010): $U = n_1 \times n_2 + n_1(n_1+1)/2 - R_1$	n_1 = group 1 observation n_2 = group 2 observation R_1 = sum of ranks assigned to Group 1

Table 2: Diversity of mangrove flora recorded in the research locations

Scientific name	English name	Habits
Avicennia alba	White mangrove	tree
Avicennia marina	Grey mangrove	tree
Cerbera manghas	Sea mango	tree
Hibiscus tiliaceus	Sea hibiscus	tree
Lumnitzera racemosa	White-flowered black mangrove	tree
Rhizophora stylosa	Spotted mangrove	tree
Rhizophora mucronata	Red mangrove	tree
Sonneratia alba	Mangrove apple	tree
Sonneratia caseolaris	Crabapple mangrove	tree
Sonneratia ovata	-	tree
Acanthus ilicifolius	Sea holly	herbs
Acrostichum aureum	Golden leather fern	herbs
Cyperus javanicus	Javanese flat sedge	herbs
Pluchea indica	Marsh fleabane	shrubs
Schoenoplectus subulatus	Coast club-rush	herbs
Typha angustifolia	Narrowleaf cattail	herbs

(*A. alba*), and mangrove apple (*Sonneratia alba*). Adjacent to the village, in former rice fields or reed swamps, the two dominating flora species are narrowleaf cattail (*Typha angustifolia*) and coast club-rush (*Schoenoplectus subulatus*). The presence of herbaceous species such as *Acrostichum aureum* and *Acanthus ilicifolius* underscores localized habitat degradation, reflecting their well-documented role as opportunistic pioneers in disturbed or open mangrove ecotones (Feller *et al.*, 2010). At the 2024 area, the species of mangrove selected as the main rehabilitation plant is the spotted mangrove (*R. stylosa*) (Table 3), strongly dominates the rehabilitation area (RD 0.99; IVI 149.43%), while the only other species in this area, i.e., *A. alba*, is found in very small quantities. The impoverished floral diversity within this rehabilitation area is further underscored by an exceptionally low Shannon-Wiener Diversity Index (H'), value of 0.04. The dominance of *R. stylosa* reflects the deliberate planting strategy rather than natural successional dynamics (Primavera and Esteban, 2008). The Shannon-Wiener Diversity Index value of H' = 0.04 indicates an extremely low species richness, approaching the theoretical minimum of zero for single-species stands (Magurran, 2021). While monoculture plantations facilitate rapid initial establishment, extensive ecological literature demonstrates that

Table 3: Mangrove plant species in the study areas

Scientific name	D	F	BA	RD	RF	RDo	IVI	H'
2024 rehabilitation area								
Rhizophora stylosa	69,400	2	-	0.9943	0.50	-	149.43	0.04
Avicennia alba	400	2	-	0.0057	0.50	-	50.57	
	69,800	4						
2019 rehabilitation area								
Rhizophora stylosa	24,200	2	-	0.90977	0.40	-	130.98	0.36
Sonneratia alba	1,600	2	-	0.06015	0.40	-	46.02	
Avicennia alba	800	1	-	0.03008	0.20	-	23.01	
	26,600	5						
2014 rehabilitation area								
Tree level:								
Rhizophora stylosa	500.0	8	7.38	1.00	1.00	1.00	300.00	0
Sapling level:								
Rhizophora stylosa	337.5	8	-	1.00	1.00	-	200.00	0
	837.5							
'Peil' secondary natural forest								
Tree level:								
Avicennia marina	388.9	0.78	10.31	0.67	0.54	0.76	197.12	0.84
Avicennia alba	122.2	0.56	1.69	0.21	0.38	0.12	72.06	
Rhizophora stylosa	66.7	0.11	1.57	0.12	0.08	0.12	30.82	
	577.8	1.44	13.58				300.00	
Sapling level:								
Avicennia marina	266.7	0.78	-	0.51	0.39	-	89.95	1.10
Rhizophora sp.	122.2	0.78	-	0.23	0.39	-	62.29	
Avicennia alba	122.2	0.33	-	0.23	0.17	-	40.07	
Sonneratia alba	11.1	0.11	-	0.02	0.06	-	7.68	
	522.2	2.00					200.00	

Notes: D (density) in stems/ha; F = frequency; BA (basal area) in m^2/ha; RD = relative density; RF = relative frequency; RDo = relative dominance; IVI (Importance Value Index) in percentage; H' = Shannon-Wiener Diversity Index

these low-diversity stands exhibit heightened vulnerability to pathogens, pest outbreaks, and environmental stressors compared to their species-rich counterparts (Bosire *et al.*, 2008; Field, 1998). *A. alba* was planted in this location as part of the rehabilitation process. However, its seedling is only incidentally available in the location; it is obtained naturally, not as a result of mangrove nursery efforts, hence its limited quantity. The 2024 rehabilitation site consists of a decommissioned aquaculture pond that was deliberately reforested, resulting in a highly waterlogged substrate. Notably, no natural regeneration or recruitment of non-planted mangrove seedlings was observed within this location. The average height of the existing *R. stylosa* seedlings is 60–70 cm. The incidental occurrence of *A. alba* through natural recruitment, rather than systematic nursery production, is noteworthy. Natural recruitment of mangroves into degraded coastal areas depends heavily on propagule availability, tidal connectivity, and suitable substrate conditions (Tomlinson, 1986; Giesen *et al.*, 2006). Given the continuous inundation regime of the decommissioned pond substrate within the 2024 area, natural recruitment is heavily constrained, particularly for target taxa that lack specialized adaptations to prolonged inundation. Incorporation of *A. alba* into future nursery programs would help diversify the stand composition and improve long-term resilience of the rehabilitation site (Bosire *et al.*, 2008). The 2019 stand has reached a canopy height of 6–7 m, and its canopy cover has been intertwined. Nonetheless, its flora diversity is still dominated by *R. stylosa* (Table 3). The species dominates this area since it has the greatest quantity, with a density reaching 24,200 stems/ha, despite its rather small trunk circumference of 9–26 cm. Notably, *S.alba* appeared to establish spontaneously prior to formal rehabilitation efforts; several individuals exhibited trunk

circumferences slightly exceeding 30 cm yet remained classified within the sapling cohort. Similarly, multiple *A. alba* saplings within this zone displayed large circumferences approaching 30 cm. Nonetheless, since the numbers of individuals are limited, the IVI value of these two species combined does not reach 10%. The 2019 area demonstrates a modest improvement in species diversity compared to the 2024 area (H' = 0.36 vs. 0.04), reflecting the early stages of natural species recruitment over a five-year period. The spontaneous establishment of *S. alba* is ecologically significant, as this pioneer species plays an important role in sediment stabilization and the facilitation of secondary species colonization in mangrove ecosystems (Tomlinson, 1986). However, the IVI values confirm that *R. stylosa* continues to overwhelmingly structure the stand (IVI = 130.98%), suggesting that natural diversity recovery in planted monocultures is a slow process that may require active intervention to accelerate successional dynamics (Bosire *et al.*, 2008; Alongi, 2009). Established in 2014, this stand represents the oldest mangrove rehabilitation cohort within the study area. Situated along the estuarine margin roughly 10 m from the riverbank, the site is subject to continuous tidal inundation. Unlike the other two areas (2024 and 2019), the 2014 stand only consists of one species of mangrove, namely *R. stylosa* (Table 3). The 10-year-old *R. stylosa* stands just reached tree level, where the largest trunk circumference has not reached 40 cm. Typically, *R. stylosa* trees are multi-stemmed, with branches emerging slightly above their prop roots. The total density of this stands is 837.5 ind/ha, with individuals at the tree level amounting to 500 stems/ha and those at the sapling level reaching 337.5 stems/ha. The total basal area for the tree level alone is 7.38 m²/ha. The forest canopy height within the 2014 stand reaches approximately 9–10 m, reflecting advanced structural development. Since this 2014 area only consists of one species, its IVI value is 100% (or 300%, as it is measured through three parameters), belonging entirely to *R. stylosa*. Meanwhile, its Shannon-Wiener Diversity Index (H') is 0 because the stands are uniform. The structural maturity of the 2014 stand, characterized by a canopy height of 9–10 m, a basal area of 7.38 m²/ha, and the presence of both tree-and sapling-level cohorts—indicates that the rehabilitation has been structurally successful in terms of biomass accumulation. However, the persistence of a monospecific composition (H' = 0) after a decade highlights a critical limitation of single-species planting approaches: structural recovery does not necessarily translate to biodiversity recovery (Feller *et al.*, 2010). The sapling cohort (337.5 stems/ha) suggests adequate natural regeneration of *R. stylosa* within the stand, the complete absence of alternative colonizing taxa suggests that dense canopy closure may severely attenuate light availability at the forest floor, thereby precluding recruitment opportunities for less shade-tolerant mangrove species. The natural mangrove forest near the research location is a quite old secondary forest, although the area is getting narrower due to land clearing for fish farming. Only about two ha of forest area remain, and it is almost always waterlogged, albeit shallow (about 10–20 cm on the south, towards the land). Some of the biggest trees, located outside the measurement plot, have trunk circumferences reaching 171 cm (*A. alba*) and 139 cm (*A. marina*). The residents of Segarajaya call this area the '*Peil* forest', possibly because it is located near the *peilschaal*, a water level measuring scale installed on the water drainage channel of Muara Tawar Power Plant (PLTGU Muara Tawar). This stand is classified as depauperate, comprising only five mangrove tree species, four of which were explicitly recorded within the sampling plots (Table 3). This is most likely due to its isolated location, far from other natural mangrove forests, with almost no dry land area. Another species found in the *Peil* forest, but not within the plot, is the red mangrove (*R. mucronata*). In terms of stem abundance, this forest exhibits a slightly higher density than the 2014 stand, supporting approximately 578

stems/ha. Conversely, its basal area (13.58 m^2/ha) is nearly twofold that of the 2014 cohort, indicating a substantially greater wood volume and structural maturity. This implies that the natural forest is likely more fertile than the rehabilitation area. Another possibility is that the *Peil* forest is older, thus having a greater amount of accumulated biomass than that in the rehabilitation area. The greater basal area of the *Peil* forest (13.58 m^2/ha) compared to the 2014 rehabilitation area (7.38 m^2/ha) reflects the superior structural complexity and accumulated biomass of the natural stand. This structural progression aligns with the expected trajectory of mangrove forest development and temporal succession. The multi-species composition of the *Peil* forest—including *A. marina, A. alba, R. stylosa*, and *S. alba*-supports a higher Shannon-Wiener Diversity Index (H' = 0.84 at tree level; H' = 1.10 at sapling level) relative to all rehabilitation areas, underscoring the ecological value of conserving remnant natural forests alongside ongoing rehabilitation efforts (Murdiyarso *et al.*, 2015; Feller *et al.*, 2010). The dominance of *A. marina* (IVI = 197.12%) in the *Peil* forest is characteristic of mature secondary mangrove forests in Java, where this species is often a late-successional dominant on muddy substrates (Duke, 2006; Giesen *et al.*, 2006). The ecological isolation of the *Peil forest* from adjacent natural mangrove stands likely severely restricts autochthonous propagule supply and constrains the recovery of species richness, highlighting the urgent priority for in situ conservation of this critical remnant patch (Bosire *et al.*, 2008). To analyze the differences in flora between the 2024 area, 2019 area, 2014 area, and natural forest, a Chi-Square Test of Independence was conducted (Table 4), with H_o: mangrove species richness is equally distributed across all four locations (no significant difference); H_1: Species richness differs significantly among locations. The result of Chi-square test indicates that the distribution of mangrove species richness did not differ significantly among the four study areas, thereby failing to reject the null hypothesis (H_0). But, ecologically, the number of flora species in each region shows differences (Table 3). Pairwise Mann-Whitney U tests were also conducted on per-species density values (D, stems/ha). Stand density (D) provides an alternative and complementary dimension of structural differentiation among the study sites, proving particularly instrumental when contrasting high-density, pioneer-stage monocultures against low-density, structurally mature stands. H_o: density distributions are equal between paired areas. Pairwise Mann-Whitney U tests (Table 5) show that mangrove diversity in all rehabilitation and natural forest areas was not significantly different. The lowest p-value (0.10) for the 2019 area and natural forest reflects the large density contrast: a mean of 8,866.7 stems/ha (2019 area) and 192.6 stems/ha (natural forest). To enhance the robustness and generalizability of future findings, expanding the sampling intensity by incorporating a greater number of replications stands across diverse age cohorts is strongly recommended to ensure improved statistical reliability, broader ecological representation, and comprehensive comparative analysis outcomes across varying environmental and management conditions. The dominance of *Rhizophora stylosa* as a near-absolute monoculture in all three rehabilitation areas—with a time span of 0 to 10 years—is likely not solely attributable to early planting decisions; it reflects a convergence of ecological mechanisms that collectively suppress spontaneous floristic diversification. Canopy closure observed in the 2014 stands generated significant shade that selectively inhibited the recruitment of intolerant pioneer species such as *Avicennia* spp. and *Sonneratia* spp. These species' seedlings necessitate high levels of solar irradiance for germination and and early vegetative growth (Tomlinson, 1986; Krauss *et al.*, 2008). Simultaneously, the former pond substrate in the 2024 area—characterized by persistent waterlogging and dense, anoxic sediments—limited colonizing species to the most resilient

Table 4: Results of the Chi-Square statistical test on the number of mangrove species per rehabilitation area

Statistic	Value
Chi-square statistic (χ^2)	3.18
Degrees of freedom (df)	3
p-value	0.36
Critical value χ^2 (α = 0.05, df = 3)	7.82
Decision	Failed to reject H_o— NS (p = 0.3644 > 0.05)

Table 5: Pairwise Mann-Whitney U tests on the number of mangrove species

Area pair	n_1	n_2	Mean D area 1	Mean D area 2	U Statistic	p-value	Decision
2024 area and 2019 area	2	3	34,900.0	8,866.7	3.00	1.00	NS
2024 area and 2014 area	2	2	34,900.0	418.8	3.00	0.67	NS
2024 area and natural forest	2	3	34,900.0	192.6	6.00	0.20	NS
2019 area and 2014 area	3	2	8,866.7	418.8	6.00	0.20	NS
2019 area and natural forest	3	3	8,866.7	192.6	9.00	0.10	NS
2014 area and natural forest	2	3	418.8	192.6	5.00	0.40	NS
Final decision	Failed to reject H_o— NS (all p-value > 0.05)						

Notes: n_1 = group 1 observation; n_2 = group 2 observation; D = density; U = Mann-Whitney test; p-value = probability value; NS = Not significant.

taxa to environmental stress, namely *Rhizophora* itself (Youssef and Saenger, 1998; Kitaya *et al.*, 2002; Friess *et al.*, 2019). The presence of these abiotic barriers explains why floral recovery in this chronosequence stalled well below levels observed in natural forests (H' = 0.84–1.10), despite a decade of growth in vegetation structure.

Terrestrial fauna diversity

Terrestrial wildlife encounters within the study area were dominated by avian species, with secondary anecdotal records documenting the presence of specific mammal and reptile assemblages. This study recorded two species of mammals, 17 species of birds, and three species of reptiles (Table 6). This clear taxonomic skew toward birds is consistent with the constraints of rapid ecological inventories in mangrove habitats. Avian species are more readily detectable during daytime surveys, whereas the cryptic and often elusive nature of local mammals and reptiles inherently limits their capture in short-term assessment (MacKinnon and Phillipps, 1993; Bibby *et al.*, 2000). The relatively low overall species richness recorded across the study sites reflects the broader pattern of reduced faunal diversity in fragmented and rehabilitated mangrove landscapes, where habitat heterogeneity and structural complexity are still developing (Feller *et al.*, 2010; Alongi, 2009). The presence of birds across the research location is widely spread according to the available habitat and its conditions. Of the 17 species of birds recorded (Table 6), 16 species were observed in the secondary natural forest, while only 10 species were recorded in the rehabilitation areas. Among the rehabilitation areas, the 2014 area has the greatest number of species, with eight species recorded - half the total found in the secondary natural forest. Notably, the 2024 area and the 2019 area supported fewer species, consistent with the lower structural complexity of younger stands. This finding indicates that the mangrove rehabilitation areas exhibit low avian species richness, a trend potentially driven by the depauperate nature of the restoration stands themselves, which similarly lack structural and taxonomic mangrove diversity. The greater bird diversity recorded in the 2014 area is most likely attributable to its more mature and closed canopy cover reaching 9–10 m in height, which provides shelter, nesting opportunities, and invertebrate prey resources largely absent in younger, open-canopy rehabilitation stands (Sodhi *et al.*, 2004; Nagelkerken *et al.*, 2008). The low taxonomic diversity of mangrove plant species in the rehabilitation areas likely constrains

Table 6: Diversity of terrestrial fauna recorded in the research locations

Scientific name	English name	Location			
		2024 Area (0 y)	2019 Area (5 y)	2014 Area (10 y)	Natural forest
Mammals:					
Aonyx cinerea	Asian small-clawed otter				✓
Rattus sp.	unidentified tree rat				✓
No. of mammal species	-				2
Birds:					
Actitis hypoleucos	Common sandpiper				✓
Alcedo coerulescens	Cerulean kingfisher	✓		✓	✓
Ardeola speciosa	Javan pond heron				✓
Butorides atricapilla	Little heron	✓		✓	✓
Chlidonias leucopterus	White-winged tern				✓
Cinnyris ornatus	Ornate sunbird		✓		✓
Collocalia linchi	Linchi swiftlet				✓
Egretta garzetta	Little egret				✓
Gerygone sulphurea	Golden-bellied gerygone	✓	✓	✓	✓
Hirundo javanica	Pacific swallow	✓			✓
Orthotomus ruficeps	Ashy tailorbird		✓	✓	✓
Passer montanus	Eurasian tree sparrow		✓	✓	
Pycnonotus aurigaster	Sooty-headed bulbul			✓	✓
Rhipidura javanica	Sunda pied fantail		✓	✓	✓
Spilopelia chinensis	Spotted dove			✓	✓
Streptopelia bitorquata	Sunda collared dove				✓
Todiramphus chloris	Collared kingfisher	✓			✓
No. of bird species	-	5	5	8	16
Reptiles:					
Cerberus schneideri	Schneider's bockadam	✓		✓	✓
Hemidactylus platyurus	Flat-tailed house gecko				✓
Varanus salvator	Asian water monitor	✓	✓	✓	✓
No. of reptile species	-	2	1	2	3
Total species richness	-	7	6	10	21

avifaunal richness by limiting the variety of trophic resources and architectural vegetation structures available to local bird communities (Feller *et al.*, 2010; MacKinnon and Phillipps, 1993). In contrast, the multi-species composition and greater structural heterogeneity of the *Peil* forest underpin its superior capacity to accommodate a more diverse and species-rich avian assemblage. No mammals were directly observed in the mangrove rehabilitation areas during this study. The absence of mammal detections is most likely attributable to the timing of surveys, which were conducted during daylight hours when human activity around the rehabilitation areas was considerable. This condition is consistent with documented trends in alternative mangrove ecosystems, where ongoing human encroachment and a lack of understory structural complexity act as primary barriers to mammal recruitment within restored stand (Alongi, 2009; Nagelkerken *et al.*, 2008). Future surveys employing camera traps and nocturnal transects would provide a more comprehensive picture of mammal presence and activity patterns across the rehabilitation gradient. Anthropogenic activities—specifically intensive aquaculture, recreational angling, and the routine transit of fishers through these habitats—likely induce disturbance-mediated avoidance behaviors among local mammalian assemblages. Of the three reptile species recorded in the research locations, two species namely the Schneider's bockadam (*Cerberus schneideri*) and the Asian water monitor (*Varanus salvator*) are also pond pests as they prey on fish and other biotas. The two species of land reptiles, both living in these waters, are found in both the natural forest area and the mangrove rehabilitation areas. Furthermore, both reptilian species exhibited

opportunistic foraging behavior, preying directly upon teleost fish captured within the study's sampling traps. The confinement of *Hemidactylus platyurus* to the natural forest underscores the dependence of certain reptile species on mature, structurally complex vegetation, as well as the limited capacity of young rehabilitation stands to support the full complement of herpetofauna characteristic of natural mangrove ecosystems (Feller *et al*., 2010; Giesen *et al.*, 2006). To analyze the differences in fauna in each rehabilitation area, the Sørensen Community Similarity Index test was carried out (Table 7). A chi-square test of independence was applied to evaluate whether the distribution of species presence/absence differed significantly across the three rehabilitation areas (Table 8). The H_o states that species presence is independent of rehabilitation age. The association was evaluated using a 2×3 contingency table (presence/absence × three study areas), utilizing the 22 documented species as the primary unit of analysis. Furthermore, the values of S_s were converted to (1-S_s) to obtain the dissimilarity between fauna communities in the research locations (Table 9). As shown in Tables 7 and 9 and Fig. 2, the community similarity of terrestrial fauna between the 2014 area and the natural forest has the highest value. However, the similarity value between the two fauna communities only reaches 58%, still far from the expected value. The faunal community similarity between the natural forest and the 2019 rehabilitation area exhibited a comparatively low value of approximately 37%. The similarity of fauna communities between rehabilitation areas is even lower, ranging from 26.67% to 52.63%. This indicates that fauna communities in rehabilitation areas remain highly variable due to ongoing ecological succession, species turnover, and habitat recovery processes.

Aquatic biota diversity

The diversity of aquatic fauna recorded in the research locations consists of two taxa: fish and crustaceans (Table 10). The documented aquatic biota was primarily captured using stationary fish traps deployed systematically across the designated sampling locations. Some decapod crustaceans (crabs) were caught directly by hand. The use of fish traps and direct hand-catching as collection methods is consistent with standard aquatic biodiversity survey protocols in mangrove and coastal wetland environments (Welcomme *et al.*, 2010). The dual-taxa approach - simultaneously monitoring fish and crustacean assemblages—provides a comprehensive assessment of aquatic community structure across different successional stages of mangrove restoration (Nagelkerken *et al.*, 2008). The study area designated in 2024 consists primarily of open, waterlogged terrain that remains submerged. Conversely, certain elevated margins along the pond embankments exhibit drier characteristics, experiencing inundation exclusively during high-tide events. The habitat partitioning observed here reflects well-documented patterns in decapod ecology. Former fish ponds undergoing restoration exhibit hydrological variability that creates microhabitat heterogeneity, supporting distinct assemblages of intertidal and semi-terrestrial crustaceans (Wolff *et al.*, 2000). The perennially waterlogged, open nature of early-stage restoration sites such as the 2024 study area characteristically favors opportunistic and euryhaline taxa that are ecologically adapted to disturbed, fluctuating environmental conditions and stressors. (Duke *et al.*, 2007). The species of decapods found in the 2024 area are Thai vinegar crabs (*Episesarma mederi*), orange signaller crabs (*Metaplax elegans*), marsh crabs (*Parasesarma* sp.), fiddler crabs (*Uca* sp.), and broad-fronted mangrove crabs (*Metopograpsus latifrons*). All of the crabs are mudflat crabs whose habitat is in slightly dense soil and exposed to outside air. The dominance of mudflat crabs (*Episesarma*, *Metaplax*, *Parasesarma*, and *Uca* spp.) in the 2024 area is ecologically significant. These semi-terrestrial sesarmid and varunid crabs are known pioneer colonisers of disturbed intertidal mudflats (Cannicci *et al.*, 2008). Their occurrence within early-successional zones signifies the nascent establishment of a detritivore guild, which serves

Table 7: Sørensen community similarity index of terrestrial fauna in the locations

Compared habitat	a	b	c	a+b+c	S_s
Natural forest and 2014 area	9	12	1	21	0.58
Natural forest and 2019 area	5	16	1	22	0.37
Natural forest and 2024 area	7	14	0	21	0.50
2014 area and 2019 area	5	5	1	11	0.63
2014 area and 2024 area	5	5	2	12	0.59
2019 area and 2024 area	2	4	5	11	0.31

Notes: a = total number of shared species (found in both communities); b = number of species found only in first community; c = number of species found only in second community; S_s = Sørensen Community Similarity Index

Table 8: Chi-Square test of independence for diversity of terrestrial fauna at three mangrove rehabilitation area

Indicators	Locations		
	2024 area	2019 area	2014 area
No. of species present	7	6	10
No. of species absent	15	16	12
Total species tested	22	22	22
Chi-square statistic (χ^2)	1.74		
Degrees of freedom (df)	2		
p-value	0.42		
Decision	H_0 is therefore not rejected. Not significant (p = 0.4200 > 0.05): species presence distribution does not differ significantly among the three rehabilitation areas		

Table 9: Distance of community dissimilarity between habitats

Natural forest	Natural forest	2014 area	2019 area	2024 area
2014 Area	0.4194	-		
2019 Area	0.6296	0.4737	-	
2024 Area	0.5172	0.4737	0.7333	-

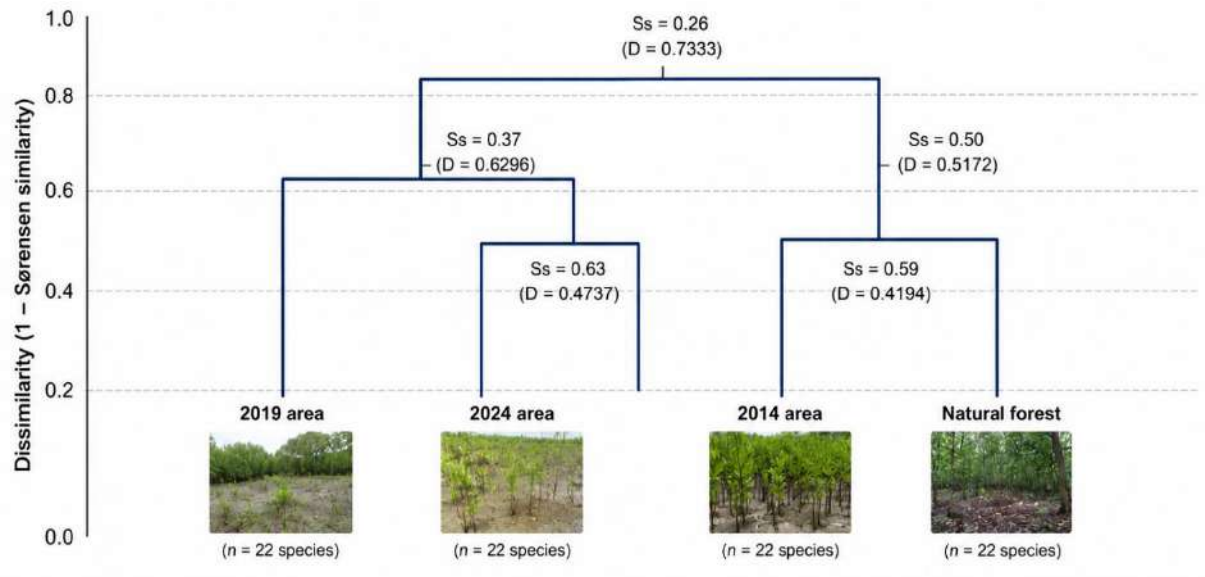

Fig. 2: Tree diagram of the community similarity between terrestrial fauna in rehabilitation areas and those in secondary natural mangrove forest

Table 10: Diversity of aquatic biota recorded in the research locations

Scientific name	English name	Location			
		2024 area (0 y)	2019 area (5 y)	2014 area (10 y)	Natural forest
Fishes:					
Ambassis cf. *vachelli*	Vachelli's glass perchlet			✓	
Chanos chanos	Milkfish	✓			
Psammogobius cf. *biocellatus*	Sleepy goby			✓	
Hexanematichthys sagor	Sagor catfish			✓	
Mayaheros urophthalmus	Mayan cichlid	✓		✓	
Monopterus javanensis	Sunda swamp eel	✓	✓		
Planiliza subviridis	Greenback mullet	✓	✓	✓	✓
Mystus cf. *gulio*	Long whiskers catfish	✓	✓		
Oreochromis mossambicus	Mozambique tilapia	✓	✓	✓	✓
Periophthalmus sp.	Mudskipper		✓	✓	✓
Plotosus canius	Gray eel-catfish			✓	
Poecilia latipinna	Sailfin molly	✓	✓	✓	
Scatophagus argus	Spotted scat			✓	✓
Terapon jarbua	Crescent grunter		✓		
Trichopodus trichopterus	Three-spot gourami		✓		
No. of fish species	-	7	8	10	4
Crustaceans:					
Metapenaeus ensis	Greasyback shrimp	✓			
Penaeus merguiensis	Banana prawn	✓	✓		✓
Episesarma mederi	Thai vinegar crab	✓			✓
Metaplax elegans	Orange signaller crab	✓			
Metopograpsus latifrons	Broad-fronted Mangrove Crab	✓		✓	✓
Parasesarma sp.	Sesarmid marsh crab	✓			
Scylla paramamosain	Green mud crab			✓	
Thranita crenata	Crenate swimming crab			✓	
Uca sp.	Fiddler crab		✓		
Varuna litterata	River swimming crab			✓	
Carcinoscorpius rotundicauda	Mangrove horseshoe crab			✓	✓
No. of crustaceans species	-	6	2	5	4
Total species richness	-	13	10	15	8

a pivotal role in mediating nutrient cycling and accelerating organic matter decomposition within mangrove sediments (Lee, 1998). The 2019 and the 2014 areas are land covered by vegetation, almost always completely submerged, even at low tide. The persistent inundation of the 2019 and 2014 areas, reflecting progressively mature mangrove canopy cover, creates conditions more suitable for fully aquatic and semi-aquatic crustaceans. Characterizing established mangrove stands requires accounting for complex microhabitats; thus, employing a combination of trapping and hand-collecting in vegetated strata serves to mitigate sampling bias against cryptic and arboreal crustacean assemblages (Kathiresan and Bingham, 2001). The species of crustaceans found in these areas include: green mud crabs (*Scylla paramamosain*), crenate swimming crabs (*Thranita crenata*), broad-fronted mangrove crabs (*Metopograpsus latifrons*), river swimming crabs (*Varuna litterata*), and mangrove horseshoe crabs (*Carcinoscorpius rotundicauda*). All of these are swimming crustaceans, while broad-fronted mangrove crabs is a species of crab that climbs on mangrove tree roots. The functional divergence between swimming crustaceans (*Scylla*, *Thranita*, *Varuna*, and *Carcinoscorpius*) and *Metopograpsus latifrons* in the older areas is consistent with increasing structural complexity in maturing mangrove habitats. As mangrove structural complexity advances, the developing root architecture provides critical attachment substrates and refugia for climbing or cryptic macrofauna, whereas the adjacent deeper channels accommodate mobile, pelagic taxa (Gilman *et al.*, 2008). This trophic and functional

diversification is an indicator of ecosystem recovery and habitat maturation over the observed 10-year restoration timeline through progressive ecological succession and stabilization across rehabilitated mangrove habitats and ecosystems.

CONCLUSION

This study provides compelling evidence that structural maturity and biodiversity recovery are fundamentally decoupled processes - and that the conventional growth-based metrics currently prescribed by Indonesian national policy are insufficient to capture the full ecological trajectory of mangrove rehabilitation. By simultaneously evaluating flora, terrestrial fauna, and aquatic fauna diversity across a chronosequence of rehabilitation stands aged 0, 5, and 10 years in the Segarajaya mangrove area, Bekasi Regency, this study demonstrates that these distinct biotic components exhibit decoupled recovery trajectories and must be assessed independently. The 2024 stand was virtually a monoculture of *R. stylosa* (IVI = 149.43%; H' = 0.04), and this dominance persisted through the 2019 stand (IVI = 130.98%; H' = 0.36) and the 2014 stand, where *R. stylosa* remained the sole species with H' = 0. Monoculture planting of *R. stylosa* produced structurally mature stands after a decade - yet failed to support floristic diversity. Despite a canopy height of 9–10 m and a basal area of 7.38 m^2/ha, the 2014 area failed to recruit additional mangrove species. This lack of diversification suggests that dense canopy closure suppressed light availability at the forest floor and thereby constrained natural colonization. This trajectory suggests that without deliberate floristic enrichment, monoculture rehabilitation stands are prone to remaining arrested in a low-diversity state indefinitely. In these systems, intense competitive exclusion exerted by the dominant canopy species effectively impedes the recruitment and establishment of incoming propagules from adjacent natural forests. In contrast, the reference secondary natural forest supported five tree species with a Shannon-Wiener Diversity Index of H' = 0.84 at the tree level and H' = 1.10 at the sapling level, underscoring the superior ecological complexity of naturally structured stands. The significantly greater basal area of the natural forest (13.58 m^2/ha) relative to the 10-year rehabilitation stand (7.38 m^2/ha) further highlights the long developmental lag inherent in monoculture restoration approaches. Terrestrial fauna diversity exhibited a consistent, age-related progression across the rehabilitation gradient, yet remained markedly impoverished relative to the natural forest. The secondary natural forest supported 21 species of mammals, birds, and reptiles, whereas the 2024, 2019, and 2014 areas hosted only 7, 6, and 10 species, respectively. The Sørensen Community Similarity Index (S_s) revealed that even the most structurally mature rehabilitation area (2014) achieved a biotic similarity of only 58% with the natural forest - a value that falls substantially below any ecologically meaningful threshold for functional recovery. The 2019 area attained the lowest community similarity index of 37.04%. This pronounced divergence underscores that early-stage successional stands support highly distinct faunal configurations compared to mature, intact mangrove forests. The absence of mammal detections in all rehabilitation areas, as well as the restriction of *Hemidactylus platyurus* to the natural forest, underscores the limited capacity of young monoculture rehabilitation stands to support the full complement of vertebrate fauna characteristic of intact mangrove ecosystems. The progressive but incomplete faunal recovery observed across the chronosequence reinforces the view that habitat structural complexity, rather than stand age alone, is the primary driver of vertebrate community assembly in restored mangroves. The surveyed aquatic biota, comprising 15 fish species and 11 crustacean species across all locations, revealed ecologically meaningful patterns of community succession. The 2024 site harbored opportunistic and semi-terrestrial mudflat crabs that serve as pioneer

detritivores, playing a critical role in driving organic matter cycling in restored sediments. Older, vegetated areas supported a shift toward swimming crustaceans reflecting progressively maturing root architecture and tidal channel development. Ichthyofaunal assemblages similarly exhibited distinct successional dynamics; notably, the 2014 rehabilitation stand supported the highest species richness among all restored sites and shared four fish species with the natural forest. Notably, the presence of commercially important species such as *Scylla paramamosain* and *Penaeus merguiensis* in older and natural forest indicates that rehabilitated mangroves can progressively recover their role as nursery habitats for coastal fisheries — a provisioning ecosystem service of direct socioeconomic relevance to local communities in Bekasi Regency. These findings expose a critical deficiency in MEF-RI Regulation No. 23/2021, which evaluates rehabilitation success solely on plant growth and canopy cover — metrics the 2014 area would pass despite near-zero biodiversity. To establish a more holistic standard for ecosystem evaluation, this study demonstrates the necessity of embedding quantitative, multi-taxa indicators within national monitoring protocols. Utilizing trajectories from spontaneously recruited flora, vertebrate fauna (specifically birds), and macroinvertebrates (specifically crustaceans) provides a highly sensitive, cross-taxonomic baseline for assessing genuine restoration success. Achieving these benchmarks will require mixed-species nursery programs, that for instance in Segarajaya case, incorporating *A. marina*, *A. alba*, and *S. alba* alongside *R. stylosa*, and active restoration of tidal connectivity to facilitate propagule dispersal and faunal recolonization. Extended monitoring beyond the 10-year horizon examined in this study is imperative to ascertain whether mixed-species stands ultimately converge toward the biodiversity levels observed in the reference natural forest, and to establish scientifically grounded recovery targets for inclusion in future revisions of national rehabilitation policy.

AUTHOR CONTRIBUTIONS

E. Yuliana, the corresponding author, conceived, designed, and conducted research, as well as data analysis, preparing the manuscript draft, and finalizing the manuscript draft. A. Winata contributed to data sampling, especially for flora sampling, and data analysis. L.E. Setijorini conducted observation of vegetation, data analysis, and also reviewed the paper draft. D. E. Yani developed research instruments and conducted flora sampling. M.H. Fathani contributed to data processing, flora and terrestrial fauna sampling, and data analysis. W.A. Djatmiko made contributions to flora, fauna, and fish identification, sampling activities, data processing, and writing the manuscript draft.

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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
χ^2	Chi-square Test of Independence
a	Total species in both communities
b	Number of species in community A
c	Number of species in community B
BA	Basal area
cm	Centimeter
df	Degrees of freedom
D	Density
Do	Dominance of a species
F	Frequency
H	Hypothesis
H_0	Null hypothesis
H1	Hypothesis 1
H2	Hypothesis 2
H3	Hypothesis 3
ha	Hectare
H'	Shannon-Wiener Diversity Index
ind	Individuals
IVI	Importance Value Index
km	Kilometer
km^2	Square kilometers
m	Meter
m^2	Meter square
mm	Millimeters
m^2/ha	Square meter per hectare
MEF-RI	Ministry of Environment and Forestry of the Republic of Indonesia
MMAF	Ministry of Maritime Affairs and Fisheries
n_i	Number of individuals per species
N	Total number of all individuals
No	Number
p	Probability
RD	Relative density
RDo	Relative dominance
RF	Relative frequency
sp	Species
S_s	Sørensen Community Similarity Index
U	Mann-Whitney U Test
y	year

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ORIGINAL RESEARCH ARTICLE

Microplastic pollution and risk assessment in urban beaches of the Caribbean region

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ABSTRACT

BACKGROUND AND OBJECTIVES: Microplastic pollution on tropical urban beaches is a growing concern due to its persistence, mobility, and potential transfer to coastal organisms. While research on marine ecosystems has advanced significantly, substantial gaps persist regarding their spatial distribution, community composition, and the ecological risks facing urban beaches in the Colombian Caribbean. The study objectives were to assess microplastic pollution and associated risks on three urban beaches in San Antero, Córdoba, considering its spatial and seasonal variability and potential anthropogenic sources.

METHODS: Surface sediments were collected from Blanca, Bucaneros and Puerto beaches, including the supralittoral, mesolittoral, and infralittoral zones during rainy, transitional, and dry periods. Microplastics were separated via density separation using a saturated sodium chloride solution, subsequently filtered, and evaluated for morphological characteristics, dimensions, and coloration through stereomicroscopic. The polymer composition was determined using Fourier transform infrared spectroscopy. In addition, pollution indices, morphological impact, potential ecological risk, pollution risk, and source contribution were applied.

FINDINGS: Abundances ranged from 530 to 1392 particles per kilogram, with the highest values during the rainy season, in the supralittoral zone, and at Puerto beach. Fibers overwhelmingly dominated the morphological composition, representing 96 percent of the particles and irregular fragments constituted 4 percent. Blue and white particles predominated within the samples, whereas infrared spectroscopic analysis of a representative subset identified polyethylene terephthalate and polypropylene as the primary polymer types. Although the indices based on abundance and polymer composition indicated low pollution and low ecological risk, the predominance of fibres and the high values of the source contribution index evidenced continuous anthropogenic inputs.

CONCLUSION: The urban beaches evaluated function as microplastic accumulation zones potentially influenced by rainfall, coastal dynamics, tourism, fishing, and urban activities. These findings emphasize the imperative to enhance plastic waste management strategies and environmental surveillance across tropical coastal zones within the Colombian Caribbean. These findings provide baseline information for tropical urban beaches and support the development of source-oriented strategies to reduce microplastic inputs into coastal ecosystems.

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INTRODUCTION

The massive use of plastic materials has generated a global environmental problem, particularly evident in aquatic and coastal ecosystems, where this waste can persist for long periods and disperse over great distances. Its widespread incorporation into products and industrial processes is largely due to properties such as its low weight, strength, versatility, and low production cost (Macheca *et al*., 2024). Consequently, worldwide plastic production has undergone sustained expansion over recent decades, currently approaching an annual volume of 400 million tons per year (Mt/y) (UNEP, 2024). This increase in production has been accompanied by a growing generation of waste. Projections indicate that the 353 Mt of plastic waste produced in 2019 could reach approximately 1,014 Mt by 2060 if current trends continue (OECD, 2022). A significant fraction of these materials undergoes improper management and ultimately enters the natural environment, a situation intensified by deficiencies in municipal waste collection, treatment, and disposal infrastructure (Kibria *et al*., 2023). In the case of the oceans, much of the plastic pollution originates on land and is transported to coastal areas via various routes, including river systems, urban runoff, drainage networks, and losses from landfills. Furthermore, anthropogenic activities conducted directly along the shoreline contribute to the persistent influx of plastic debris into marine and coastal ecosystems (Macafee and Löhr, 2024). The persistence of plastic waste in the environment promotes its gradual transformation through physical, chemical, and biological processes. Exposure to ultraviolet radiation and temperature variations progressively alters the properties of these materials. Abrasion, waves, and currents contribute to their wear and fragmentation (Khoaele *et al*., 2023). The continuous action of these factors can reduce larger plastic objects to particles smaller than 5 millimeters (mm), commonly called microplastics (Sun *et al*., 2022; Pulikkoden *et al*., 2026). Depending on their origin, microplastics are categorized as primary when purposefully manufactured at microscopic scales, or as secondary when formed via the degradation and fragmentation of larger polymeric materials (Takarina *et al*., 2022; Aydın *et al*., 2023). The small size, persistence, and high mobility of microplastics explain their widespread occurrence across diverse environments. These particles have been identified in oceans, beaches, sediments, freshwater systems, soils, and the atmosphere, even in regions far removed from major pollution sources (Zhang *et al*., 2020a, 2020b). Their ubiquitous distribution has heightened concerns regarding potential adverse implications for environmental integrity and human health (Ghosh *et al*., 2023; Go *et al*., 2024). Numerous marine organisms can ingest microplastics through feeding or contact with the surrounding environment. Exposure to these particles has been linked to feeding disturbances, oxidative stress, changes in gene expression, reproductive effects, and digestive tract problems (Bhuyan, 2022; Nnoruka *et al*., 2022). Furthermore, the ecological risks posed by microplastics are heavily influenced by their surface characteristics; these particles are capable of adsorbing persistent organic pollutants, heavy metals, and other environmental contaminants, thereby facilitating their transport and subsequent bioaccumulation within trophic webs (Kinigopoulou *et al*., 2022). Their surfaces can also be colonized by microbial communities and serve as dispersal pathways for various microorganisms, including some with pathogenic potential (Madureira *et al*., 2025). Sandy beaches are coastal environments subject to continuous change due to the interaction between the ocean, the atmosphere, and the land. Their widespread presence globally gives them a significant role from ecological, economic, and social perspectives (Defeo *et al*., 2021). These ecosystems sustain diverse biological communities, provide natural shoreline protection, and facilitate socioeconomic

activities associated with recreation, tourism, and artisanal or commercial fisheries (Costa *et al*., 2023; Ronda *et al*., 2023). Their position at the boundary between land and sea also facilitates the arrival and retention of plastic waste from various sources. Currents, tides, and surface runoff move materials toward the coast, while activities carried out directly on the beaches generate local inputs (Mao *et al*., 2022). The distribution of microplastics in sediments is non-uniform, with spatial variability governed by beach morphology and dynamics, wave and current regimes, coastal transport processes, fluvial inputs, and the intensity of anthropogenic and recreational activities (Ronda *et al*., 2023). Knowledge about the presence of microplastics on the beaches of Latin America and the Caribbean still has significant gaps. Studies conducted to date have focused on specific areas, leaving large sections of the coastline with little information on the abundance of these particles and their spatial distribution (Kutralam-Muniasamy *et al*., 2020; Mesquita *et al*., 2022). This lack of data contrasts sharply with the region's participation in the global plastics economy, accounting for approximately 4 percent (%) of production and almost 8% of global consumption (Mesquita *et al*., 2022). Ongoing urban transformations in coastal municipalities, driven by demographic expansion and escalating tourism pressure, are projected to accelerate the accumulation of plastic debris in these environments in forthcoming decades. Expanding the scope of research would allow for a more precise determination of the extent of microplastic pollution, identify the areas under the greatest pressure, and generate useful information to guide prevention, control, and management measures in coastal areas. In Colombia, microplastics have been found in a wide variety of environments, from beaches and coastal waters to mangroves, lagoons, and marine organisms, reflecting the extent of this pollutant's presence in the country's aquatic and coastal ecosystems (Garcés-Ordóñez *et al*., 2019; Garcés-Ordóñez *et al*., 2020a; Rangel-Buitrago *et al*., 2021). The Colombian Caribbean experiences severe ecological pressure from plastic debris, driven by coastal population density, tourism, maritime port operations, commercial fisheries, and land-based pollutant inputs (Garcés-Ordóñez *et al*., 2020b). The available information is still insufficient to accurately determine the extent of microplastic pollution on many urban beaches in this region and the risks associated with its presence. An integrated evaluation combining spatial and seasonal variability, polymer characterization, pollution indices, ecological risk assessment, and source contribution analysis remains largely unavailable for urban beaches of the Colombian Caribbean, limiting a comprehensive understanding of microplastic dynamics in these tropical coastal ecosystems. This study aims to assess the microplastic pollution and associated risks across three urban beaches in San Antero, Córdoba, by analyzing abundance, spatial distribution, morphological characteristics, coloration, and chemical composition in surface sediments sampled from the supralittoral, mesolittoral, and infralittoral zones. The study was conducted in San Antero, a municipality in the Department of Córdoba, Colombia, in 2023.

MATERIALS AND METHODS

It is hypothesized that microplastic pollution on urban beaches of the Colombian Caribbean varies according to season, littoral zone, and beach characteristics because of anthropogenic activities.

Study area

The municipality of San Antero is in the department of Córdoba, in the Caribbean region of Colombia, approximately at 9 degrees (°), 22 minutes (’), 39 seconds (”) north (N) and 75°45’37” west (W) (Fig. 1). For the purposes of this study, three urban beaches within the municipality were selected: Blanca, Bucaneros and Puerto beaches, areas closely linked to the region's tourism and economic activities. The territory of San Antero

covers approximately 191 square kilometers (km²) and features a coastal landscape where sandy beaches, mangroves, and bay-related intertidal coastal environments converge (Arregocés-Garcés *et al*., 2024). These environments fulfill crucial ecological roles by serving as vital refugia, feeding grounds, and nursery habitats for a diverse array of marine and coastal species. The municipality's economic activity is primarily linked to agriculture, livestock farming, commerce, artisanal fishing, and tourism. The latter two activities are especially pronounced within the coastal zone, thereby driving continuous interaction among resident populations, visitors, and adjacent coastal ecosystems. San Antero has the warm conditions typical of the Colombian Caribbean, with average temperatures ranging from 23 to 33 degrees Celsius (°C) and an annual rainfall of approximately 1500 mm.

Sample collection

Sampling was conducted at Puerto, Bucaneros, and Blanca beaches, located in the municipality of San Antero (Fig. 1). The selected urban beaches are subjected to different intensities of tourism, artisanal fishing, and urban development—factors recognized as primary drivers of microplastic accumulation across the Colombian Caribbean (González-Curbelo *et al*., 2025). At each study site, triplicate surface sediment samples were gathered across the supralittoral, mesolittoral, and infralittoral zones throughout five monthly sampling campaigns spanning from November 2022 to March 2023. November and December corresponded to the rainy season, January to the transitional period, and February and March to the dry season (Franco-Herrera *et al*., 2022). The sampling design comprised a total of 135 surface sediment samples. A 50 × 50 per centimeter (/cm) frame partitioned into 25 quadrats was used, from which 10 were selected using systematic random sampling (Kunz *et al*., 2023). Sediment samples were collected to a depth of 5 cm, thoroughly homogenized, and one-quarter of the composite sample was retained for transport to the Ecology Laboratory at the University of Córdoba. The samples were dried at room temperature for 48 hour (h) and then sieved successively to 5 and 1 mm. For density separation, 50 grams (g) of sediment were mixed with 200 milliliters (mL) of a saturated sodium chloride (NaCl) solution, stirred for 2 minute (min) and left to stand for 5 h. The supernatant was vacuum filtered using 0.45 micrometer (µm) microcellulose filters, which were individually stored in Petri dishes and dried at room temperature for 48 h before particle analysis (Ilechukwu *et al*., 2025).

Microplastic quantification, morphological characterization and polymer identification

Filters containing the recovered particles were analyzed under a Leica EZ4 stereomicroscope to identify and isolate potential microplastics (Almeida *et al*., 2023). Suspected particle was carefully extracted using capillary tubes and visually categorized based on their morphological properties. Microplastics were categorized according to shape (fibers and irregular fragments), size (less than <1 mm and 1–5 mm), and color groups: warm (red), cool (blue and green), and neutral (white and black). Polymer composition was analyzed via Fourier transform infrared spectroscopy (FTIR) utilizing a Nicolet iS5 spectrometer coupled with an attenuated total reflectance (ATR) accessory. A total of 15 representative particles, comprising five from each beach and representing 11% of the 135 visually identified suspected microplastics, were selected for polymer identification based on their morphology, color, and size to accurately reflect the diversity of particles recovered from the study area. Spectra were acquired over the range of 4000-400/cm at a spectral resolution of 4/cm, using standardized analytical procedures to ensure reliable, reproducible, and accurate spectral measurements throughout. Polymer identification was performed by comparison with the OMNIC spectral library (Thermo Fisher Scientific), and assignments were accepted when the spectral match was ≥70%.

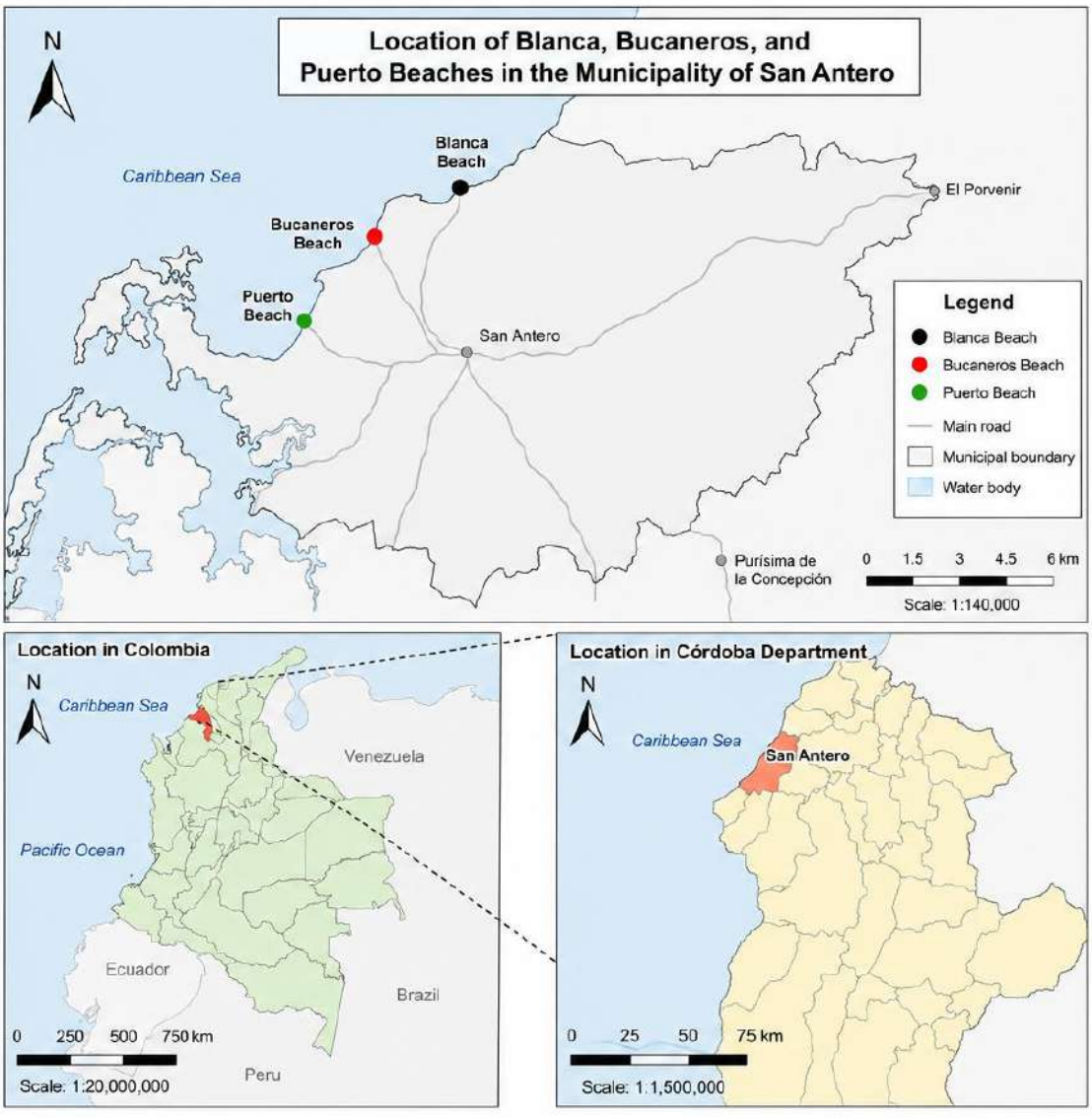

Fig. 1: Geographic location of the study area and sampling sites on the urban beaches of San Antero, Colombian Caribbean

Risk assessment of microplastic pollution

Pollution load index (PLI)

The degree of beach pollution was evaluated using the PLI, determined by calculated from the ratio between the microplastic concentration recorded at each sampling site and a designated reference value representing baseline environmental contamination conditions across beaches.This index provides an integrated expression of relative pollution levels and has been utilized in various coastal studies. The calculation began with the determination of the contamination factor (CF), defined using Eq. 1 (Ranjani *et al*., 2021; Soursou *et al*., 2024; Faisal *et al*., 2025):

$$CF = \frac{C_m}{C_{Bm}} \quad (1)$$

Where: C_m represents the measured concentration of microplastics in each sample and C_{Bm} corresponds to the reference background concentration.

Subsequently, the PLI was determined using the geometric means of the contamination factors obtained for the evaluated conditions, as shown in Eq. 2 (Ilechukwu *et al*., 2025):

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_n)^{1/n} \quad (2)$$

Where: CF_1, CF_2, $CF_3 \ldots CF_n$ represent the contamination factors calculated for each sampling condition, and n corresponds to the total number of evaluated groups.

Since standardized background thresholds for microplastic contamination in coastal environments remain undefined, the minimum microplastic abundance recorded in this study was adopted as the local baseline concentration, consistent with established methodologies (Ranjani *et al*., 2021; Faisal *et al*., 2025; Ilechukwu *et al*., 2025). Therefore, the lowest recorded value was selected as the C_{Bm} for CF estimation and subsequent PLI calculation. The approach provides a relative baseline for comparing contamination among the evaluated conditions within the study area rather than an absolute environmental background concentration. CF and PLI values reflect relative comparisons among the assessed conditions within the study area rather than absolute quantifications of environmental contamination. The obtained PLI values were interpreted according to the following pollution categories: low pollution (PLI <10), high (10–20), hazardous (20–30), and extremely hazardous (greater than >30).

Microplastic pollution index (MPPI)

MPPI was determined to evaluate microplastic abundance based on the total number of particles identified in sediment samples, expressed as particles per kilogram of dry sediment from the surveyed area—in accordance with Eq. 3 (Ranjani *et al*., 2021; Abelouah *et al*., 2022):

$$MPPI = \frac{\sum MPs}{Surveyed\ area} \quad (3)$$

Where: ΣMPs represents the total number of identified microplastic particles. MPPI values were categorized as very low (0–2), low (2–5), moderate (5–15), high (15–25), and very high abundance (>25).

Coefficient of microplastic impact (CMPI)

This coefficient examines the relationship between specific microplastic morphologies and total beach microplastic abundance, determined using Eq. 4 (Ranjani *et al*., 2021; Abelouah *et al*., 2022):

$$CMPI = \frac{Specific\ MPs\ shape}{Total\ MPs} \quad (4)$$

Where: CMPI for each observed microplastic shape is classified as minimum CMPI: 0.0001–0.1; average CMPI: 0.11–0.5; maximum CMPI: 0.51–0.8; extreme CMPI: 0.81–1.

Potential ecological risk index (PERI) and pollution risk index (PRI)

The PERI was calculated to evaluate the ecological threat associated with microplastic contamination by integrating microplastic abundance and polymer toxicity across all sampled coastal environments collectively.The toxic response factor (TRF) was calculated by accounting for the relative contribution of each identified polymer alongside its respective hazard score (S) as established by Lithner *et al*. (2011). PERI was calculated following the proposed approach using Eqs. 5 to 7 (Li *et al*., 2020):

$$TRF = \left(\frac{P_t}{P_i}\right) \times S \quad (5)$$

$$E_i = CF \times TRF \quad (6)$$

$$PERI = \sum E_i \quad (7)$$

Where: P_t represents the abundance of a specific polymer type, P_i is the total microplastic abundance and E_i represents the ecological risk factor.

The PRI was employed as an integrated indicator combining polymer hazard with pollution intensity. PRI was calculated according to Eq. 8 (Al Nahian *et al*., 2022; Haque *et al*., 2024):

$$PRI_i = PHI_i \times PLI_i \quad (8)$$

Where: PHI_i represents the polymer hazard index obtained from the sum of polymer-specific toxic response factors, and PLI_i corresponds to the pollution load index. PERI and PRI values were used as complementary indicators to assess the potential ecological risk associated with microplastic abundance and polymer composition. Polymer composition was established using a representative subset characterized via FTIR, thereby providing the foundation for estimating these indices.

Microplastic source contribution index (MSCI)

To complement the pollution assessment, an exploratory MSCI was proposed to integrate multiple microplastic characteristics potentially associated with anthropogenic inputs. The index integrates contamination pressure (CP), particle morphology, color distribution, and polymer composition to yield a qualitative reflection of source-related patterns rather than definitive source attribution.

The CP was estimated by normalizing the CF and MPPI values, using Eq. 9 (Li *et al*., 2021):

$$CP_i = \frac{(CF_i/CF_{max}) + (MPPI_i/MPPI_{max})}{2} \quad (9)$$

Subsequently, the MSCI was calculated through the weighted integration of the main indicators associated with potential microplastic sources, according to Eq. 10 (Li *et al*., 2021):

$$MSCI = (0.40 \times CP) + (0.25 \times F) + (0.20 \times C) + (0.15 \times P) \quad (10)$$

Where: F corresponds to the proportion of fiber-shaped particles, C represents the contribution of the dominant color, and P corresponds to the proportion of the predominant polymer identified by FTIR analysis. MSCI was conceived as an exploratory integrative index inspired by the microplastic diversity integrated index (MDII) proposed by Li *et al*. (2021) and adapted to the objectives of the present study. Weighting factors of 40%, 25%, 20%, and 15% were assigned using an expert-based approach, reflecting the relative environmental significance of each variable as documented in the literature. Likewise, the classification thresholds proposed here serve as operational parameters tailored for data interpretation within the scope of this investigation rather than serving as universally applicable standards. The obtained values were classified as follows: moderate source contribution (MSCI < 0.65), high source contribution (0.65–0.75), and very high source contribution (MSCI greater than or equal to (≥) 0.75). Consequently, the MSCI functions as a preliminary index that necessitates subsequent sensitivity evaluations and independent verification.

Quality control

For sample processing, all utensils and glassware were thoroughly decontaminated using a residue-free laboratory detergent and a vegetable sponge, followed by three rinses with 10% nitric acid, distilled water, and a final rinse with Type I ultrapure water with Milli-Q, 18.2 megaohm centimeter (MΩ·cm) at 25 °C produced by Milli-Q Easy Pure II deionizer (Thermo Scientific). Throughout all preparation procedures, samples and laboratory equipment were maintained under aluminum foil covers to minimize the risk of airborne contamination. To minimize contamination from laboratory clothing, only 100% cotton laboratory coats were worn throughout the extraction and analytical procedures, and the use of synthetic laboratory garments was avoided. Procedural blanks were processed concurrently with the environmental samples, undergoing identical extraction,

filtration, and microscopic examination procedures. Prior to and following sample preparation, all filters and blanks underwent rigorous inspection to confirm the absence of background contamination. No microplastic particles were detected in the procedural blanks; therefore, blank correction was not required, and the reported microplastic abundances were not affected by laboratory contamination.

Statistical analysis

Statistical analyses were performed using the R software (version 4.2.2). Data normality and homogeneity of variances were evaluated using the Shapiro–Wilk and Levene tests, respectively. To evaluate microplastic abundance, a generalized linear mixed model (GLMM) featuring a negative binomial distribution was implemented, treating sampling period, beach, littoral zone, and their respective interactions as fixed effects, while incorporating the sampling unit as a random effect. Pairwise comparisons between factor levels were conducted utilizing estimated marginal means with a Tukey adjustment and statistical significance was set at p value (p) < 0.05 across all analyses.

RESULTS AND DISCUSSION

Spatiotemporal distribution and abundance patterns of microplastics

Fig. 2 summarizes the spatiotemporal distribution of microplastic abundance on the urban beaches of San Antero, considering the influence of climatic season, littoral zonation, and sampling sites. The GLMM revealed significant effects of sampling period (Chi-square statistic $\chi^2 = 10.88$, $p = 0.0043$), beach ($\chi^2 = 34.33$, $p < 0.001$), and littoral zone ($\chi^2 = 20.56$, $p < 0.001$) on microplastic abundance. Significant interactions were detected between beach and littoral zone ($\chi^2 = 11.17$, $p = 0.0247$) and among sampling period, beach, and littoral zone ($\chi^2 = 16.87$, $p = 0.0315$). No significant interactions were observed between sampling period and beach ($p = 0.1923$) or between sampling period and littoral zone ($p = 0.2485$). Subsequent Tukey-adjusted post-hoc evaluations utilizing estimated marginal means revealed multiple significant pairwise variations across sampling periods, beaches, and littoral zones. Variable microplastic abundances were recorded among the evaluated seasons, with the highest concentration observed during the rainy season with 1392 microplastic particles per kilogram (MPs/kg), followed by the dry season (670 MPs/kg) and the transition season (530 MPs/kg) (Fig. 2a). The significant influence observed across sampling periods highlights the impact of seasonal hydrometeorological patterns on microplastic levels, underscoring the vital function of precipitation in driving the transport, dispersion, and accumulation of debris within coastal environments. The high abundance observed during the rainy season is likely associated with increased continental inputs derived from surface runoff, urban drainage systems, and fluvial transport of plastic residues toward coastal areas (Belioka and Achilias, 2024). Within tropical environments, heavy precipitation events accelerate the mobilization of accumulated plastic debris from urban and peri-urban sectors, thereby enhancing their propensity for transport into coastal-marine ecosystems (Shahariar *et al.*, 2025). This pattern has also been observed in coastal environments, where rainfall favors the transport of pollutants from continental areas to marine systems (Dris *et al.*, 2015). Temporal fluctuations in microplastic abundance across coastal environments are largely driven by seasonal shifts in precipitation, surface runoff, and watershed inputs (Ilechukwu *et al.*, 2025). Extreme rainfall events and the associated increase in riverine discharge and stormwater runoff may further enhance the transport of plastic debris from urban watersheds toward the Caribbean coastal environment. Consequently, seasonal climatic fluctuations govern not merely the volume of microplastics delivered to coastal beaches, but additionally their spatial redistribution mediated by shifts in hydrological connectivity and coastal transport mechanisms

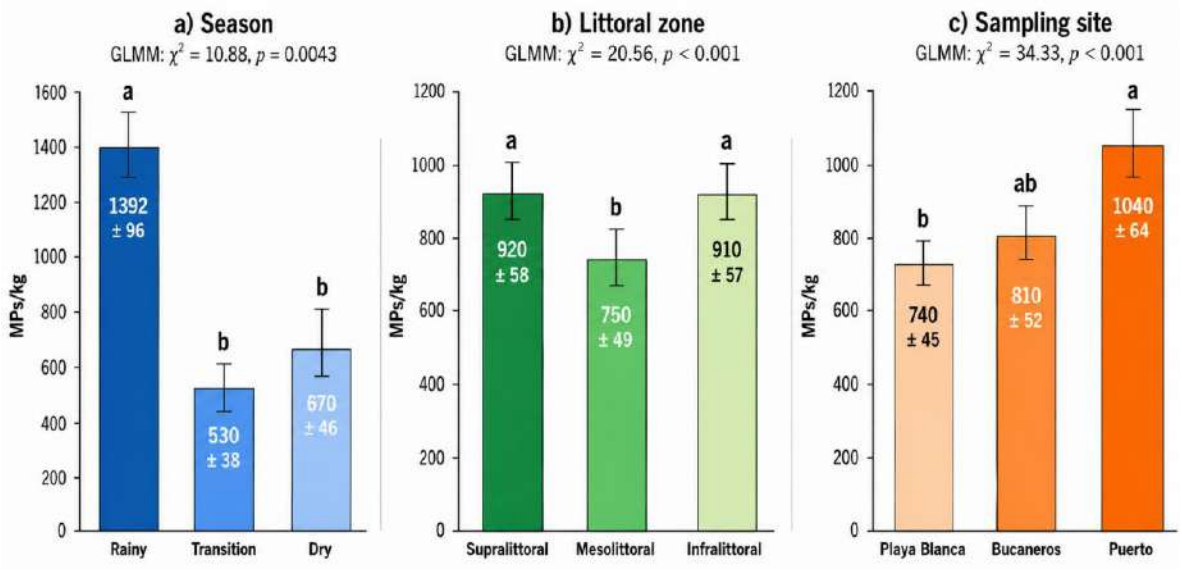

Fig. 2: Spatiotemporal distribution of MPs/kg in urban beaches of San Antero. (a) Variation according to climatic season; (b) distribution across littoral zones; and (c) differences among sampling sites

(Belioka and Achilias, 2024; Shahariar *et al*., 2025). Regarding distribution across littoral zones, the highest microplastic abundance was recorded in the supralittoral zone (920 MPs/kg), followed by the infralittoral (910 MPs/kg) and mesolittoral zones (750 MPs/kg) (Fig. 2b). Spatial pattern was supported by the GLMM, which identified a significant effect of littoral zone on microplastic abundance (χ^2 = 20.56, p < 0.001), indicating that microplastic accumulation differed significantly among beach zones. The accumulation patterns identified in the supralittoral zone align with prior findings on sandy beaches, confirming that this region serves as a primary deposition sink for debris driven by tidal and wave dynamics (Iannacone *et al*., 2020; De-la-Torre *et al*., 2020). Since the supralittoral zone is located above the ordinary tidal influence, deposited particles experience lower removal by hydrodynamic processes, favoring their progressive accumulation in surface sediments. From an ecological perspective, microplastic accumulation in this zone is particularly relevant due to the presence of several organisms associated with supralittoral environments, including amphipods, isopods, beetles, and myriapods. Such organisms may experience direct exposure to plastic particles through accidental ingestion or interaction with tainted sediments, potentially triggering adverse physiological consequences linked to microplastic pollution (Riascos *et al*., 2025). Conversely, the reduced abundance observed within the mesolittoral zone can be attributed to the heightened hydrodynamic energy, tidal fluctuations, and sediment resuspension characteristic of this transition region. Similar results were reported by De-la-Torre *et al*. (2020), who observed differences in microplastic accumulation among beach zones subjected to different degrees of tidal influence. Regarding spatial distribution, Puerto beach showed the highest microplastic abundance (1040 MPs/kg), followed by Bucaneros (810 MPs/kg) and Blanca beaches (740 MPs/kg) (Fig. 2c). Similarly, the GLMM revealed a significant effect of beach location (χ^2 = 34.33, p < 0.001), indicating that local environmental conditions and anthropogenic activities significantly influenced microplastic abundance across the evaluated beaches. The elevated concentration recorded at Puerto are

likely linked to intensive local anthropogenic pressures, encompassing artisanal fisheries, maritime traffic, commercial operations, and heightened tourism. The highest abundances of microplastics are usually recorded on urban beaches and areas near maritime infrastructure, where recreational, fishing and commercial activities generate multiple potential sources of these pollutants (Preston-Whyte *et al*., 2021; Ilechukwu *et al*., 2025). Fishing activity in Puerto beach could contribute to the presence of microplastics in its sediments. The degradation, loss, or discarding of synthetic fishing gear, including nets, ropes, and lines—represents a well-documented contributor to plastic pollution in coastal ecosystems, particularly within regions characterized by intensive artisanal fisheries (Andrady, 2017). The location and geomorphological characteristics of Puerto beach may also favor the retention of particles transported by local coastal currents. In urban beaches of the Colombian Caribbean, the accumulation of plastic and microplastic waste is conditioned by the shape of the coastline and by the dynamics of wind, waves and ocean currents (Galindo-Montero *et al*., 2023). The significant interactions among beaches, littoral zone, and sampling period demonstrate that the impact of coastal zonation on microplastic accumulation varied spatially and temporally, underscoring the synergistic effects of local hydrodynamic processes and seasonal hydrometeorological conditions. These findings are consistent with studies conducted on tropical and subtropical sandy beaches, where microplastic abundance is determined by the interaction among terrestrial sources, marine transport processes, and coastal geomorphological characteristics (De-la-Torre *et al*., 2020; Ilechukwu *et al*., 2025). Beyond precipitation-induced runoff, the spatial dispersion and temporal accumulation of microplastics across the investigated beaches appear to be governed by the interplay of coastal hydrodynamics, wave dynamics, tidal fluctuations, prevailing winds, and sediment transport mechanisms. Wave-induced sediment resuspension and tidal oscillations may promote the repeated mobilization and redeposition of microplastic particles between littoral zones, whereas prevailing winds and local coastal currents can facilitate the alongshore transport and retention of floating debris in specific beach sectors (De-la-Torre *et al*., 2020; Galindo-Montero *et al*., 2023). Collectively, these interacting physical processes, together with the geomorphological attributes of the coastline likely drive the heterogeneous spatial distribution and temporal accumulation patterns observed across the studied beaches (Ilechukwu *et al*., 2025).

Morphological features and size distribution of microplastics

The identified microplastics encompassed different morphological categories and size ranges across the evaluated urban beaches (Fig. 3). The results showed a marked predominance of fibers, which represented 96% of the total identified particles, whereas irregular fragments accounted for only 4% (Fig 3a). Representative stereomicroscopic images confirmed the presence of both morphologies, showing elongated and thin fibers as well as irregularly shaped fragments associated with the fragmentation processes of larger plastic materials (Fig 3b). The pronounced dominance of fibers implies that the primary drivers of microplastic contamination within the study area stem predominantly from anthropogenic activities across adjacent coastal and inland zones (Savuca *et al*., 2022). Synthetic fibers represent the most prevalent form of microplastic pollution in marine habitats, driven by the continuous discharge from textile laundering, the weathering of ropes and fishing gear, maritime operations, and the breakdown of industrial and domestic polymer-based materials, including polyester, nylon, and polyamide (Gago *et al*., 2018). In coastal ecosystems with important fishing activities, such as the municipality of San Antero, the progressive deterioration of fishing gear manufactured from synthetic polymers may

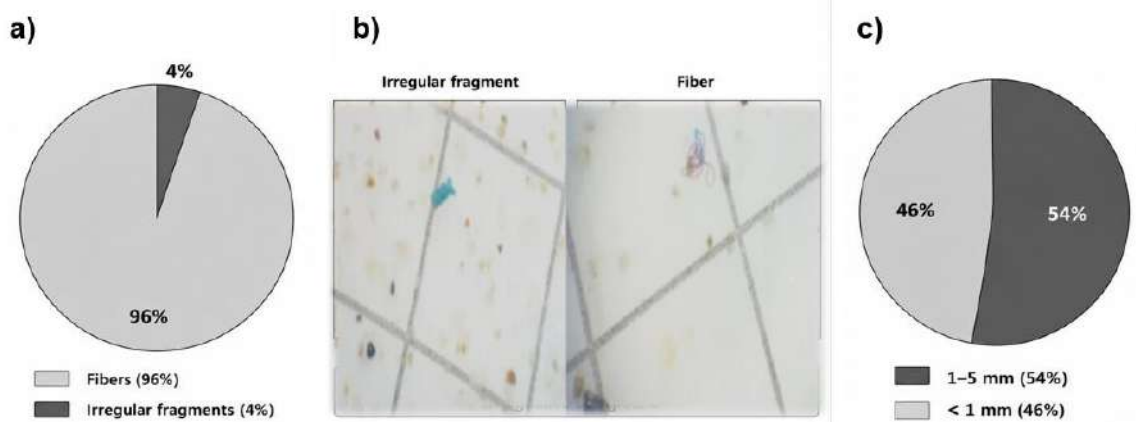

Fig. 3: Morphological features and size distribution of microplastics collected from urban beaches of San Antero. (a) Relative abundance of fibers and irregular fragments; (b) representative stereomicroscopic images of the identified microplastic morphologies; and (c) classification of microplastics according to particle size. Scale bars represent 500 µm

represent a significant source of fibers accumulated in coastal sediments (Andrady, 2017). The high prevalence of fibers documented across the investigated beaches is consistent with findings from other coastal environments. In the Okinawa Islands, Japan, Ilechukwu *et al*. (2025) found that this form accounted for more than half of the microplastics identified. An even higher proportion was documented by Shaji *et al*. (2026) on the coast of Odisha, India, where 98.9% of the particles recovered from beach sediments were identified as fibers. High proportion of fibers observed in San Antero may also be related to their physical characteristics. Unlike other microplastic morphologies, fibers exhibit a high length to diameter ratio and low settling velocity, which enhance their transport over long distances through marine and river currents before deposition in coastal sediments (Gago *et al*., 2018). This attribute enables beaches to function as primary deposition sinks for microplastic particles derived from both local and regional origins (Guesmi *et al*., 2025). In contrast, irregular fragments represented only 4% of the identified particles (Fig. 3a and 3b). Although their abundance was considerably lower compared with fibers, their presence may be associated with physical, photochemical, and mechanical degradation processes affecting larger plastic debris (Lakshmipraba, 2024). Particles ranging from 1 to 5 mm accounted for 54% of the total microplastics recovered, whereas particles under 1 mm comprised 46% (Fig. 3c). Representatives of both size fractions were identified across all three beaches throughout every climatic periods. Particles measuring 1 to 5 mm remained slightly predominant throughout the study, accounting for 55.5% of the particles during the rainy period, 51.5% during the transitional period, and 52.1% during the dry period. Puerto and Bucaneros beaches exhibited a marginally greater proportion of 1 to 5 mm particles relative to Blanca beach, reflecting slight spatial variations in particle-size distribution. The predominance of microplastics measuring 1 to 5 mm has also been recorded on tropical and subtropical sandy beaches (Madureira *et al*., 2025). This fraction usually results from the gradual weathering of larger plastic debris built up in coastal environments (Andrady, 2011). The proportion of particles smaller than 1 mm, close to half of the total recorded, is especially relevant due to its possible ecological implications. The size of microplastics influences their availability to marine organisms. Smaller particles can be ingested by various groups, including benthic invertebrates, filter-

feeding organisms, and juvenile fish (Cole *et al*., 2013; Wright *et al*., 2013). Furthermore, particle size reduction elevates the surface-area-to-volume ratio, a characteristic that promotes the adsorption of persistent organic pollutants and trace metals within marine ecosystems. Interaction with these substances can modify the risk associated with the presence of microplastics and contribute to their potential ecotoxicological effects (Bhaumik and Chakraborty, 2024). Furthermore, the consistent presence of both size fractions across all beaches and climatic periods implies the ongoing contribution of continuous of plastic inputs and coastal hydrodynamic drivers, which collectively govern the redistribution and retention of microplastics within sandy sediments (Onink *et al*., 2022; Jiang *et al*., 2024).

Color distribution and FTIR-based polymer identification of microplastics

The color classification of microplastics identified on the urban beaches of San Antero revealed a marked predominance of blue particles, which represented 62% of the total particles analyzed. Lower proportions of white (26%), red (10%), green (1%), and black (1%) microplastics were recorded (Fig. 4a). The characterization photomicrographs disclosed particles exhibiting diverse coloration and morphology, characterized by a prominent abundance of fibers and irregular fragments (Fig. 4b–f). Blue particles were particularly visible and appeared mostly as fibrous structures and small fragments (Fig. 4b). The high proportion of blue particles coincides with the results obtained in other marine and coastal environments. A high presence of blue microplastics has been recorded on sandy beaches in Okinawa, Japan (Ilechukwu *et al*., 2025). This coloration similarly represented one of the most prevalent findings within the coastal sediments of Tanzania (Nchimbi *et al*., 2022). The high abundance of blue particles is commonly associated with the degradation of plastic materials widely used in maritime, fishing, and recreational activities, including synthetic fibers, ropes, fishing nets, and other pigmented polymeric materials. Given the significance of artisanal fisheries, tourism, and recreational sectors within the municipality of San Antero, these anthropogenic activities likely constitute a substantial input of blue microparticles into coastal sediments. White particles represented the second most abundant color group (26%), mainly appearing as light-colored and translucent fragments (Fig. 4f). Their occurrence may be attributed either to plastic refuse originally fabricated in lighter hues or to advanced environmental weathering processes impacting pigmented polymers. The presence of plastic waste in the environment progressively alters its original appearance. Ultraviolet radiation, abrasion from waves, and surface oxidation promote pigment loss and generate changes in the material's structure (He *et al*., 2023). As a result, some particles acquire whitish tones or become transparent. This phenomenon is likely particularly pronounced within the tropical environments of the Colombian Caribbean, where intensive solar radiation accelerates the photo-oxidative degradation of plastics on sandy beaches. Red microplastics constituted 10% of the identified particles (Fig. 4d). Their proportion was lower than that recorded for blue and white particles. This color could be related to waste from packaging, containers, recreational items, and other plastic products used in domestic, commercial, and tourism activities. The diverse spectrum of colors observed indicates the potential influx of debris originating from varied sources onto the beaches of San Antero. Green and black particles were the least frequent, with a proportion of 1% for each color (Fig. 4c-e). Comparable coloration has also been documented among microplastics recovered from sandy

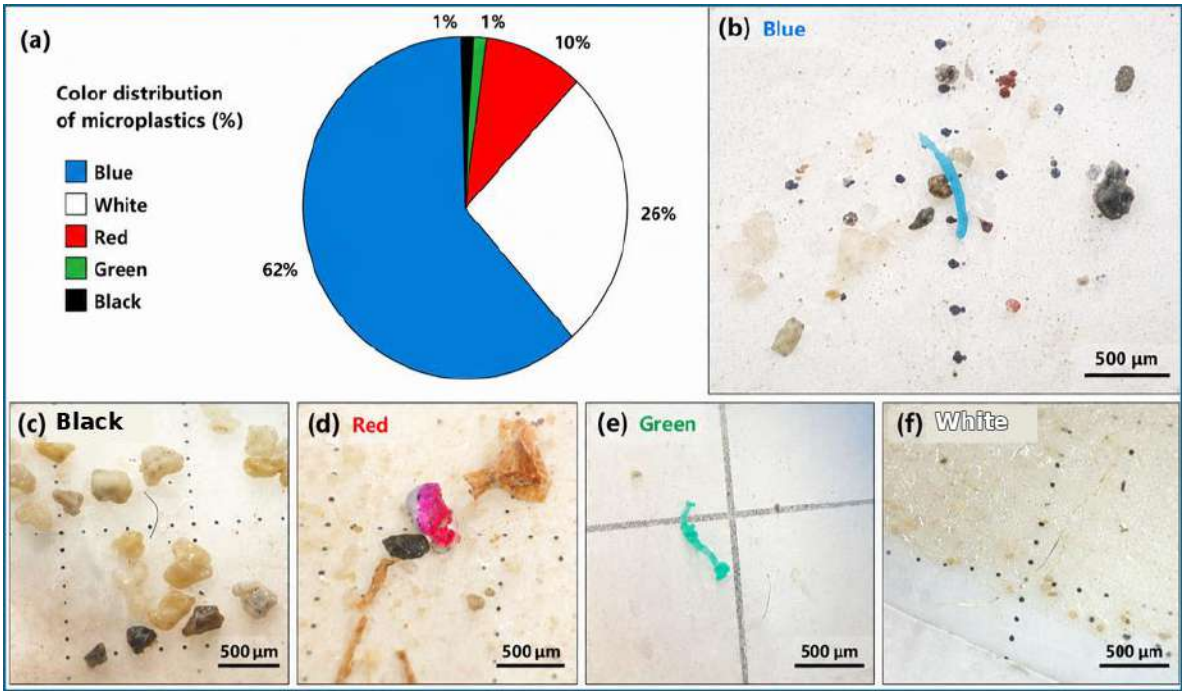

Fig. 4: Percentage color distribution and representative microphotographs of microplastics identified on urban beaches of San Antero. (a) Relative abundance of particles according to color classification; (b–f) representative microscopic images of blue, black, red, green, and white microplastics, respectively

beaches and alternative marine habitats, pointing to potential contributions from fishing, industrial, and urban activities (Nchimbi *et al*., 2022). The color of microplastics can play an important role in their interaction with marine fauna. Numerous species rely on visual stimuli to locate and select food. Particles with certain hues can be mistaken for prey or organic material, increasing the likelihood of accidental ingestion (Thompson *et al*., 2024). The elevated prevalence of blue and white microplastics documented across the beaches of San Antero likely heightens the vulnerability of resident benthic organisms, fish, and invertebrates populations within these coastal ecosystems. Polymeric characterization by FTIR analysis allowed the chemical composition of the recovered microplastic particles to be identified, confirming the predominance of two polymer types: polyethylene terephthalate (PET) and polypropylene (PP). Among the 15 representative particles analyzed by FTIR, PET accounted for 67%, whereas PP represented the remaining 33% (Fig. 5a). The higher relative abundance of PET is likely linked to its widespread utilization in beverage containers, food packaging, and synthetic textiles, which are recognized as primary contributors to secondary microplastic generation in aquatic ecosystems. FTIR spectrum corresponding to PET (Fig. 5b) exhibited characteristic absorption bands associated with polyester-based polymeric materials. Among the most representative signals, the stretching vibration of the ester carbonyl (carbon–oxygen double bond-C=O) group at approximately 1715 /cm was identified, which is considered a diagnostic band for this polymer. The bands located at 2960–2900 /cm were attributed to the stretching vibrations of aliphatic C–hydrogen (H) bonds in methylene ($–CH_2–$) groups, while the band near 1405 /cm was related to

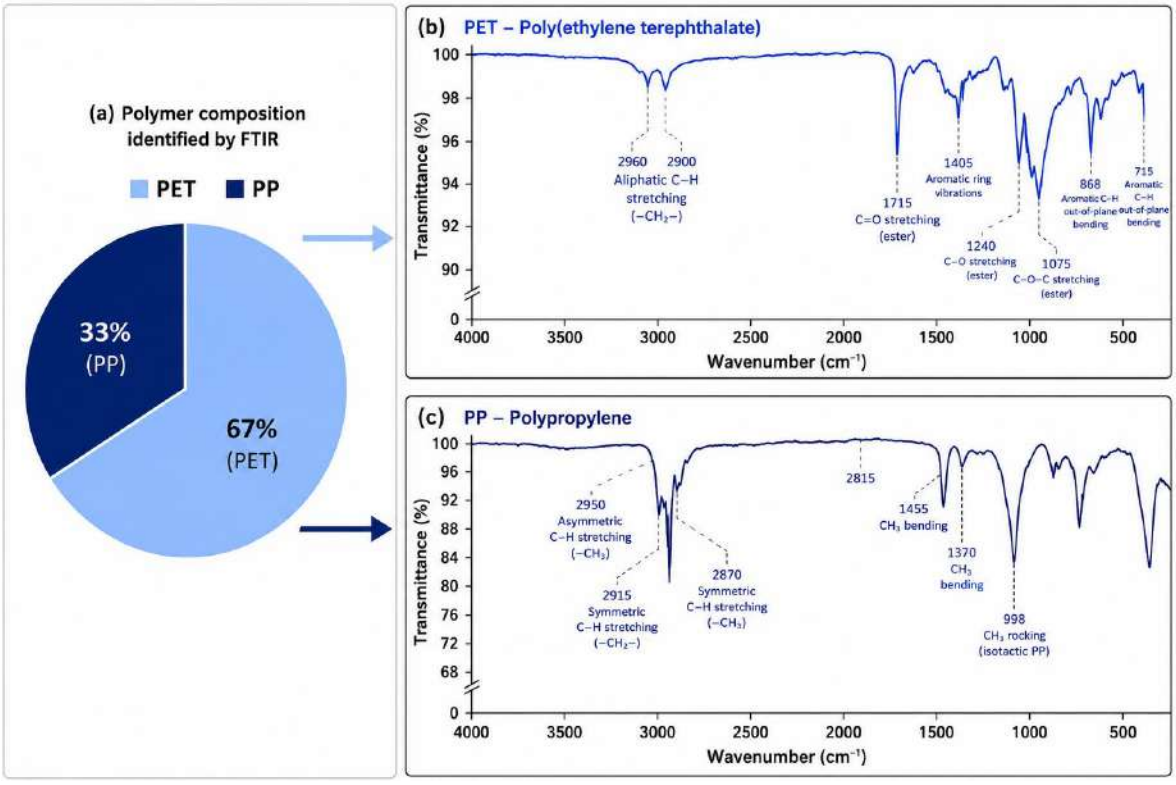

Fig. 5: Percentage distribution and FTIR characterization of the identified microplastics: (a) relative abundance of PET and PP polymers, (b) FTIR spectrum corresponding to PET, and (c) FTIR spectrum corresponding to PP

aromatic ring vibrations present in the PET structure. The bands observed at 1240 and 1075 cm^{-1} corresponded to C–O and C–O–C stretching vibrations associated with ester bonds, whereas the signals detected around 868 and 715 /cm were assigned to aromatic C–H out-of-plane bending vibrations. The combined presence of these functional groups confirmed that the analyzed particles were PET. The spectrum obtained for PP showed the absorption pattern characteristic of a polyolefin structure (Fig. 5c). The signals located around 2950, 2915, 2870 and 2815 /cm were associated with the symmetric and asymmetric stretching vibrations of methyl (-CH_3) and CH_2 groups present in the PP hydrocarbon chain. The bands near 1455 and 1370 /cm corresponded to deformation vibrations of the CH_3 group, used as characteristic signals for the identification of this polymer. The set of bands observed was consistent with the chemical structure of PP. While FTIR analysis verified the primary polymers present in the tested subset, the broader microplastic population may comprise additional polymers—such as polyethylene, polyamide, or nylon—that were unrepresented within that sample. The frequent detection of PET and PP in aquatic ecosystems has been linked to their high production volumes, the diversity of products in which they are used, and their persistence once released into the environment (Defontaine *et al.*, 2020; Campanale *et al.*, 2020).

The PET is among the most extensively manufactured plastic materials worldwide and, consequently, one of the most frequently identified polymers in aquatic and coastal habitats

(Thompson *et al.*, 2024). Their elevated prevalence within the sediments of San Antero indicates a substantial influence from municipal waste and recreational activities along the coastal zone. Conversely, PP is extensively utilized in a multitude of everyday and marine applications, such as ropes, fishing nets, bottle caps, and storage containers. Its low density enhances buoyancy, enabling particles to stay afloat at the water's surface while being transported by ocean currents. This high mobility facilitates their subsequent transport and deposition in coastal regions situated far from their original source (Nchimbi *et al.*, 2022). The identification of PET and PP within the representative subset analyzed by FTIR is consistent with findings in coastal ecosystems in Asia, Africa, and Europe, where both polymers frequently appear among the predominant materials (Nchimbi *et al.*, 2022; Thompson *et al.*, 2024; Ilechukwu *et al.*, 2025). In addition to their widespread use, the environmental persistence of PET and PP is influenced by their physicochemical properties. PET demonstrates robust mechanical resilience and resistance to natural degradation, promoting its prolonged accumulation within coastal sediments, whereas the reduced density of PP facilitates its transport by coastal currents prior to final deposition. The continuous input of these polymers from local anthropogenic activities, together with their distinct environmental behavior, may contribute to their widespread occurrence across the studied beaches.

Comparison with other studies

The abundance of microplastics recorded on the beaches of San Antero was within the range reported for coastal ecosystems in Latin America (Table 1), although it was higher than those observed in several locations in Brazil, Mexico, Cuba, Costa Rica, and Peru (Castro *et al.*, 2020; Álvarez-Zeferino *et al.*, 2020; Zarate and Iannacone, 2021; Madureira *et al.*, 2025; García-Varens *et al.*, 2025). These spatial variations may be attributed to differences in anthropogenic activity levels along coastal zones, alongside oceanographic and geomorphological drivers that govern the transport, retention, and accumulation of microplastics within sedimentary deposits. Methodological differences among studies, including sampling depth, sediment mass, particle size detection limits, extraction procedures, identification techniques, and reporting units, may contribute to the variability observed across regions. Compared with other studies conducted in Colombia, the pollution levels observed in San Antero were lower than those reported for Cispatá Bay and the beaches of Caño Dulce and Puerto Velero but higher than those recorded in Buenaventura Bay (Pertuz and Vizcaíno, 2020; Vásquez *et al.*, 2021; Garcés-Ordóñez *et al.*, 2022). Conversely, the findings demonstrated a closer alignment with those documented for San Andrés Island (Garcés-Ordóñez *et al.*, 2020a). Overall, this comparison demonstrates that Colombian coastal ecosystems exhibit considerable variability in microplastic abundance, likely associated with differences in tourism pressure, fishing activities, proximity to urban areas, and inputs from land-based sources. Regarding morphological distribution, the predominance of fibers documented in San Antero aligns closely with findings from across Colombia and other Latin American countries, where this category constitutes one of the most prevalent forms of microplastics recovered from coastal sediments (Pertuz and Vizcaíno, 2020; Vásquez *et al.*, 2021; Garcés-Ordóñez *et al.*, 2022). Some locations have reported a higher abundance of fragments or pellets, reflecting differences in the main pollution sources and plastic waste degradation processes. The elevated concentration of fibers detected in San Antero likely points to inputs from fishing operations and urban discharges—specifically

Table 1: Comparison of microplastic abundances recorded on San Antero beaches with microplastic abundances reported in Latin America

Location	Country	MPs/kg	Predominant morphology	Source
Beaches of the Jurujuba and Itaipu Embayments,	Brazil	138.4	Fragment and fibers	Castro *et al*., (2020)
Playa del estado de Sinaloa	México	545.8	Fragmentos rígidos (92%)	Álvarez-Zeferino *et al*., (2020)
Tetas de Tomasa	Cuba	23.3	Fragment (55%)	García-Varens *et al*., (2025)
Beaches of the Caribbean coast of Limón	Costa Rica	70.3	Pellets	Madureira *et al*., (2025)
Sandy beaches on the central coast	Peru	202	Fragment and fibers	Zarate and Iannacone, (2021)
San Andrés Islas	Colombia	1109	Fragmentos	Garcés- Ordoñez *et al*., (2020b)
Playas de Caño Dulce y Puerto Velero	Colombia	1496	Fiber	Pertuz and Vizcaino, (2020)
Bahía de Buenaventura	Colombia	277.3	Fiber and Fragment	Vásquez *et al*., (2021)
Bahía de Cispata	Colombia	1825	Filamentos	Garcés- Ordóñez *et al*., (2022)
Playas de San Antero	Colombia	864	Fibras	This study

those linked to synthetic textiles, cordage, and fishing equipment—which are widely acknowledged as primary contributors to microplastic generation in marine and coastal habitats.

Risk assessment of microplastic pollution

Table 2 presents the results of the microplastic contamination risk assessment using the CF, PLI, MPPI, CMPI, MSCI, PERI, and PRI indices. The integrated evaluation of these indicators enabled a comprehensive assessment of particle abundance, contamination intensity, ecological risk, predominant morphology, polymer-associated hazards, and the potential contribution of diverse sources. This evaluation broadens the scope of data acquired via conventional methodologies, which traditionally concentrate exclusively on microplastic abundance (Ranjani *et al*., 2021; Ilechukwu *et al*., 2025). CF values ranged from 1.00 to 2.63, with differences observed among seasons, coastal zones, and sampling sites. The highest value was recorded during the rainy season (CF = 2.63). Puerto beach had a CF of 1.96, and the supralittoral zone had a CF of 1.75. These findings demonstrate an enhanced accumulation of microplastics under precipitation- conditions associated with rainfall and within specific coastal zones of the beach. Runoff, drainage discharges, coastal dynamics, and anthropogenic activities could contribute to the transport and retention of particles in coastal sediments. Temporal fluctuations in microplastic abundance are frequently governed by hydrological dynamics that drive the land-to-sea transport of particulate matter into marine environments. PLI values were 1.49 for weather stations, 1.62 for coastal areas, and 1.61 for beaches, with an overall value of 1.57. All conditions evaluated fell into the low pollution category established for PLI values below 10 (Li *et al*., 2020; Ranjani *et al*., 2021). On the sandy beaches of Okinawa-Japan, PLI values ranging from 1.93 to 8.4 were recorded, also classified as low levels of pollution despite the continued presence of microplastics (Ilechukwu *et al*., 2025). The recreational beaches of Patenga and Parki, in the northern Bay of Bengal, had values of 1.66 and 1.43, respectively. These findings indicate that the PLI represents a relative measure of contamination rather than an explicit evaluation of ecological safety on its own (Bappy *et al*., 2025). MPPI values ranged from 0.53 to 1.39, meaning that all conditions evaluated were classified as having very low abundance. This trend aligns with results derived from the PLI, pointing to a comparatively modest accumulation level relative to coastal zones experiencing higher anthropogenic pressure. Low MPPI values were also reported on the beaches of Okinawa (Ilechukwu *et al*., 2025). In contrast, the beaches of Patenga and Parki exhibited a different profile, recording values exceeding 25 that were linked to

Table 2: Microplastic pollution risk assessment based on CF, PLI, MPPI, CMPI and MSCI indices in sandy beaches of San Antero, Colombian Caribbean

Assessment scale	Category	MPs/kg	CF	PLI	PLI category	MPPI	MPPI category	PERI	PERI category	PRI	PRI category	MSCI	MSCI category	CMPI	CMPI category
Season	Rainy	1392	2.63	1.62	Low	1.39	Very low	7.92	Low ecological risk	4.88	Low risk	–	–	–	–
	Transition	530	1.00	1.00	Low	0.53	Very low	3.01	Low ecological risk	3.01	Low risk	–	–	–	–
	Dry	670	1.26	1.12	Low	0.67	Very low	3.79	Low ecological risk	3.37	Low risk	–	–	–	–
Coastal zone	Supralittoral	927	1.75	1.32	Low	0.93	Very low	5.27	Low ecological risk	3.97	Low risk	–	–	–	–
	Mesolittoral	751	1.42	1.19	Low	0.75	Very low	4.27	Low ecological risk	3.58	Low risk	–	–	–	–
	Infralittoral	914	1.72	1.31	Low	0.91	Very low	5.18	Low ecological risk	3.94	Low risk	–	–	–	–
Beach	Blanca	743	1.40	1.18	Low	0.74	Very low	4.21	Low ecological risk	3.55	Low risk	0.749	High	–	–
	Bucanero	810	1.53	1.24	Low	0.81	Very low	4.60	Low ecological risk	3.73	Low risk	0.776	Very high	–	–
	Puerto	1039	1.96	1.40	Low	1.04	Very low	5.90	Low ecological risk	4.21	Low risk	0.864	Very high	–	–
Morphology	Fiber	96%	–	–	–	–	–	–	–	–	–	–	–	0.96	Extreme
	Fragment	4%	–	–	–	–	–	–	–	–	–	–	–	0.04	Minimum

intense tourism, maritime operations, and inadequate plastic waste management (Bappy *et al*., 2025). CMPI incorporated particle morphology as an indicator of the relative predominance of different microplastic shapes, complementing abundance-based indices. Fibers reached a CMPI value of 0.96, reflecting their predominance among the recovered particles, whereas fragments showed a value of 0.04. These results describe morphological composition rather than direct environmental impact. CMPI should be construed as a supplementary metric reflecting morphological dominance rather than an independent assessment of ecological consequence (Ilechukwu *et al*., 2025; Bappy *et al*., 2025). MSCI values ranged from 0.749 to 0.864, indicating stronger signatures of anthropogenic influence and source-related patterns. Puerto beach had the highest value (MSCI = 0.864), followed by Bucanero (MSCI = 0.776) and Blanca beach (MSCI = 0.749). Fishing activities, tourism pressure, urban inputs, and rainfall-driven transport could all contribute to this pattern; however, the methodology employed does not allow the relative contribution of each potential source to be quantified. The MSCI supplied valuable insights regarding potential contamination sources that remain undetected by indices derived exclusively from particle abundance. The PERI ranged from 3.01 to 7.92, indicating a low ecological risk under all evaluated conditions. Peak values were documented during the rainy season—an interval characterized by an elevated abundance of microplastics and

increased pollution factor metrics. The PRI ranged from 3.01 to 4.88 and remained within the low-risk category. The results of both indices were influenced by the predominance of PET and PP, polymers with hazard scores lower than those assigned to materials such as polyvinyl chloride (PVC). The abundance indices and those associated with polymer type indicated a low ecological risk. The MSCI and CMPI values depicted an alternative scenario defined by substantial anthropogenic inputs and a pronounced abundance of fibers within the evaluated samples. It is important to emphasize that the assessed indices yield complementary insights into various dimensions of microplastic contamination. PERI and PRI primarily reflect the ecological hazard associated with polymer composition and contamination levels, which remained low due to the predominance of PET and PP, polymers assigned relatively low hazard scores. Conversely, the MSCI and CMPI delineate the magnitude of human impact and the dominance of specific particle morphologies rather than evaluating ecological risk per se. Therefore, the low ecological risk identified in this study should not be interpreted as the absence of anthropogenic pressure, but rather as evidence that continuous microplastic inputs occur under conditions currently dominated by polymers with comparatively lower hazard potential. The spatial and temporal dynamics documented herein carry significant implications for the sustainable management and conservation of tropical urban beaches. Greater microplastic accumulation during the rainy season and in the supralittoral zone identifies priority periods and areas for environmental monitoring, beach cleanup, and coastal management strategies. The high prevalence of PET and PP, combined with persistent anthropogenic inputs indicated by MSCI values, underscores the critical need for enhanced preventive strategies to mitigate plastic debris generated by coastal tourism, urban development, and small-scale fisheries. Incorporating these findings into long-term monitoring programs and coastal management strategies could contribute to reducing microplastic inputs to tropical urban beaches. Considering that the studied beaches support recreational activities and resources of importance to local communities, the continuous presence of microplastics may also have implications beyond ecological risk. Microplastics can be ingested by marine organisms and act as carriers of associated contaminants, creating potential pathways for human exposure through seafood consumption. Furthermore, while recreational users may experience direct exposure to sedimentary microplastics, the precise magnitude of these exposure pathways remains unquantified in the present study. These findings highlight the importance of maintaining environmental monitoring and developing integrated risk assessments that consider both ecosystem and human health perspectives (Prata *et al.,* 2020).

Limitations and future recommendations

Although the present study provides novel information on microplastic pollution in urban beaches of the Colombian Caribbean, several methodological limitations should be considered. While providing a robust regional evaluation under specific environmental parameters across five monitoring campaigns, the sampling design implemented across the three urban beaches does not account for interannual fluctuations. Direct hydrodynamic measurements and source-tracking analyses were beyond the scope of the investigation; therefore, potential anthropogenic sources were inferred from particle characteristics, polymer composition, and complementary assessment indices. While FTIR was employed to identify polymers within a

representative particle subset, subsequent density separation using saturated NaCl potentially constrained the recovery rates of higher-density plastic types. Additional methodological improvements should include recovery assays using certified reference microplastics to quantify extraction efficiency and improve the robustness and comparability of environmental assessments. Future research should expand ecological risk assessments by incorporating biological exposure, trophic transfer, bioavailability, and microplastic-associated contaminants, including trace metals, persistent organic pollutants, and plastic additives. To quantify the relative impacts of environmental and anthropogenic forces and to further validate the proposed MSCI under varying regimes, subsequent research must integrate nanoplastic analysis, hydrodynamic and GIS modeling, advanced source attribution, and extended spatial-temporal monitoring. Complementary management actions, including community-based environmental education initiatives and long-term monitoring programs, could further contribute to reducing plastic inputs and mitigating anthropogenic pressures on these coastal ecosystems.

CONCLUSION

Microplastic pollution on urban beaches of the Colombian Caribbean showed spatial and seasonal variations associated with the interaction of climatic conditions, coastal dynamics, and anthropogenic activities. The ubiquitous presence of microplastics along the San Antero coastline—coupled with the predominance of fibers, PET, and PP identified via ATR-FTIR analysis—points to a high prevalence of secondary microplastics originating mainly from fishing operations, tourism, synthetic materials use, and deficient waste management practices. Integrated application of pollution, ecological risk, morphology, and source contribution indices (PLI, MPPI, PERI, PRI, CMPI, and MSCI) enabled a more comprehensive interpretation of microplastic contamination. Although conventional indices indicated low pollution levels and limited ecological risk, CMPI and MSCI results revealed persistent anthropogenic pressure associated with fiber accumulation and continuous plastic inputs. These findings highlight that microplastic risk assessment must extend beyond particle abundance alone to integrate particle abundance by incorporating particle morphology, polymeric properties, and origin-specific indicators. Integration of these complementary lines of evidence demonstrates that reliable environmental assessment requires consideration of both quantitative and qualitative characteristics of microplastics, thereby improving identification of contamination patterns and anthropogenic pressures that may remain undetected when particle abundance is used as the sole evaluation criterion. The insights derived from this study advance current knowledge regarding microplastic dynamics in tropical urban beach ecosystems, emphasizing the interactive roles of terrestrial inputs, tourism, fishing operations, and coastal hydrodynamic processes. Simultaneous evaluation of spatial distribution, seasonal variability, polymer composition, morphological characteristics, ecological risk, and source contribution provided a broader understanding of contamination processes and strengthened interpretation of the environmental factors controlling microplastic accumulation in urban coastal environments. Furthermore, these findings help bridge the existing data gap concerning urban beaches in the Colombian Caribbean, where multi-indicator integrated assessments remain scarce despite mounting concern over plastic pollution in tropical marine ecosystems. Knowledge generated through this investigation therefore provides a valuable

scientific baseline for future comparative studies and long-term environmental assessments throughout the Caribbean region. While the integrated assessment framework established herein offers a valuable reference for future investigations in tropical coastal settings, broader application necessitates further validation, particularly regarding the proposed MSCI. Application of comparable multidisciplinary approaches could improve consistency among studies, facilitate regional comparisons, and strengthen the evidence required for environmental policies and coastal management programs. The resulting evidence can inform the design of source-specific mitigation strategies, enhanced plastic waste management protocols, and sustained monitoring initiatives aimed at curbing microplastic accumulation across Caribbean coastal ecosystems through coordinated policy and stakeholder engagement.

AUTHOR CONTRIBUTIONS

J. Pinedo-Hernández, the corresponding author, supervised the research and participated in the data analysis, interpretation of the results, and writing of the manuscript. M. Mogollón-Arismendy contributed to the preparation of most tables and figures and assisted in the writing of the manuscript. A. Hernandez-Martínez participated in the development of the research proposal, was responsible for the experimental work and critically revised the manuscript. F. Fuentes-Gandara, supervised the study, contributed to the interpretation of the results, and participated in manuscript preparation.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
<	Less than
>	Greater than
≥	Greater than or equal to
°	Degrees
′	Minutes
″	Seconds
–CH_2–	Methylene
–CH_3	methyl
/cm	Per centimeter
µm	micrometer
ΣMPs	Total number of identified microplastic particles
ATR	Attenuated total reflectance
°C	Degrees Celsius
C	Contribution of the dominant color
C=O	Carbon–oxygen double bond
C_{Bm}	Background concentration.
CF	Contamination factor
CP	contamination pressure
C_m	Concentration of microplastics
CMPI	Coefficient of microplastic impact
Eq.	Equation
E_i	Ecological risk factor
g	Grams
Fig.	Figure
FTIR	Fourier Transform Infrared Spectroscopy
H	Hydrogen
h	Hour
km^2	Square kilometer
GLMM	Generalized linear mixed model
MDII	Microplastic diversity integrated index
Min	Minute
mL	Milliter
mm	Millimeter
MPPI	Microplastic pollution index
MPs/kg	microplastic particles per kilogram
Mt	Million tons
Mt/y	Million tons per year
N	North
n	Total number of evaluated groups
NaCl	Sodium chloride
MΩ·cm	Megaohm-centimeter
MSCI	Microplastic source contribution index
p	P value
P	Proportion of the predominant polymer
PERI	Potential ecological risk index
PET	Polyethylene terephthalate
PHI_i	Polymer hazard index
P_i	Total microplastic abundance
PLI_j	Pollution load index
PLI	Pollution load index
PP	Polypropylene
PRI	Pollution Risk Index
P_t	Abundance of a specific polymer type
PVC	Polyvinyl chloride
S	Hazard score
TRF	The toxic response factor
W	West
χ^2	Chi-square statistic

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ORIGINAL RESEARCH ARTICLE

Exploring the factors influencing community adaptations to coastal flooding using the adaptive capacity framework

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ABSTRACT

BACKGROUND AND OBJECTIVES: Impacts of coastal flooding driven by climate change are intensifying worldwide. Significant efforts have been made across levels to help affected communities adapt to unpredictable changes. Institutional disaster management frameworks consistently overlook the inherent adaptive capacities of these localized communities. The study objectives were to explore the factors that shape community resilience and drive its responses to environmental changes by focusing on Tambak Lorok, the largest and most vulnerable fishing community in Central Java, Indonesia. The primary contribution of this study is the application of the adaptive capacity framework to examine the determinants of localized adaptation, paired with a spatial visualization of how these capacities are distributed across different neighborhoods.

METHODS: To collect data, this study employed face-to-face questionnaires, field observations, unstructured interviews, and document reviews. The data gathered were analyzed using Multinomial Logistic Regression and Principal Component Analysis with International Business Machines' Statistical Package for Social Sciences version 31. A simple random sampling design was employed, yielding a final sample size of 181 respondents. To elucidate the determinants of community-level responses to coastal flooding, this study operationalized the adaptive capacity framework, evaluating its five core dimensions: agency, assets, social capital, institutions, and local knowledge.

FINDINGS: The findings revealed four adaptive capacity typologies representing community resilience across the five neighborhoods of Tambak Lorok: attentive observers, cultural stewards, social activists, and self-assured individuals. Among these categories, cultural stewards, who possess strong local knowledge but lack access to credit, tend to take no action in response to coastal flooding. The majority of respondents were categorized as 'attentive observers,' a cohort characterized by a high propensity for financial saving, active engagement in decision-making, frequent information sharing, and strong leadership capabilities. Despite receiving minimal institutional support, these individuals demonstrate the ability to promote in situ adaptations. Additionally, the study further found that agency (B=-4.206, p<.005) and access to credit (B=3.453, p<.005) significantly influence communities' adaptations, yet with different directions.

CONCLUSION: Elucidating the adaptive capacity of vulnerable populations enables policymakers to discern specific facilitators of and barriers to effective coastal flooding adaptation, thereby informing the design of targeted interventions to foster community resilience.

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63	5	5

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INTRODUCTION

Climate change, exacerbated by human activity, is expected to intensify natural disasters, particularly affecting coastal communities in low-lying areas. Socio-ecological vulnerabilities in these areas are exacerbated by sea-level rise, severe weather anomalies, and saltwater intrusion—drivers that simultaneously jeopardize potable water reserves and degrade biophysical protective barriers. Rapid urbanization and population growth heighten these vulnerabilities (Monioudi *et al*., 2025; Nicholls *et al.*, 2007; Saha *et al*., 2024; UNDP, 2010), particularly in developing countries (Saha *et al*., 2024). For instance, consecutive cyclones in Bangladesh in 2007 and 2009 resulted in 3,406 deaths and over 55,000 injuries (Kabir *et al.,* 2016), while Indonesia experiences significant flood disasters, impacting agriculture, fisheries, and tourism (Monioudi *et al.,* 2025). In Indonesia, nearly 70 percent (%) of its total populations reside across its 81,000 kilometers (km) coastline (PAIR, 2026), making them susceptible to unprecedented threats from climate events. To address these systemic challenges, targeted state interventions are required to bolster community-level adaptive capacity. Drawing from established frameworks, this capacity entails both the proactive ability to adapt to anticipated damages (Adger, 2006; Bennett *et al*., 2014; Galappaththi *et al*., 2019) and the reactive resilience to withstand disaster impacts (IPCC, 2019). Integrating disaster management policies with a nuanced understanding of the community's adaptive capacity can improve resilience. Gaining insights into these dimensions can be facilitated through targeted research focused on communities' experiences of natural disasters that shape their perceptions (Ngo *et al*., 2020) and disaster responses. By adopting a perception-based approach, policymakers can gain a comprehensive understanding of the impacts, the adaptation strategies in place (Llausàs and Nogué, 2012), and the factors that hinder local adaptations from the perspectives of the at-risk communities (Pyhälä *et al*., 2016). Adaptive capacity serves as a foundational prerequisite for effective adaptation, encompassing an intersection of social, economic, and biophysical determinants. These factors collectively enable individuals to execute proactive responses across all phases of a disaster lifecycle—specifically pre-disaster preparation, active crisis response, and post-disaster recovery (Chapagain *et al*., 2025; Galappaththi *et al*., 2019). This term refers to the ability of a system, institution, or organism to adapt to potential threats, anticipate changes (Adger, 2006; Bennett *et al*., 2014; Galappaththi *et al*., 2019), and respond effectively to disaster impacts (IPCC, 2019). Various dimensions of adaptive capacity have been delineated in literature; specifically, Barceló *et al*. (2025) proposed a five-dimensional model: 1) agency is defined as the capacity of an individual to act as an autonomous agent of change; 2) assets, which refer to access to various livelihood resources; 3) social capital, a dimension intrinsically linked to civic engagement, institutional leadership, collective decision-making, and information exchange; 4) institutions, which highlights the interactions with agencies and government programs; and 5) local knowledge (Barceló *et al.*, 2025), described as collective knowledge derived from observations, experiences, lessons learned, and expertise passed down through generations (Galappaththi *et al.,* 2019). Disparities in adaptive capacity systematically exacerbate localized vulnerabilities, ultimately leading to divergent and unequal resilience outcomes. For instance, smallholder farmers in Rwanda showed varying abilities to adapt to uncertainties. Those without access to national crop intensification programs and lands struggled to effectively respond to those events (Kabir *et al.,* 2016). In the context of India and Pakistan, extended or joint family structures characterized by pooled labor resources, land

tenure, and intergenerational knowledge transmission—exhibit greater systemic resilience compared to their nuclear counterparts (Nixon *et al*., 2023). Coastal communities need a range of protective measures to become more resilient. These measures can be categorized into five types: 1) hard strategies, which use permanent structures to protect critical infrastructure; 2) soft strategies, which leverage natural processes; 3) accommodation strategies, which involve behavioral modifications; 4) retreat strategies, which involve relocations; and 5) attack strategies, which focus on extending the coastline seaward (Lee, 2014). On an individual scale, adaptive behaviors encompass both financial risk-mitigation strategies, such as insurance acquisition, and information-seeking patterns, including the monitoring of weather forecasts to evaluate environmental hazards. These responses are typically influenced by personal experiences with the environment, which then shape how they perceive it. The interplay between the environment, perceptions, and adaptations has been illustrated by Christiaanse and Haartsen (2020). Respectively, changes in the environment are interpreted based on the meanings individuals ascribe to their place. Subsequent evaluation of these impacts initiates a secondary interpretive process, wherein individuals formulate coping attitudes conditioned by their social capital and self-efficacy. The outcome defines the final responses to those changes. Evaluations of environmental changes are cyclical and contingent upon the effects of prior responses. For instance, if individual perceptions of impact align with perceptions of collective actions, they may be encouraged to engage in community efforts, which in turn enhance place meaning (Christiaanse and Haartsen, 2020). Extending beyond the mere recognition of environmental shifts, an individual's perception of risk constitutes a critical determinant in predicting adaptive actions amid hazardous events (Lindell and Hwang, 2008; Perry and Lindell, 1990; Terpstra and Lindell, 2013; Wei and Lindell, 2017). Risk perceptions often arise from a complex social-psychological process, encompassing cognition, personal experiences, social and cultural factors, and demographic traits (Ngo *et al.,* 2020; van der Linden, 2015). This study examines Tambak Lorok, the largest fishing community in Semarang, Central Java, which has chosen to remain in its high-risk area despite escalating risks posed by coastal flooding. This decision was profoundly shaped by the population's deeply rooted place attachment and their foundational socio-ecological dependency on the marine environment. To protect the community from coastal flooding, the government has built sea walls and installed breakwaters; however, these measures may disrupt beach ecosystems, alter the migration routes of marine creatures, and change beach morphology (Sanitwong-Na-Ayutthaya *et al*., 2023). Current climate adaptation policies remain structurally incomplete; they are neither informed by empirical assessments of community adaptive capacity nor supported by the rigorous development regulations necessary to counter land subsidence. This oversight is particularly concerning, considering Tambaklorok's designation as a maritime village and a traditional fish landing port. This situation is also compounded by the sectoral ego of the National Development Planning Agency and the Ministry of Environment and Forestry, resulting in ineffective implementations of adaptation policies. Discrepancies in their adaptation policies are evident in planning, financing, vulnerability assessment, and actions (Apresian, 2025), highlighting the inadequacy of the existing coastal management and institutional frameworks in building community resilience. The body of literature dedicated to identifying the underlying factors that drive or constrain adaptation strategies has grown substantially in recent decades. Some studies found that limited access

to public services affected the risk perceptions of fishing communities in Cauca, Colombia, ultimately acting as a barrier to effective adaptations (Eitzinger *et al.*, 2018). In the United States, local perceptions of benefits from Natural Infrastructure (NI) implemented in other areas influenced community decisions to adopt the same measures (Kochnower *et al.,* 2015). Furthermore, indigenous ecological knowledge significantly influenced the community's decision to undertake mangrove rehabilitation within the Village of Tongke-Tongke (Ali *et al*., 2022; Ketaren *et al.,* 2026). However, research on community adaptive capacity and its effects on adaptation remains limited (Wong-Parodi *et al.*, 2024), with previous studies mainly focusing on socio-demographic factors as predictors of disaster responses. For instance, Christian *et al.* (2021) found that women and individuals with a college education are more likely to underestimate their vulnerability, compared to males and those with no education. Consequently, such a disposition may impede the adoption of proactive disaster response strategies. Research also found that gender significantly influences risk reduction efforts in Kurigram, Bangladesh (Rakib *et al.*, 2017). Additionally, studies on adaptive capacity often focus on singular indicators, such as assets (Chapagain *et al.,* 2025) or governance capacity (Alfian *et al.,* 2026), rather than investigating multiple indicators. Furthermore, existing literature frequently overlooks context-specific nuances, demonstrating a distinct scarcity of empirical insights derived from localized perspectives in the Global South (Chapagain *et al.*, 2025). Among the research addressing multiple indicators of adaptive capacity and their effects on community responses is the work of Barceló *et al.* (2025). These scholars identified three types of adaptive capacity within fishing communities along the coast of Southern Chile and the potential of indicators in motivating responses to a hypothetical decline in income due to climate change. Although the existing framework provides a robust mechanism for evaluating adaptive capacity, the present study advances this research by visualizing the geographical distribution of these capacity typologies at the neighborhood level. Those maps should allow policymakers to better understand the varying adaptive capacities of each neighborhood and to design appropriate interventions to overcome barriers to adaptation. The distinct contribution of this study is twofold: it evaluates the precise effects of adaptive capacity indicators on coastal community responses and visually maps the geographical distribution of the resulting capacity typologies at the neighborhood level. Moreover, previous studies taking place in Tambak Lorok have largely concentrated on topics other than adaptive capacity, such as relocation and the impacts of developments and flooding on local livelihoods. In light of the identified research gap and the escalating challenges of climate change, this study investigates two primary research questions: first, how the distinct dimensions of adaptive capacity influence the Tambak Lorok community's responses to coastal flooding; and second, what specific factors determine these responses. Data were gathered through surveys with 181 residents, field observations, unstructured interviews, and document reviews, and analyzed with multinomial logistic regression (MLR) and principal component analysis (PCA). The findings indicate that "agency" and "access to credits" serve as pivotal determinants of local adaptation strategies. Using the adaptive capacity framework of Barceló *et al.* (2025), the study further identified four categories of individuals, each exhibiting varying levels and quality of adaptive capacity. Multiple adaptive capacity indicators influence local responses, demonstrating divergent directions of effects. The "attentive observers" typology, which is prominent in this area, demonstrates strong assets and social capital along with moderate agency and local knowledge. This typology

consistently fosters proactive adaptations strategies, even in environments characterized by relatively weak institutional support. Conversely, local knowledge exerts a negligible influence on community responses, suggesting a critical disconnect that may serve as a barrier to long-term adaptive efficacy. The study aims to explore the factors that shape community resilience and drive its responses to environmental changes. It was conducted in Tambak Lorok, Semarang, Indonesia, in 2025 and 2026.

MATERIALS AND METHODS

Study area

Tambak Lorok, located in North Semarang and bordered by the Java Sea, covers about 84.48 hectares (ha). It has two major neighborhoods: Tambakmulyo (neighborhood units 12-15) in the west and Tambarejo (neighborhood unit 16) in the east (Fig. 1). As of 2019, its population was nearly 7,791 (1,931 households) (Kistanto, 2019), comprising 1,295 residents in neighborhood unit 12, 1,417 residents in neighborhood unit 13, 2,098 residents in neighborhood unit 14, 2,000 residents in neighborhood unit 15, and 981 residents in neighborhood unit 16. Reportedly, 38% households currently live below the poverty line. Most residents have completed junior high school, and 80% work as fishermen. This area was first settled by fishermen from Demak in the 1940s. Since the 1990s, the relocation of the state-owned port enterprise has exacerbated land-use tensions and precipitated ongoing conflicts between local residents and state authorities. Recent developments, including harbor construction, have heightened Tambak Lorok's vulnerability to climate change. Despite residents possessing official land certificates dating back to the 1990s, the state-owned port enterprise imposes land-use restrictions and mandates lease payments, undermining local tenure security. The ongoing construction is exacerbating land subsidence, rendering existing flood measures ineffective in addressing flooding impacts (Fig. 2). In tandem with these issues, the reduction of river channels due to interconnected natural and anthropogenic drivers has strained social cohesion, generating localized conflicts over spatial and environmental resources. The resulting environmental changes have limited traditional fishermen's activities, prompting their call for river revitalization, which requires acquiring land currently occupied by fishponds. Concurrently, aquaculture operators have articulated concerns regarding the ways in which designated fishing routes disrupt localized aquatic habitats.

Sampling and data collection

The study employed simple random sampling to minimize selection bias, ensuring every individual in the population had an equal chance of selection. Given that residents across the five neighborhoods exhibit highly consistent socio-economic and spatial attributes, this specific method was deemed most appropriate for capturing representative data. The targeted sample size ranged from 150 to 370 respondents, suitable for populations under 10,000 (Ahmed, 2024). Data on respondents' evaluations of climate-induced disasters were collected through questionnaires and unstructured interviews. The questionnaire featured a 5-point Likert scale and included both closed- and open-ended questions across four sections: demographics, perceived impacts of environmental changes, types of adaptations, and adaptive capacity, providing comprehensive insights into community perceptions, responses, and resilience (Table 1). Utilizing Google Forms, the survey instrument required approximately 60 minutes (min) for completion, following protocol established by Sharma (2022). Data collection was administered by ten undergraduate students from a local university.

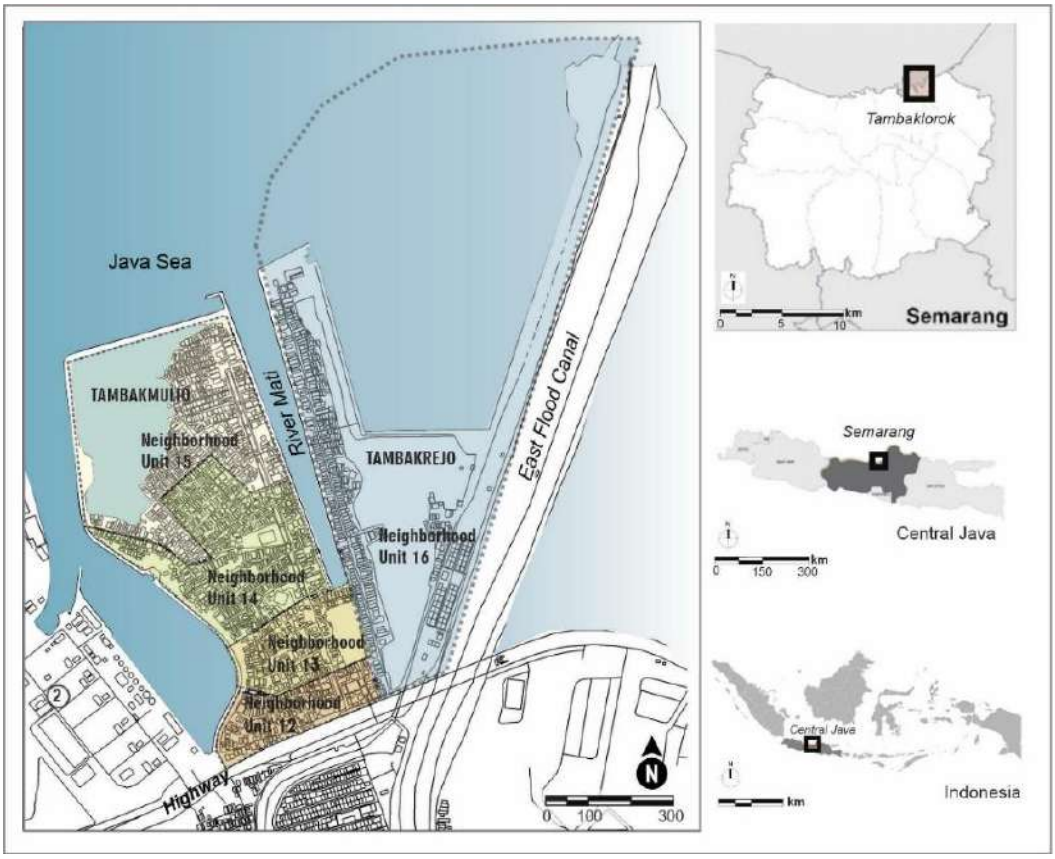

Fig. 1: Geographical location of the study area in Tambak Lorok, Semarang, Indonesia

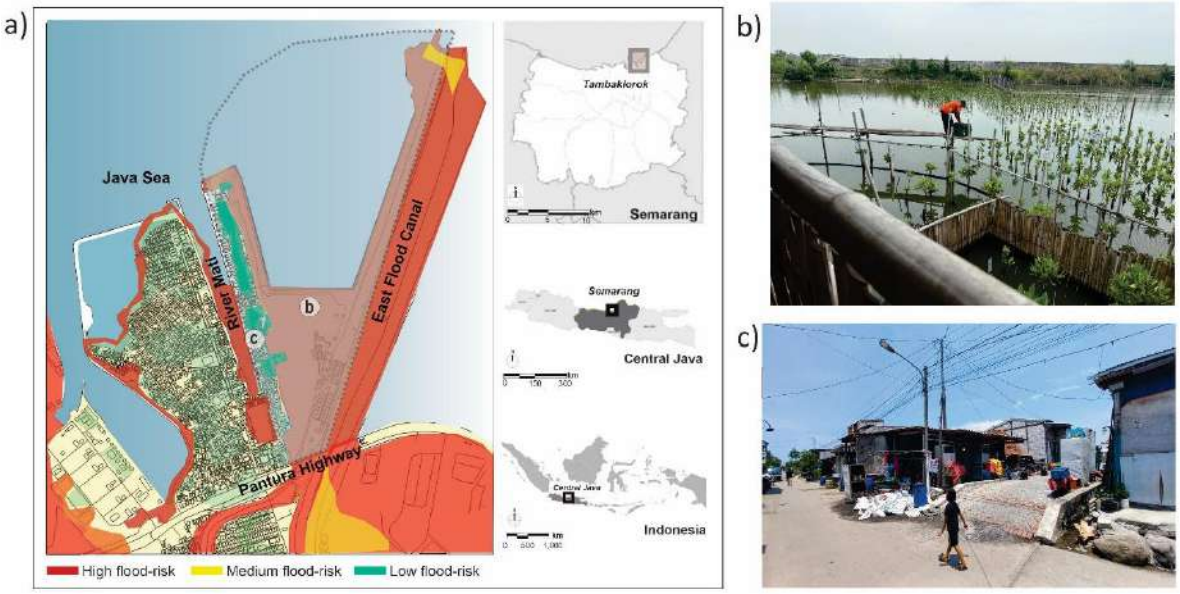

Fig. 2: The land inundation in Tambak Lorok, as surveyed and seen from (a) the flood risk map, (b) an image of an inundated area, converted into a mangrove conservation area, (c) an image of an elevated local street

Table 1: Dimensions and indicators of adaptive capacity

Dimension	Indicator	Questions	Data type
Agency	Agency (Norm_Agcy)	Can my actions be considered changing agents in the productivity of my activities or livelihoods?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
Asset	Occupational multiplicity (Norm_TR_AsOcc)	How many jobs do you currently have?	Continuous
	Access to credit (Norm_AsCre)	How easy is it to access a financial loan in a formal institution?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
	Save money (Norm_AsSav)	How easy is it to save money?	Likert scale (1-5), ordinal (5 categories, very easy-very difficult)
Social capital	Social activities (Norm_TR_SocAc)	How many community activities/associations do you participate in?	Continuous
	Leadership (Norm_SocLead)	In the last 5 years, have you held any representative positions in the community?	Binary (Yes/No)
	Participation in decision making (Norm_SocPart)	Do you agree that you actively participate in the decision-making of your community?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
	Sharing information (Norm_SocInf)	Do you often share valuable information related to livelihoods with your neighbors/community?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
Institutions	Institutional relations (Norm_InsInt)	Do you often coordinate with other entities, such as the government, NGOs, private institutions, or other communities?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
	Institutional funding (Norm_InsFund)	Over the past 5 years, have you received any grants or subsidies from a certain institution?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
	Institutional training (Norm_InsTrn)	Over the past 5 years, have you received any training from a certain institution?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
Local knowledge	Mastering local knowledge (Norm_LKMast)	Do you feel that you have mastered local or traditional knowledge?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)
	Practicing local knowledge (Norm_LKPrac)	Do you practice local or traditional knowledge in your everyday life?	Likert scale (1-5), ordinal (5 categories, strongly disagree-strongly agree)

Data processing and analysis

Out of the 200 surveys attempted, 183 were completed and returned. However, two were incomplete, yielding 181 usable responses and a response rate of 90.5%. This high rate is likely due to face-to-face administration of the surveys. The data gathered were then analyzed quantitatively (Fig. 3) with the International Business Machines' statistical package for the social sciences version 31 (IBM SPSS 31). In the preliminary stage, a rigorous data cleaning protocol was executed to eliminate statistical anomalies and ensure distributional normality across the dataset. Subsequently, principal component analysis (PCA) was applied to examine correlations among the adaptive capacity indicators. The factor extraction process yielded four distinct factors meeting the eigenvalue greater than or equal to 1, which were subsequently utilized in the hierarchical cluster analysis. Consequently, this approach identified four unique typologies; a radar plot was subsequently employed to visualize the configurations and interactions of their underlying indicators. Regarding their effects on community adaptations, a Multinomial Logistic Regression (MLR) was employed. This method is particularly useful when the dependent variable to be predicted is nominal and comprises more than two categories that do not have a designated rank/order (Hashimoto *et al.,* 2020).

Reliability and validity tests

The questionnaire's reliability was tested using Cronbach's Alpha. It yielded a score of 0.671, which is acceptable according to scholars (El-Hajjar, 2018; Raharjanti *et al*., 2022). This instrument utilized 13 adaptive capacity indicators as independent variables to predict coastal flooding responses as the dependent variable. Within this framework, 61.5% of the observed

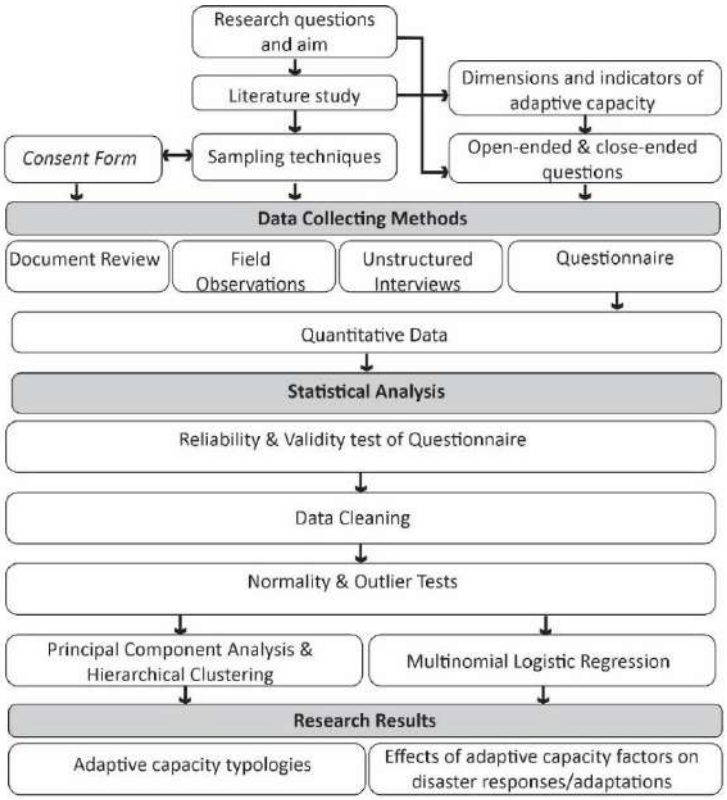

Fig. 3: The study flows with a quantitative approach

data demonstrated sufficient construct validity, adequately reflecting the underlying theoretical dimensions. Regarding the questionnaire's validity, Confirmatory Factor Analysis revealed a Kaiser-Meyer-Olkin (KMO) value of 0.686, exceeding the minimum threshold of 0.50, and Bartlett's test showed significance below 0.001. These results confirmed that factor analysis tests could be appropriately conducted.

Statistical analysis

The respondents' adaptive capacity was evaluated using PCA to achieve dimensionality reduction and identify the core underlying structures within the dataset. Prior to this, the adaptive capacity indicators were normalized using Z-Score Standardization, which transformed the data to have a mean of "0" and a standard deviation of "1". Using the min-max formula, new datasets were obtained. The dataset demonstrated sufficient sampling adequacy, yielding a KMO value of 0.697, which exceeds the acceptable 0.5 threshold. Furthermore, Bartlett's Test of Sphericity was statistically significant (0.001), confirming that the data were highly suitable for factor analysis. Analyzing the total variance from the set of 13 variables resulted in the extraction of four factors, each with eigenvalues greater than 1. Factor 1 accounts for 26.922% of the variance, Factor 2 explains 16.535%, Factor 3 contributes 11.687%, and Factor 4 accounts for 9.229%. Together, the extracted factors exhibited robust explanatory power, capturing 64.373% of the total variance inherent in the underlying construct. After conducting a Varimax rotation, the results confirmed the validity of all questions in the instrument (Table 2). These factors are

Table 2: Varimax rotated component matrix on normalized adaptive capacity data

Independent variables	Component			
	1	2	3	4
Norm_Agcy	.175	.363	.330	-.586
Norm_AsCre	.329	.146	.071	.785
Norm_AsSav	.672	-.315	.031	.163
Norm_SocLead	-.218	-.634	.051	.037
Norm_SocPart	.808	.062	.046	-.022
Norm_SocInf	.600	.338	.070	.328
Norm_InsInt	.703	.376	.098	.013
Norm_InsFund	.148	.677	.144	.386
Norm_InsTrn	.759	.115	-.028	-.010
Norm_LKMast	.021	.058	.963	.045
Norm_LKPrac	.073	.067	.954	-.060
Norm_TR_AsOcc	.256	.453	-.097	-.318
Norm_TR_SocAc	-.211	.708	.224	-.059

Extraction method: Principal component analysis.
Rotation method: Varimax with Kaiser Normalization.
a. Rotation converged in 9 iterations.

interpreted as follows: 1) The variables of "capacity to save money" (0.672), "participation in decision-making" (0.808), "sharing information" (0.600), "institutional relations" (0.703), and "institutional training" (0.759) exhibit relatively large positive loadings on factor 1; therefore, this factor reflects the individuals' high awareness of environmental changes and active involvement in promoting resilience; 2) The variables of "institutional funding" (0.677), "occupational multiplicity" (0.453), and "social activities" (0.708) have large positive loadings on factor 2; therefore, this factor reflects the individuals' capacity to cope with disaster impacts using their socio-economic resources; 3) The variables of "mastering local knowledge" (0.963) and "practicing local knowledge" (0.954) have large positive loadings on factor 3; therefore, it indicates the individuals' capacity to cope with disaster impacts using traditional skills; 4) Within Factor 4, 'agency' possesses a moderate negative loading (-0.586), denoting its inverse effect, whereas 'access to credit' displays a strong positive loading (0.785). This latter finding underscores how an individual's capacity to secure financial credit enhances their capacity for resilience-building. The PCA results facilitated the classification of adaptive capacity typologies through hierarchical clustering analysis, which categorized data based on similarities. Agglomerative clustering was chosen for its ability to reveal unknown relationships among adaptive capacity indicators and uncover nested clusters. While hierarchical cluster analysis can result in low-density clusters, the removal of such anomalies is not automatic and must be explicitly justified by the investigator based on research design (Almeida *et al*., 2007). In this study, discarded data were merged into the formed clusters to demonstrate different adaptive capacity characteristics across neighborhoods. Nevertheless, the presence of low-density clusters highlights a limitation that future studies should address by increasing the sample size and adopting more complex sampling frameworks to improve data generalizability. As for policymakers, the small number associated with this cluster must not be overlooked if community resilience is of concern. Regarding the determined number of clusters, the study employed a single linkage, with the "nearest neighbor" technique. This algorithm executes an iterative, pairwise evaluation of data points from the sorted index, progressively merging clusters until the specified cluster solution is achieved. It begins by evaluating the

first pair, representing the two closest data points (Sokhonn *et al.,* 2024). The generated dendrogram plot revealed four clusters with distinct adaptive capacity for further interpretations. To visualize and compare the distinct multi-dimensional profiles of these clusters, a radar plot was constructed. Prior to executing the regression analysis, data preprocessing and diagnostic testing were conducted to ensure the dataset conformed to the necessary statistical assumptions. These procedures resulted in new datasets (N= 178) after removing three outliers. Regarding multicollinearity, potentially present following the high number of independent variables, the test showed that the Variance Inflation Factor (VIF) values were below 10 and the collinearity tolerance values exceeded 0.1, indicating no multicollinearity. In the regression analysis, the 13 adaptive capacity indicators were evaluated to determine their predictive influence on disaster response outcomes. MLR was employed due to the categorical-nominal nature of the dependent variable with three categories: "in-situ adaptations", "ex-situ adaptations', and "no adaptations." The reference category determined was "no adaptations", representing the preference for taking no action in response to disaster impacts. To facilitate meaningful interpretation, the probability estimate for this target category was cross-referenced with the corresponding probabilities of the remaining two categories. Upon evaluating the regression model's goodness of fit and Pseudo R-Square for each experiment, it was found that incorporating all variables in the regression diminished its explanatory power. However, by retaining "Norm_Agcy", "Norm_AsCre", and "Norm_SocPart" and adding two demographic-related variables, "Age" and "Native born", the model's stability and predictive power improved. Variable selection for the final regression architecture was strictly deductive, predicated on established theoretical paradigms rather than empirical exploration. Previous studies have highlighted that a sense of agency (Barceló *et al.,* 2025; Barnes *et al.,* 2025), access to credits (Barceló *et al.,* 2025; Malmin, 2023), and participation in decision-making (Que *et al.*, 2022) are significant predictors of disaster responses. Similarly, demographic factors such as age (Clar *et al*., 2023) and nativity (Adeola, 2007) have been demonstrated to significantly condition community risk perceptions, which subsequently shape specific behavioral responses to disaster impacts.

RESULTS AND DISCUSSION

Sociodemographic characteristics of respondents

Based on statistical analysis of all responses (N=181), the average age of respondents is 45.07, with ages ranging from 19 to 83 (Table 3). In terms of demographic distribution, male participants predominated the sample at 61.3%, while the prevailing educational attainment levels were concentrated among those who had completed elementary school (39.2%) and senior high school (37.6%). Nearly 24.9% identify as fishermen, and 22.1% are market sellers. On average, the monthly household income is United States Dollar (USD) 147.31, below the regional minimum wage of USD 201.24. Most respondents (81.2%) live in Tambakmulio, and nearly 40.3% hold land certificates, with 38.7% stating the land belongs to their ancestors. A significant majority of the sample exhibited deep-rooted generational tenure, with 86.2% residing in Tambak Lorok for over 15 years and 68% being native-born; this high level of residential permanence fosters strong place attachment and heightened longitudinal awareness of local environmental changes. Additionally, 45.9% live in households of 4-5 members, while 17.1% have more than five members, highlighting the community's vulnerability to climate threats.

Table 3: Descriptive statistics of respondents' demographic profiles

Demographic attributes	N	Min.	Max.	Mean	Standard deviation (SD)
Age	181	19	83	45.07	13.956
Gender	181	1	2	1.39	.488
Education level	181	1	5	2.93	1.028
Occupation	181	1	8	3.65	2.500
Household monthly income	181	0	10000000	2528176.80	1689043.612
Neighborhood unit	181	1	5	3.39	1.222
Land legal status	181	1	6	2.24	1.268
Duration of stay	181	2	5	4.75	.698
Native born	181	1	2	1.32	.468
Family members	181	1	4	2.79	.730
Land size	181	18	940	75.41	82.156
Home size	181	16	300	68.68	44.077
Floor level	181	1	3	1.18	.401
Valid N (listwise)	181				

Adaptive capacity typology

As Fig 4a indicates, cluster 1 includes respondents who excel in "capacity to save money" (Norm_AsSav, 0.60), "participation in decision-making" (Norm_SocPart, 0.67), "sharing information" (Norm_SocInf, 0.70), and "leadership" (Norm_SocLead, 0.89), while the capacity related to the "institutions" dimension is at the lowest. Comprising 173 respondents, this cluster represents the predominant typology within the sample and was designated as the "attentive observers" cohort due to its distinct indicator profile." Cluster 2 is defined by high values in "mastering local knowledge" (Norm_LKMast, 0.963) and "practicing local knowledge" (Norm_LKPrac, 0.954), with no values concerning access to credits. While encompassing just one participant, this individual outlier exhibited robust localized capacity, prompting its classification as a unique typology termed "Cultural Stewards". Cluster 3 is defined by its high values in "leadership" (Norm_SocLead, 1.00), "institutional funding" (Norm_InsFund, 1.00), "occupational multiplicity" (Norm_TR_AsOcc, 1.00), "social activities" (Norm_TR_SocAc, 0.83), "agency" (Norm_Agcy, 1.00), and "access to credit" (Norm_AsCre, 1.00). Reflecting these specific characteristics, this group was designated as the "social activists" typology; notably, like cluster 2, it functions as a singleton cluster encompassing only one respondent. Lastly, cluster 4 is marked by high values in "participation in decision-making" (Norm_SocPart, 0.92), "sharing information" (Norm_SocInf, 0.92), "interactions with other agencies" (Norm_InsInt, 1.00), and "institutional training" (Norm_InsTrn, 1.00), with moderate values for "agency" (Norm_Agcy, 0.75) and "access to credit" (Norm_AsCre, 0.50), while the "local knowledge" dimension is lacking. Based on these defining characteristics, this micro-cluster was designated as "self-assured individuals" and comprises a small cohort of four respondents. Linking these typologies to the neighborhoods, the study identified their spatial distributions (Fig. 4b), summarized as follows: 1) Neighborhood units 12, 14, and 15 have only one typology, cluster 1 (attentive observers); 2) Neighborhood unit 13 has two typologies: cluster 1 (attentive observers) and cluster 3 (social activists); and 3) Neighborhood unit 16 features three typologies: cluster 1 (attentive observers), cluster 2 (cultural stewards), and cluster 4 (self-assured individuals). Within the spatial analysis, neighborhood unit 16 displays the highest degree of typological diversity regarding adaptive capacity; furthermore, it represents the exclusive geographic sector containing the "cultural steward" typology. It aligns with the fact that this

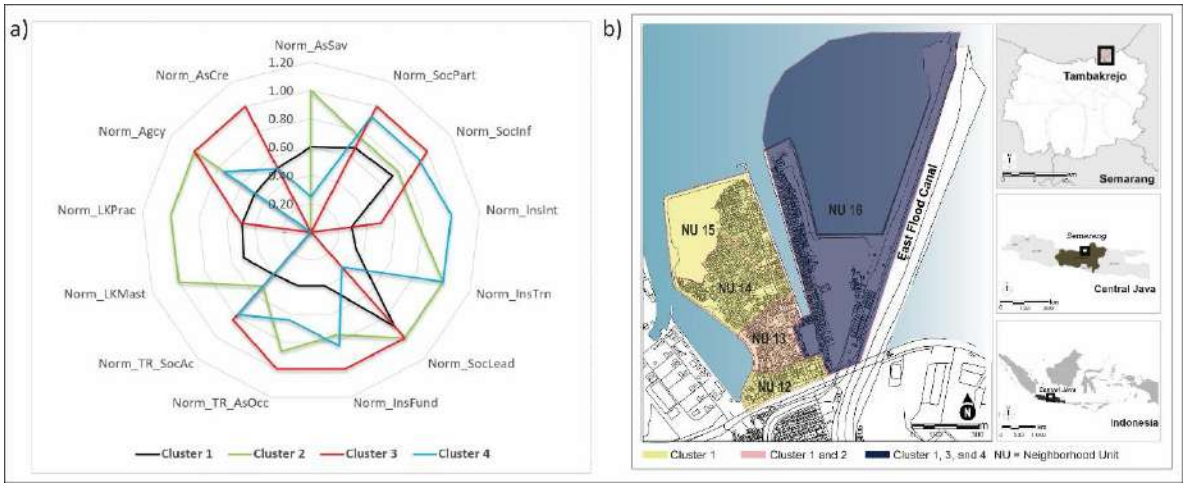

Fig. 4: Spiderweb plot displaying the adaptive capacity of different clusters with values ranging from 0 to 1 for each indicator (a) and the spatial distribution of the adaptive capacity typologies (b). Variations in community adaptations

neighborhood supports various environmental activities, such as mangrove conservation, managed by the local association called Cinta Alam Mangrove Asri dan Rimbun (CAMAR), or Nature-affection over the lush and dense mangrove. Coastal flooding poses a severe threat to the livelihoods of vulnerable populations, a challenge exacerbated by the compounding uncertainties of anthropogenic climate change. These events can lead to heightened human and economic costs, as well as the loss of critical assets, infrastructure, and even lives (Dube *et al.,* 2022). Climate change exacerbates environmental changes that ultimately compel the communities to alter their strategies for sustaining livelihoods. Disruptions to critical natural capital (such as freshwater reservoirs and arable land) and physical infrastructure typically generate cascading effects across broader livelihood asset portfolios (Rahman *et al.,* 2024). For instance, in Tambak Lorok, these challenges have made it hard for residents to access freshwater, damaged local fishponds due to saltwater intrusion, and caused health problems like skin rashes. Recurrent marine hazards, such as tidal inundation and storm surges, exacerbate occupational and financial instability within coastal communities. These shocks actively disincentivize maritime foraging, degrade critical marine habitats, diminish yield volumes, and compromise aquaculture infrastructure. To mitigate the risks, they depend on the government-initiated flood control infrastructure while also leveraging local assets, such as mangrove, to provide natural protection and promote economic sustainability through marine-based tourism. In the absence of targeted institutional interventions to bolster resilience, recurrent coastal inundation is projected to worsen systemic poverty, deepen social inequalities, and accelerate displacement risks within vulnerable populations. This situation is particularly evident in Tambak Lorok, where accelerating land subsidence combined with increasing inundation forces the residents to restore their homes and raise the home platforms annually, all while struggling against poverty and limited access to livelihood resources. For statistical analysis, community responses to climate change are categorized into “in-situ adaptations”, “ex-situ adaptations”, and “no adaptations”. The “no adaptations” classification signifies a structural inertia or resistance toward

implementing critical mitigative measures, a state frequently reinforced by a deficiency in institutional and state support. Opting for inaction on climate change, however, can result in socio-economic repercussions, including accelerated poverty traps, exacerbated systemic inequalities, and severe structural and well-being crises. This dynamic is profoundly concerning given that the baseline socio-economic status of most coastal residents falls below the poverty threshold, drastically limiting their capacity to absorb the compounding, long-term impacts of climate change. In contrast, the other two categories show proactive responses that can enhance resilience. In-situ adaptations refer to disaster responses that occur within an affected place, as people prefer to stay in place. Conversely, ex-situ adaptation pathways entail the deliberate relocation of livelihoods, assets, and/or whole systems because of preferences for moving outside the affected area (Omar and Bardsley, 2024). While ex-situ adaptations are more effective in reducing risks, their adoption presents significant challenges. Displacement and relocation are predominantly conceptualized by local populations as ultimate contingencies, initiated only when localized, in-situ adaptive capacities are thoroughly exhausted. The reluctance also often stems from concerns about disrupted social networks and economies, which can lead to psychological distress (Depari and Lindell, 2023). This study found that "in-situ adaptations" were the most frequently mentioned (93.26%), followed by "no adaptations" (5.62%) and "ex-situ adaptations" (1.12%). Such a strong inclination toward in-situ strategies signifies a profound determination to preserve socio-economic structures within high-risk zones, reflecting a resistance to displacement despite intensifying climate stressors. The specific strategies mentioned most include constructing flood defenses, using pumps to manage flooding, elevating home platforms and street levels, participating in communal works, and seeking government assistance (Fig. 5). A significant portion of the participants conceptualized these adaptive measures as collective, multi-tiered responses, rejecting the efficacy of isolated, singular interventions. For example, 14.10% mentioned both "elevating homes and streets"and "flood defense" to respond to coastal flooding.

Factors influencing adaptations

The MLR generated the parameter estimates as shown in Table 4. The regression model with respect to the dependent variable "in-situ adaptations" and the baseline variable "no adaptations" can be developed using Eq. 1, which follows the typical multinomial logit function (Liu, 2016). As for the dependent variables "ex-situ adaptations" and "no adaptations", the regression model using Eq. 2 that follows the same logit function and estimation procedure was applied (Liu, 2016) is:

$$\mathrm{Ln}\frac{\mathrm{P(in-situ)}}{\text{no response}} = 3.682 - 4.206\text{Agency} + 3.453\text{Access to credit} + 1.482\ \text{Participation in decision} - \text{making} - 0.08\ \text{AgeNativeborn} \quad (1)$$

$$\mathrm{Ln}\frac{\mathrm{P(in-situ)}}{\text{no response}} = 89.273 - 82.502\text{Agency} - 79.637\text{Access to credit} + 167.174\ \text{Participation in decision} - \text{making} - 0.802\ \text{AgeNativeborn} \quad (2)$$

The study interprets data by using the "no adaptations" category as a reference, estimating models for "in-situ adaptations" and "ex-situ adaptations" relative to it. Regarding the choice of

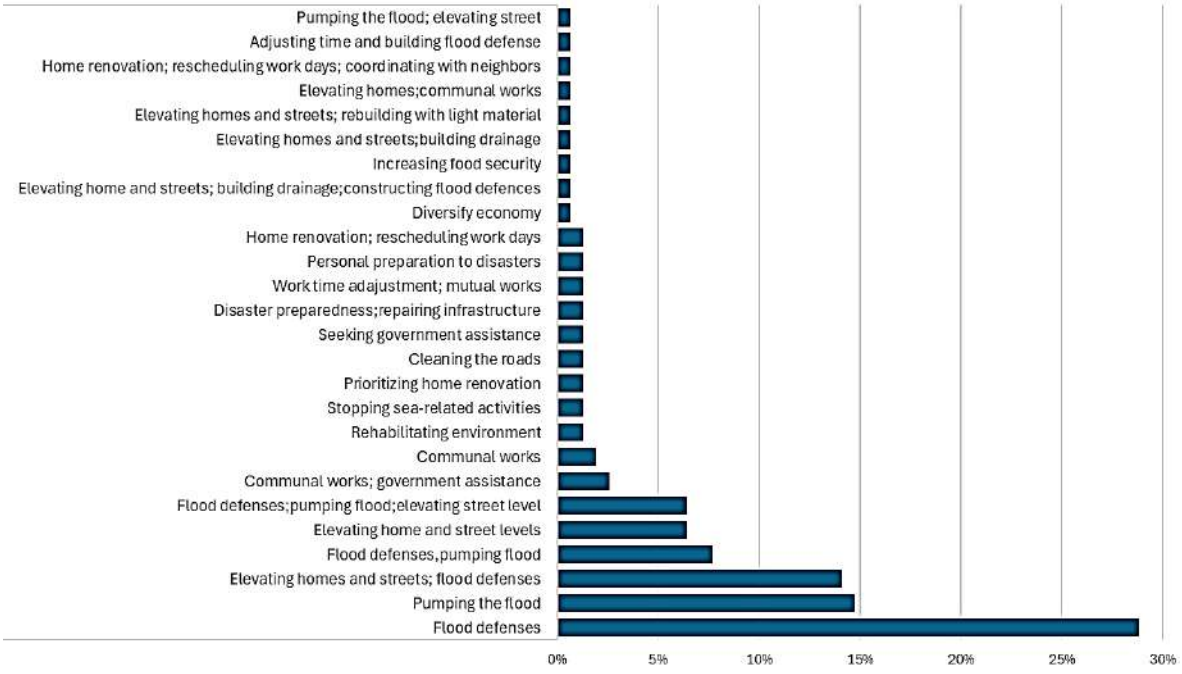

Fig. 5: Specific types of local in-situ adaptations according to respondents (N = 178)

Table 4: Parameter estimates or coefficients of the MLR model

Handled resp (Disasters)[a]		B	Standard error (SE)	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B)	
								Lower Bound	Upper Bound
In-situ adaptations	Intercept	3.682	1.676	4.827	1	.028			
	Norm_Agcy	-4.206	1.840	5.224	1	.022	.015	.000	.549
	Norm_AsCre	3.453	1.657	4.341	1	.037	31.598	1.227	813.726
	Norm_SocPart	1.482	1.351	1.204	1	.273	4.401	.312	62.099
	Age*Native born	-.008	.012	.488	1	.485	.992	.969	1.015
Ex-situ adaptations	Intercept	89.273	8610.591	.000	1	.992			
	Norm_Agcy	-82.502	9858.288	.000	1	.993	1.478E-36	.000	.[b]
	Norm_AsCre	-79.637	9379.226	.000	1	.993	2.595E-35	.000	.[b]
	Norm_SocPart	-167.174	.000	.	1	.	2.496E-73	2.496E-73	2.496E-73
	Age*Native born	-.802	107.759	.000	1	.994	.449	8.465E-93	2.377E+91

a. The reference category is: No adaptations.

b. Floating point overflow occurred while computing this statistic. Its value is therefore set to system missing.

"in-situ adaptation" relative to the baseline of "no adaptation": a one-unit increase in individual agency corresponds to a 4.206-unit decrease in the multinomial log-odds of preferring in-situ strategies, assuming all other covariates remain constant; 2) an increase in “access to credit” by one point is expected to increase the multinomial log-odds of preferring “in-situ adaptations” by 3.453 units while holding other variables in the model constant; 3) Conversely, a one-unit increase in “participation in decision-making” is associated with a 1.482-unit increase in the multinomial log odds of preferring “in situ adaptation” over non-adaptation. However, this relationship is not statistically significant (p = 0.273). Consequently, the null hypothesis cannot be rejected, indicating that when adjusting for “agency” and access to credit, the effect of participation on the

preference for “in situ adaptation” is statistically indistinguishable from zero and 4) an increase in “age” and “nativeborn” by one point is expected to decrease the log-odds by 0.008, however, with the associated p-value of 0.485, the null hypothesis was failed to be rejected and conclude that for “in-situ adaptations” relative to “no adaptations”, the regression coefficient for the interrelated “age” and “native born” have not been found to be statistically different from zero given “agency”, “access to credits”, and “participation in decision-making” are in the model. For “in-situ adaptations” relative to “no adaptations”, the interpretation is if a subject has an increase in either “agency”, “access to credit”, “participation in decision-making”, or the interrelated “age” and “native born”, the multinomial log-odds of preferring “ex-situ adaptations” to “no adaptations” is expected to decrease by 82.502, 79.637, 167.174, and 0.802, respectively, while holding other variables in the model constant. With their associated p-values of above 0.005, it could be concluded that for” ex-situ adaptations” relative to “no adaptations”, the regression coefficient for each variable has not been found to be statistically different from zero, given that other variables are in the model. Focusing on the statistically significant comparisons ($p < 0.05$) between "in-situ adaptation" and the baseline scenario of non-adaptation, the interpretations of the odds ratios are structured as follows: 1) Accounting for all model covariates, the relative risk ratio interpretations for the statistically significant predictors ($p < 0.05$) reveal two opposing pathways for "in-situ adaptation" versus the baseline of "no-adaptation". First, a one-unit increase in individual "agency" is associated with a dramatic decrease in the relative likelihood of preferring in-situ strategies (0.015), indicating that more empowered subjects are substantially more likely to opt for "no adaptation" over localized modifications. Second, holding all other variables constant, a single-unit increment in "access to credit" expands the relative risk of preferring "in-situ adaptation" over "no adaptation" by a factor of 31.598. Generally, if a subject were to increase the “access to credit”, the expected outcome would be the subject being more likely to prefer “in-situ adaptations” over “no adaptations.”

Adaptive capacity typologies and effects on adaptations

By assessing the adaptive capacity indicators and employing hierarchical clustering analysis, the study has identified four typologies of adaptive capacity and mapped their distribution across five neighborhood units. Categorizing structural frameworks into building typologies facilitates localized resource deployment and the design of targeted interventions, thereby enabling the formulation of bespoke climate adaptation and risk-mitigation strategies optimized for distinct localized vulnerabilities. The “attentive observers” typology (neighborhood units 12-16) is characterized by a strong ability to save money, participate in decision-making, share information, and demonstrate strong leadership. It is likely to perform “in-situ adaptations”, even when the institutional support and occupational multiplicity are relatively low. The typology’s strong socio-economic capacities reflect its awareness of disaster impacts and self-efficacy, which are important for addressing flooding challenges. In the face of intensifying flood regimes, residents of Tambak Lorok rely heavily on incremental, in-situ adaptations; this is demonstrated by their consistent, self-funded efforts to elevate municipal road levels and maintain failing drainage infrastructure. These initiatives are primarily driven and funded by the community, necessitating collaboration among members, participation in community meetings, sharing valuable information, and strong leadership,

especially when institutional support is minimal. The “cultural steward” typology (neighborhood units 16) displays a strong capacity regarding local knowledge but lacks access to credit. While adaptive capacity indicators are high, responses to coastal flooding fall in the “no adaptations” category, highlighting that credit access is crucial for addressing future threats. Restricted access to credit facilities significantly constrains local adaptive capacity in the face of intensifying flood regimes. Over the past decade, this vulnerability has been heavily compounded by acute environmental degradation, notably an exceptional land subsidence rate of approximately 30 cm annually. The community typically adapts by elevating streets and improving the drainage system. At the household level, residents predominantly engage in incremental, "in-situ adaptation" by elevating their residential foundations on an annual basis as an alternative to permanent relocation. Without access to financial resources, these abilities would likely be restricted. The “social activists” typology (neighborhood units 13) is marked by strong leadership, institutional funding, occupational multiplicity, social activities, participation in decision-making, sharing information, agency, and access to credit. Pronounced capacities in these domains are likely to foster in-situ adaptation, even in the presence of constrained financial savings and limited formal training. Access to institutional support critically influences coastal community resilience. Without it, people would struggle to recover quickly from environmental shocks. In Tambak Lorok, institutional support manifests as the government’s coastal protection initiatives (e.g., sea walls) that address flooding impacts and safeguard local livelihoods. The capacity of resource-dependent coastal populations in Ghana to resume economic activities is heavily constrained by institutional inefficiencies and top-down governance frameworks that fail to address community-specific needs. By favoring transient, short-term relief interventions over structural livelihood rehabilitation strategies, state-led initiatives inadvertently protract the post-disaster recovery timeline and entrench systemic socioeconomic precarity (Gbedemah *et al.,* 2026). These two cases show how differences in institutional support can lead to variations in adaptive capacity and possible resilience outcomes. The “self-assured” typology (neighborhood units 16) is characterized by strong agency, access to credit, participation in decision-making, sharing information, institutional support, occupational multiplicity, and social activities involved. Although localized knowledge capacity remains limited, the presence of these specific individual traits appears to significantly foster the adoption of in-situ adaptation strategies. A comparative analysis was subsequently conducted to deepen the discussion, with corresponding outcomes systematically structured in Table 5. Scholarly works belonging to (Barceló *et al.,* 2025) and (Ruiz-Mallén *et al*., 2017) were reviewed to specifically discuss the research findings related to adaptive capacity typologies and adaptation responses to climate-induced disasters. With the exception of the “Vulnerable” category, all typologies proposed in this study and identified by previous scholars exhibit elevated levels of specific adaptive capacities. In their study on household adaptive capacity in the Tsimane’, Bolivia, the “Vulnerable” typology was identified as those with low adaptive capacities in all respects, leading to the high likelihood to adapt ineffectively (Ruiz-Mallén *et al*., 2017). Comparatively, the cluster demonstrating a corresponding response trajectory in the present study is represented by the "Cultural Stewards", a group defined primarily by credit constraints. While Barceló *et al.* (2025) emphasized local knowledge as the strongest predictor of fishers’ responses on the coast of

Table 5: Comparative studies of adaptive capacity

Research concerns	Aspects	Present study	Prior studies
Adaptive Capacity Typologies	Number	4	3 (Barceló *et al.,* 2025); 3 (Ruiz-Mallén *et al*., 2017)
	Types	1) Attentive observers; 2) Cultural stewards; 3) Social activists; 4) Self-assured individuals	1) Local leadership; 2) Heritage Custodians; 3) Asset Agiles (Barceló *et al.,* 2025); 1) Commoners; 2) Vulnerable; 3) Leaders; 4) Subsidized (Ruiz-Mallén *et al*., 2017)
	Effects on adaptations	1) Attentive observers: Likely to lead to disaster responses, even when institutional support and occupational multiplicity are low; 2) Cultural stewards: Likely to lead to inaction, without access to credit. 3) Social activists: Likely to lead to disaster responses, even when the capacity to save money, institutional training, and local knowledge are lacking; 4) Self-assured individuals: Likely to lead to disaster responses, even when the capacity to save money, institutional training, and local knowledge is lacking	1) Local leadership: Likely to lead to disaster responses, due to the strong ability to save money, participation, and institutional relations. 2) Heritage Custodians: Likely to lead to disaster responses, due to the strong diversity of values and local knowledge; 3) Asset Agiles: Likely to lead to disaster responses, due to the strong access to credit and occupational multiplicity (Barceló *et al.,* 2025); 1) Commoners: Likely to effectively adapt, due to strong participation; 2) Vulnerable: Likely to ineffectively adapt, due to low adaptive capacities; 3) Leaders: Likely to effectively adapt, due to strong positions; 4) Subsidized: Likely to effectively adapt, due to strong government remittances (Ruiz-Mallén *et al*., 2017)
Factors influencing adaptation responses	Dimension 1. Agency	Agency: Significant effects, but inclined to opt for no adaptations	Agency: Significant effects, but inclined to opt for no adaptations (Barnes *et al.,* 2025; Brown and Westaway, 2011; Catalano and Hall, 2026; Nateghi *et al.,* 2016; Scarci *et al.,* 2026; Sharot, 2011)
			Agency: Significant effects, and inclined to opt for in-situ adaptations (Barceló *et al.,* 2025; Cinner *et al*., 2018)
	Dimension 2. Asset	Access to credit: Significant effects, and inclined to opt for in-situ adaptations	Access to credit: Significant effects, and inclined to opt for in-situ adaptations (Barceló *et al.,* 2025; Chen and Flatnes, 2019)

Southern Chile, this study contrastingly indicated this indicator as unable to promote disaster responses, despite its high scores and strong socio-economic capacities. While local knowledge successfully structures everyday resilience, its capacity to mitigate environmental shocks is frequently undermined by state-led infrastructural interventions—such as sea walls, which disrupt critical ecological baselines like mangrove ecosystems. Top-down bureaucracies often leave the local community to deal with the maladaptive consequences of projects that were unsuitable for local circumstances (Rahman *et al.,* 2023; Schipper, 2020). In addition, the mismatch between rapidly changing, unpredictable weather events and the slow, rigid nature of traditional knowledge may cause local communities to abandon the generational practices in favor of more modern, adaptable strategies (Filho *et al.,* 2023). The findings indicate that a subset of participants engage in knowledge hybridization to mitigate extreme weather risks, combining traditional agricultural seasonal indicators (pranoto mongso) with real-time meteorological data obtained via mobile applications and websites. This study found that “agency” (B=-4.206, p<.005) and “access to credit” (B=3.453, p<.005) have a significant effect on local

responses, yet with different directions of effects. Agency refers to the capacity of an individual to act independently and make free choices. It is influenced by the cognitive belief structure, social and individual perceptions, and the structures of the environment (Brown and Westaway, 2011). Agency is inherently linked to power dynamics and structural social forces. Having positions in social network structure can provide access to resources and opportunities for learning, which can enable people to exercise individual agency (Barnes *et al.,* 2025). The results indicate that individuals with higher "agency" are more inclined to opt for "no adaptations" rather than performing "in-situ adaptations." This outcome aligns with empirical evidence indicating that while respondents exhibit minimal variation in community-led adaptation strategies, they demonstrate a pronounced preference for government-initiated coastal protective measures. The implementation of structural protective infrastructure, such as hard flood defenses, can paradoxically elevate a community's perceived agency; however, this often induces a false sense of security that ultimately suppresses proactive adaptation behaviors (Catalano and Hall, 2026). For instance, the presence of a seawall along the Pacific coast of the Tohoku region fostered a sense of security that encouraged greater developments behind the seawall and led to decreased evacuation rates during tsunamis (Nateghi *et al.,* 2016). Additionally, studies suggest that strong agencies promote optimistic appraisals and abstract construal of negative events, thereby contributing to optimism bias (Sharot, 2011), lowering perceived risks, and attitudes of downplaying threats (Scarci *et al.,* 2026). Nevertheless, the agency variable yields an odds ratio near unity—reflecting a marginal difference of just 0.015—which implies that its impact on the preference for the "no-adaptation" baseline is negligible. Framed alternatively, elevated agency appears to function as a facilitator of localized, "in-situ adaptation" strategies. For example, Barceló *et al.* (2025) found that high levels of agency improve the livelihoods of fishing communities on the coast of Southern Chile; therefore, resilience to threats posed by climate change (Barceló *et al.,* 2025). Consistently, empirical evidence from Cinner *et al.* (2018) highlights that individual agency acts as an activating mechanism, enabling actors to leverage other assets and indicators of adaptive capacity in response to environmental shifts (Cinner *et al.*, 2018). However, the interplay between agency and other adaptive capacity indicators can create reinforcing feedback loops. During environmental shocks, for instance, social networks, leadership, and participation in community decision-making can serve as catalysts for mobilizing the agency dimension (Barnes *et al*., 2025). Besides agency, access to credit can also increase the capacity to cope with disaster impacts. Borrowing from community leaders serves as a critical post-disaster coping mechanism that buffers households against extreme climate events. By providing localized financial security, this form of social capital lowers the propensity for climate-induced migration and facilitates in-situ resilience. Access to credit also enables people to diversify their portfolios and save money to prepare for any disasters (Chen and Flatnes, 2019).

Limitations

Despite its promising outcomes for climate adaptation planning, this study is not without limitations. Firstly, the use of close-ended questions in questionnaires restricted the exploration of complex adaptive capacities. While face-to-face surveys increased response rates, the isolated location of Tambak Lorok made recruitment challenging, especially given the conflicting availability of the surveyors and the respondents. To enrich the interpretative quality of the data, the study utilized unstructured

interviews, relying on the principle of data saturation as the primary criterion for establishing sample size. This process led to the selection of three respondents for the interviews. Nevertheless, the complexity of the 13 adaptive capacity framework posed risks of obtaining uneven depth of information. Local weather forecasting knowledge and institutional support were frequently discussed, while personal capacities like agency and savings were sensitive topics that limited follow-up questions. Future studies would benefit from employing semi-structured interviews and expanding the use of open-ended questions—a methodological shift that would capture hidden granularities and mitigate asymmetries in data richness. Secondly, the limited number of survey questions representing local knowledge may hinder a nuanced understanding of the community's adaptive capacities. Future studies should consider incorporating more detailed queries, such as those focusing on local species and ecological traditions. Furthermore, there is significant merit in scaling the adaptive capacity framework for application across alternative coastal settings; however, any such empirical extensions must be systematically calibrated to the study's foundational research goals. Thirdly, simple random sampling led to a disproportionate selection of respondents across neighborhoods, potentially clustering adaptive capacities into small groups, such as "cultural stewards", "social activists", and "self-assured individuals" typologies. Future research should employ more complex sampling methods to increase the representativeness of the sample, such as stratified sampling, which divides the entire population into strata based on shared traits before applying random sampling within each stratum. Lastly, the study is constrained by the instability of the MLR parameter estimates; the presence of exceedingly wide 95% confidence intervals points to a lack of statistical precision that warrants cautious interpretation. These intervals span a broad range of plausible values, making it difficult to determine the true population parameter with high certainty. The imprecision may stem from a small sample size. Future studies should increase sample sizes to validate these findings further. To enhance the research robustness, integrating methods with spatial analysis, climate projections, and longitudinal datasets is essential. This holistic framework facilitates a deeper exploration of adaptive capacity dynamics by systematically investigating the specific contexts, timelines, mechanisms, and drivers under which it evolves. It will also reveal the critical factors influencing the community's adaptive capacities over time, recognize persistent barriers and enablers for community adaptations, track local adaptive capacity trajectories, and assess community responses to climate scenarios. Spatial maps will help visualize the distribution of adaptive capacities and the impacts derived from scenario-based climate projections.

CONCLUSION

The study has demonstrated how multiple indicators of adaptive capacity predict community responses to coastal flooding impacts and found that two indicators—agency and access to credit—significantly influence the variations in those responses, performed within their high-risk settlement (i.e., in-situ adaptations). Specifically, heightened agency may paradoxically culminate in a non-adaptation trajectory, a finding that mirrors the relatively constrained variation observed in localized adaptation strategies. Their reliance on the government's hard protective measures raises concerns about the potential rise of a false sense of security. Additionally, the four adaptive capacity typologies and their spatial distribution across the neighborhood units of Tambak Lorok

offer valuable insights for policymakers to identify the enablers and barriers to local adaptations, allowing for the development of targeted interventions aimed at enhancing community resilience. Illustratively, a pronounced deficiency in institutional support is evident among neighborhood units exhibiting the “attentive observer' typology. At the same time, the neighborhood unit with cultural steward typology demonstrates a substantial deficiency in access to credit, even with its strong repository of local knowledge. This study provides critical insights that directly inform both existing theoretical frameworks and the strategic formulation of climate adaptation policies. Firstly, the lack of institutional support has been counterbalanced by the considerable social and economic capital within the community. However, this warrants the regional government to expand its role in improving community livelihoods, particularly if the resilience of Tambak Lorok’s social-ecological systems is to be prioritized. The ecological resilience of coastal zones is widely understood to be fundamentally coupled with community dynamics, specifically requiring the retention and application of localized ecological expertise. Consequently, policy frameworks must prioritize the preservation of traditional ecological knowledge, such as the Javanese seasonal calendar, and systematically integrate it into contemporary climate adaptation agendas. Merging culturally resonant environmental indicators with modern meteorological forecasting can optimize localized early warning systems. Furthermore, co-producing strategies via participatory planning is vital to eliminating institutional inefficiencies and top-down programmatic misalignments that frequently obstruct community resilience. Secondly, the absence of access to credit, despite the community possessing strong local knowledge and other socio-economic capacities, is likely to result in inaction regarding the impacts of extreme weather events. Research consistently underscores the role of local knowledge as a catalyst for enhancing other adaptive capacity indicators. Nevertheless, the findings suggest a structural constraint: robust local knowledge is insufficient as a standalone driver of proactive adaptation; it must be coupled with financial liquidity or credit access to be effectively operationalized. It is recommended that policymakers facilitate this capacity by integrating climate funding into community-based strategies to strengthen resilience. Lastly, “agency” and “access to credit” are critical in determining local responses to coastal flooding. Although agency may not always lead to the expected outcomes, policymakers need to recognize the potential “levee effects” of coastal development, which can undermine local agency.

AUTHOR CONTRIBUTIONS

C.D.A. Depari serves as the corresponding author. All contributions made for this study, including the manuscript preparation, data visualization, data acquisition, analysis, interpretations, and revisions, are attributed solely to this author, who also supervised the research process and approved the final manuscript**.**

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
<	Less than/below
AsOcc	Occupational multiplicity variable
B	Unstandardized regression coefficient
CAMAR	Cinta Alam Mangrove Asri dan Rimbun (Nature-affection over the Lush and Dense Mangrove)
dF	Degree of freedom
Eq.	Equation
Exp(B)	Odds ratio
ha	Hectare
IBM SPSS 31	International Business Machines' Statistical Package for the Social Sciences version 31
km	Kilometer
KMO	Kaiser-Meyer-Olkin
KNN	K-Nearest Neighbor
K-S	Kolmogorov-Smirnov
Ln	Natural logarithm
min.	Minute
MLR	Multinomial Logistic Regression
N	Total number
NI	Natural Infrastructure
Norm_Agcy	Normalized data of the agency variable
Norm_AsCre	Normalized data of the access to credit variable
Norm_AsSav	Normalized data of the capacity to save money variable
Norm_InsFund	Normalized data of the institutional funding variable
Norm_InsInt	Normalized data of the institutional relations variable

Norm_InsTrn	Normalized data of the institutional training variable
Norm_LKMast	Normalized data of the mastering local knowledge variable
Norm_LKPrac	Normalized data of practicing local knowledge variable
Norm_SocPart	Normalized data of the participation in the decision-making variable
Norm_SocLead	Normalized data of the leadership variable
Norm_SocInf	Normalized data of the sharing information variable
Norm_TR_AsOcc	Normalized and transformed data of the occupational multiplicity variable
Norm_TR_SocAc	Normalized and transformed data of the social activities' variable
p	Probability value
PCA	Principal Component Analysis
S-W	Shapiro-Wilk
Sig	Significance level
SocAc	Social activities variable
SE	Standard Error
Std-MK	Standard Mark
USD	United States Dollar
VIF	Variance Inflation Factor

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ORIGINAL RESEARCH ARTICLE

Parasitoid community structure and ecosystem services for biological control of armored scale insects in tropical citrus agroecosystems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Armored scale insects (Diaspididae) are important pests of citrus agroecosystems; nevertheless, their natural enemies remain largely undocumented in tropical regions. The study objectives were to characterize parasitoid community structure and evaluate the ecosystem services delivered by parasitoid communities for biological control across tropical citrus agroecosystems.

METHODS: Field surveys were conducted for 20 months at eight sites in East Java, Indonesia, along an elevational gradient of 23–1,181 meters above sea level with monthly sampling visits covering both dry and wet seasons. Infested botanical specimens, including fruit, foliar, and branch material, were harvested and maintained under controlled environmental conditions to facilitate parasitoid emergence. Morphological criteria were employed for the taxonomic identification of host and parasitoid species. Subsequently, community diversity was characterized using Hill numbers, while the architecture of host–parasitoid interactions was evaluated through bipartite network analysis.

FINDINGS: From 1,050 samples five Aphelinidae parasitoid species were identified parasitizing five Diaspididae host species, comprising a functionally structured community dominated by two generalists (*Aphytis melinus* and *Encarsia perniciosi*) and one specialist (*E. suzanae*), with two additional rare taxa of limited biological control relevance. A total of 830 individuals were recovered, representing an overall parasitism rate of 6.57 percent. Within the parasitized samples, the mean abundance was 12.03 individuals per sample. Although relatively modest, this rate is characteristic of unmanaged conditions, with substantially higher rates documented in comparable systems under augmentative management. The community diversity exhibited structural stability across both elevational zones and seasonal periods. Bipartite network analysis revealed moderate specialization (H2' = 0.35), with 56 percent of potential host–parasitoid links realized. Significant differences in parasitism were detected across plant organs, with rates in fruits (11.14 percent) exceeding those in leaves (7.43 percent and branches (1.14 percent). This hierarchical variation demonstrates that the specific plant organ serves as a primary driver of host–parasitoid interaction structure. Multi criteria decision analysis, incorporating six equally weighted criteria, identified *A. melinus*, *E. perniciosi*, and *E. suzanae* as high-priority candidates for augmentative biological control, with rankings confirmed as robust through sensitivity analysis.

CONCLUSION: This study presents the first systematic characterization of parasitoid community architecture and its associated ecosystem services in tropical citrus agroecosystems. The plant organ was identified as the primary determinant of host–parasitoid interaction structure. Consequently, these findings yield an empirically validated integrated pest management strategy scalable to tropical citrus agroecosystems with comparable pest-parasitoid complexes.

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INTRODUCTION

Armored scale insects (Hemiptera: Diaspididae) are among the most economically important citrus pests worldwide. As phloem-feeding insects, these pests deplete vital plant sap, directly precipitating reductions in both crop yield and quality while simultaneously compromising host defenses against secondary phytopathogenic infections (Mansour *et al.,* 2017; Quesada *et al.,* 2018). Among the 2,650 identified species (García Morales *et al.,* 2016), approximately 15–20 are primary pests of commercial *Citrus*, including *Aonidiella aurantii* (California red scale), *Lepidosaphes beckii* (purple scale), and *Parlatoria ziziphi* (black parlatoria scale). Prolonged reliance on broad-spectrum insecticides has facilitated the development of resistant pest populations, induced non-target mortality, and destabilized beneficial arthropod communities (Parra *et al.,* 2022)—consequences that underscore the critical imperative for parasitoid-based integrated pest management (IPM) as a viable alternative. Aphelinidae parasitoids are the most common natural enemies of Armored scales in citrus systems. There are more than 89 species of parasitoids from 15 hymenopteran families that have been found on citrus plants around the world. Members of the family Aphelinidae consistently exhibit both the highest taxonomic diversity and the greatest numerical dominance within the studied assemblages (Cusumano *et al.,* 2016; Mansour *et al.,* 2017). *Aphytis melinus* is the most widely deployed biological control agent against *A. aurantii* achieving parasitism rates exceeding 80 percent (%) in integrated California systems (van Lenteren, 2018). *Encarsia perniciosi* and specialist *Encarsia* spp. exhibit niche complementarity by targeting distinct ontogenetic stages of the host population (Correa *et al.,* 2016). In Southeast Asia, *A. melinus*, *A. lingnanensis*, and *Comperiella bifasciata* have been recorded on *L. beckii* and *P. ziziphi* (Basheer *et al.,* 2014; Kondo and Watson, 2022; Xi *et al.,* 2025). Notwithstanding these historical records, regional parasitoid diversity region remains poorly characterized. This ongoing knowledge gap is exacerbated by the fact that molecular tools, such as deoxyribonucleic acid (DNA) barcoding, continually uncover cryptic species complexes within the genera *Aphytis* and *Encarsia* that confound conventional morphological diagnosis (Heraty *et al.,* 2013). Three critical knowledge gaps persist in Indonesian citrus systems. First, there is no systematic inventory of Aphelinidae parasitoids associated with Diaspididae in any agroecosystem in Indonesia, as no comparable quantitative documentation has been described earlier in the regional literature (Mansour *et al.,* 2017; Jangir *et al.,* 2025). Second, community-level attributes, including host–parasitoid network architecture, microhabitat partitioning across distinct plant organs, and altitudinal diversity gradients—remain entirely undocumented (Ramos Aguila *et al.,* 2023; Rappa *et al.,* 2024). Third, a lack of empirical evaluation regarding indigenous parasitoid communities as biological control agents for Indonesian citrus, creates a critical data gap, thereby limiting the capacity of IPM programs to systematically incorporate natural enemies. The need for ecologically grounded, localized IPM is further indicated by concurrent regional constraints, such as intensive pesticide use, ant–scale mutualisms (Calabuig *et al.,* 2014), and climate warming (Furlong and Zalucki, 2017; Cebolla *et al.,* 2018). Although these specific variables fell outside the measurement scope of the current study, their documented impacts on parasitoid suppression and reduced *Aphytis* performance underscore their broader relevance (Rosen and DeBach, 2011). To effectively translate global knowledge into locally applicable IPM strategies, community-level analyses are required to explicitly link parasitoid diversity to ecosystem service delivery must be conducted. Citrus agroecosystems in East Java, which span an elevational gradient of 23 to 1,181 meters above sea level (masl), provide an ideal model system for investigating these ecological dynamics. The specific objectives of this study are to: 1) identify and document parasitoid species associated with Diaspididae along an elevational gradient; 2) characterize community diversity,

abundance, and seasonal dynamics; 3) analyze the structure of host–parasitoid interactions using bipartite network analysis; and 4) assess the preliminary biological control potential of identified parasitoid species using multi-criteria decision analysis (MCDA) based on field-derived ecological attributes. This study was conducted in eight citrus-producing sites in East Java Province, Indonesia during 2023 to 2025.

MATERIALS AND METHODS

Study area and sampling

Field surveys were conducted at eight citrus-producing sites in East Java Province, Indonesia, spanning an elevational gradient of 23 to 1,181 masl (Fig. 1 and Table 1). Sites were selected based on two criteria: 1) active commercial citrus production with a minimum orchard area of 0.5 hectares (ha) and 2) Sites were selected based on a documented history of armored scale infestation, which was confirmed via preliminary visual inspections that recorded an infestation rate of 10% or greater per canopy. Sites represented *Citrus reticulata*, *C. sinensis*, *C. aurantifolia*, and *C. nobilis*. Three sites were in the low elevation category (<400 masl), three in medium (400–700 m asl), and two in high (>700 masl). To avoid confounding chemical effects, a minimum 30-day post-pesticide application window was required; orchards falling outside this threshold were excluded. Detailed orchard management histories beyond this criterion were not systematically recorded and represent a limitation of the sampling design. Sites were selected based on two criteria: 1) active commercial citrus production with a minimum orchard area of 0.5 ha; and 2) documented history of armored scale infestation, confirmed by preliminary visual inspection recording ≥10% infested shoots per canopy. Elevations were recorded by global positioning system (GPS) (Garmin eTrex 30x) and seasons classified as wet (November–March, >200 mm/month) and dry (April–October, <150 millimeters per month (mm/month). To achieve a fully balanced experimental design, monthly sampling was conducted over 20 months, yielding exactly 10 dry-season and 10 wet-season collection events per site across all sites and elevation categories.

Sample collection and rearing

At each site, 3–5 linear transects with 100–200 m was established, using a systematic parallel placement design, with a minimum inter-transect distance of 30 m, sampling 5–8 trees per transect (15–40 trees per site per visit). Infested plant material was harvested from both the canopy periphery and mid-canopy zones. At each site, sampling comprised: (1) 5 to 10 fruits measuring 4–8 centimeters (cm) in diameter; (2) 10 to 20 composite leaf samples; and (3) 3 to 5 sections of woody branches measuring 15–25 cm in length. Only samples with ≥10 armored scales were retained. Samples were placed in ventilated containers and transported to the Entomology Laboratory, Brawijaya University, within 6 hours. Rearing was conducted under controlled conditions with 25 ± 2.5 degrees Celsius (°C), 70 ± 5% relative humidity (RH), ~12L:12D) with daily monitoring for parasitoid emergence over 21 days. Sample numbers varied among plant organs to reflect differences in armored scale infestation density across the canopy. Because fruits and leaves typically harbored higher infestation densities than branches, fewer sample units were required to achieve the target threshold of ≥10 individuals per sample. This organ-specific sampling approach is consistent with standard practice in emergence-based parasitoid surveys (Correa *et al.,* 2016; Dao *et al.,* 2017). Samples yielding at least one adult parasitoid emergence were recorded as parasitized. At the conclusion of the rearing period, all remaining scales insects were dissected under a stereomicroscope to detect un-emerged parasitoid immatures (eggs, larvae, or pupae). Scales containing visible parasitoid immatures but yielding no adult emergence were recorded separately as parasitized-but-failed and excluded from parasitism rate calculations.

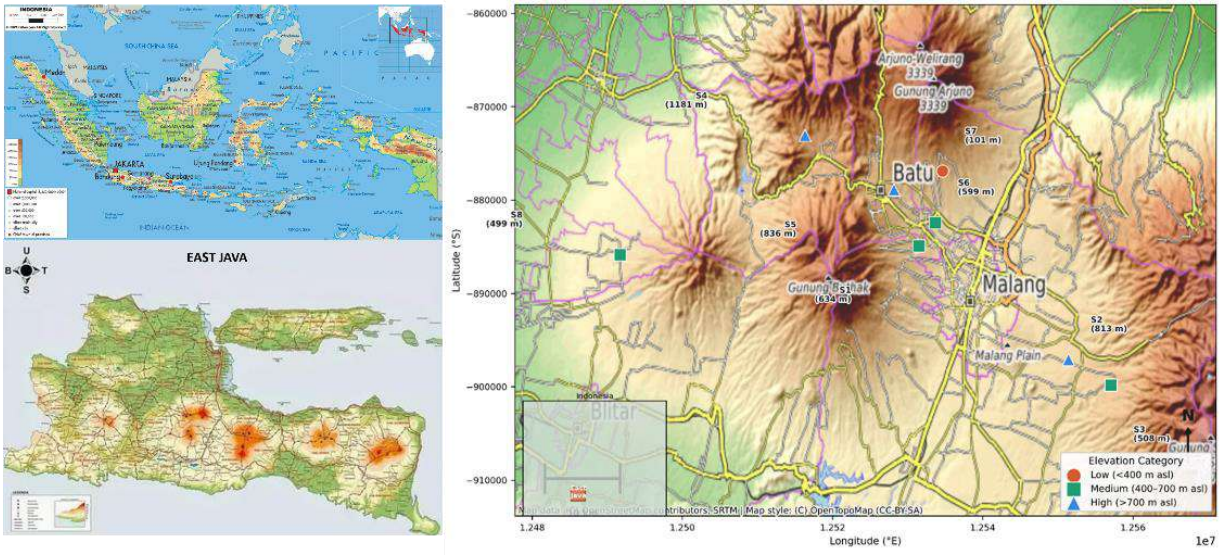

Fig. 1**:** Geographical location of the study area. Upper left: Map of Indonesia showing the location of East Java Province (red box). Lower left: Map of East Java Province showing the distribution of sampling sites across the province. Right: Detailed topographic map of the sampling area in Malang, Batu, and surrounding districts, East Java, Indonesia, showing the eight citrus orchard sampling sites (S1–S8) with elevation indicated in parentheses. Symbols denote elevation categories: circle = low (<400 m asl), square = medium (400–700 m asl), and triangle = high (>700 m asl). Map data: OpenStreetMap contributors, SRTM; Map style: © OpenTopoMap (CC-BY-SA)

Table 1: Ecological and climatic characteristics of the eight citrus orchard sampling sites in East Java Province, Indonesia

Site	Location	Coordinates	Elevation (m asl)	Elevation Category	Citrus species	Mean Temp. (°C)	Mean Precip. (mm/mo)	Dominant Season
S1	Dau, Malang	7°55'26"S, 112°34'20"E	634	Medium	*C. reticulata*	23.3	93.5	Dry
S2	Poncokusumo, Malang	8°01'56"S, 112°45'04"E	813	High	*C. reticulata*	23.3	91.8	Dry
S3	Karangploso, Malang	8°03'24"S, 112°48'08"E	508	Medium	*C. reticulata*	22.5	216.4	Wet
S4	Pujon, Malang	7°49'07"S, 112°26'10"E	1.181	High	*C. nobilis*	20.4	190.4	Wet
S5	Pandanrejo, Batu	7°52'13"S, 112°32'33"E	836	High	*C. reticulata*	22.2	148.4	Wet
S6	Pendem, Batu	7°54'06"S, 112°35'32"E	599	Medium	*C. sinensis*	23.5	36.1	Dry
S7	Ngunut, Tulungagung	7°51'09"S, 112°36'02"E	101	Low	*C. aurantifolia*	21.2	95.6	Dry
S8	Ngancar, Kediri	7°55'56"S, 112°12'54"E	499	Medium	*C. reticulata*	24.4	98	Dry

Note: Temperature and precipitation represent means derived from recent historical data (Open-Meteo, 2025). Elevation categories: Low (<400 masl), Medium (400–700 m asl), and High (>700 m asl). Season at time of initial sampling: Dry (April–October) and Wet (November–March). Citrus species: *C. reticulata* Blanco (mandarin), *C. nobilis* Lour. (King mandarin), *C. sinensis* (L.) Osbeck (sweet orange), and *C. aurantifolia* (Christm.) Swingle (lime). Temperature and precipitation data are sourced from Open-Meteo API based on site coordinates.

Specimen identification

Emerged parasitoids were preserved in 80% ethanol at 4°C, slide-mounted in Canada balsam following clearance and graded ethanol dehydration, and examined at 100–400× (Olympus CX23) against Aphelinidae keys (Hayat, 1998; Polaszek *et al.,* 1999). Armored scale species were identified based on the morphological characteristics of their scale covers and slide-mounted adult females, including associated second-instar female exuviae (Miller and Davidson, 2005; García Morales *et al.,* 2016). Voucher specimens were deposited at Museum Zoologicum Bogoriense (MZB), BRIN, and are publicly accessible upon request. Molecular barcoding was not performed in the present study; all taxonomic identifications should be interpreted as morphospecies-level assignments pending genetic confirmation through future molecular validation studies.

Statistical analysis

Parasitism rate was calculated as the proportion of samples yielding confirmed adult parasitoid emergence. Generalized linear mixed models (GLMMs) with a binomial error distribution and logit link function were fitted to evaluate the data. Host species, plant organ, elevation category, and season were included as fixed effects; while sampling site and sampling occasion were treated as random effects (Brooks *et al.,* 2017). Model selection was guided by the corrected Akaike information criterion (AICc). Effect sizes are reported as odds ratios with corresponding 95% confidence intervals (CI), and model fit was assessed using marginal and conditional R^2 values (Nakagawa and Schielzeth, 2013). Finally, potential overdispersion was evaluated using the residual diagnostics for hierarchical regression models (DHARMa) (Hartig, 2022). Parasitoid and host diversity were quantified using Hill numbers ($q = 0, 1, 2$) with Interpolation and extrapolation of species diversity (iNEXT), (Hsieh *et al.,* 2016); sampling completeness was assessed via rarefaction curves; and differences among elevation zones and seasons were tested with Kruskal–Wallis. Host–parasitoid interactions were analyzed as bipartite networks using the framework outlined by Dormann *et al*. (2009) and Feala *et al*. (2012). To evaluate network robustness, a null model analysis based on 1,000 permutations were conducted. All five host and five parasitoid taxa were retained in the network regardless of abundance, with unobserved host–parasitoid combinations assigned a value of zero to represent unrealized interactions rather than missing data. Biological control potential was assessed using MCDA incorporating six equally weighted criteria: field abundance, host range breadth, parasitism rate, geographic distribution, collection frequency, and host specificity efficiency. Each criterion was normalized to a 0–1 scale using min-max scaling, ensuring that higher values consistently reflected superior biological control traits. These normalized values were subsequently averaged to generate an unweighted composite biocontrol potential score (BPS) for each species. Sensitivity analysis varying criterion weights from 0.10 to 0.30 across 30 combinations confirmed BPS ranking stability. Spatial autocorrelation was not formally tested; the sampling site random effect provides partial control for spatial non-independence. All analyses used R v4.3.1 ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Five Diaspididae host species and five Aphelinidae parasitoid species were identified from 1,050 samples collected across eight East Java sites (Table 2). While fewer than the 14–21 species found in similar Southeast Asian surveys (Dao *et al.,* 2018; Dao *et al.,* 2023), the five recorded Diaspididae reflect the targeted sampling approach rather than a comprehensive regional inventory. Focused faunistic surveys would undoubtedly reveal further species diversity within these agroecosystems. *Aphytis melinus* is consistent with its wide Indo-Pacific distribution as the dominant ectoparasitoid of *A. aurantii* (DeBach and Rosen, 1991; Boyero *et al.,* 2014). *Encarsia perniciosi*, primarily documented from California (Correa *et al.,* 2016), here achieves high abundance across all five host species, which extends its known range to tropical East Java. Members of the genus *Marietta* are predominantly documented as an obligate hyperparasitoid. If a hyperparasitic strategy was maintained in this system, its net effect on biological control would be inherently disruptive (Tena *et al.,* 2011a; Hoddle *et al.,* 2013; Tougeron and Tena, 2019); consequently, dissection-based or molecular confirmation of its precise trophic status remains a critical priority for future research. Several associations, including *E. perniciosi* parasitizing *L. gloveri*, *P. ziziphi*, and *P. aspidistrae*, and the occurrence of *E. suzanae* and *Marietta* sp. in East Java, represent new records requiring molecular verification. Exclusive reliance on morphological identification is associated with uncertainty; cryptic species within *Aphytis* and *Encarsia* (Heraty *et al.,* 2013; Qin *et al.,* 2018) may mean that the true number of interacting taxa is higher than reported. Among 1,050 collected

Table 2: Taxonomic classification of armored scale insects and their parasitoids

No.	Species	Order	Family
	Hosts (Armored Scale Insects)		
H-1	*Aonidiella aurantii* Maskell (1879)	Hemiptera	Diaspididae
H-2	*Lepidosaphes beckii* Newman (1869)	Hemiptera	Diaspididae
H-3	*Lepidosaphes gloveri* Packard (1869)	Hemiptera	Diaspididae
H-4	*Parlatoria ziziphi* Lucas (1853)	Hemiptera	Diaspididae
H-5	*Pinnaspis aspidistrae* Signoret (1869)	Hemiptera	Diaspididae
	Parasitoids		
P-1	*Encarsia perniciosi* (Tower 1913)	Hymenoptera	Aphelinidae
P-2	*Encarsia suzanae* (Pedata and Giorgini, 2016)	Hymenoptera	Aphelinidae
P-3	*Encarsia* sp.	Hymenoptera	Aphelinidae
P-4	*Aphytis melinus* DeBach, 1959	Hymenoptera	Aphelinidae
P-5	*Marietta* sp.	Hymenoptera	Aphelinidae

samples, 69 (6.57%) yielded parasitoid emergence, producing a total of 830 individuals with a mean of 12.03 individuals per parasitized sample. Shannon diversity (H') varied across low (1.087), medium (1.190), and high (0.858) elevation categories, as well as between dry (0.892) and wet (0.895) seasons. However, generalized linear modeling indicated that neither elevation ($p = 0.986$) nor season ($p = 0.938$) significantly influenced community diversity (Fig. 2 and Table 3). Rarefaction curves approached asymptote for both communities, indicating adequate sampling effort. The recorded parasitoid emergence rate of 6.57% aligns with the lower range established for unmanaged citrus agroecosystems (5–15%) (DeBach and Rosen, 1991). Several factors are likely associated with this modest rate: conventional management practices including periodic broad-spectrum insecticide applications; ant–scale mutualisms not controlled or measured at sampling sites (Calabuig *et al.,* 2014); and sampling bias toward heavily infested material. Consequently, the 6.57% emergence rate characterizes a community subjected to environmental or management-driven suppression. This suggests that substantial increases in parasitism are biologically feasible through the implementation of optimized habitat or pest management practices. The stability across elevation and seasons is consistent with broad thermal tolerance of dominant *A. melinus* and *E. perniciosi* (Mohammed *et al.,* 2020), though direct physiological measurements were not conducted. Three species were dominant: *A. melinus* (334 individuals, 40.2%), *E. perniciosi* (280 individuals, 33.7%), and *E. suzanae* (203 individuals, 24.5%), collectively accounting for 98.4% of total emergence. *Marietta* sp. (7, 0.8%) and *Encarsia* sp. (6, 0.7%) were documented with very low abundance, both in only two locations. The co-dominance of *A. melinus* and *E. perniciosi* aligns with the host-stage differentiation documented in similar systems, although this mechanism was not explicitly evaluated in the present study. The substantially higher abundance of *E. perniciosi* in East Java (33.7%) compared to Mediterranean systems (2.4%) (Boyero *et al.,* 2014) aligns with the hypothesis of relaxed competitive displacement under tropical thermal conditions (Cebolla *et al.,* 2018), though this geographical variation awaits experimental verification. The specialist-advantage hypothesis suggests that certain species have superior host-location efficiency (Rossinelli and Bacher, 2015). The restriction distribution of these two rare taxa implies a sensitivity to localized microhabitat characteristics. Their presence within a community dominated by generalist competitors is consistent with the insurance hypothesis, highlighting their potential role in buffering ecosystem services under fluctuating environmental and ecological conditions, thereby enhancing long-term community stability and resilience. For *Marietta* sp., low abundance may be associated with hyperparasitoid dependence on primary parasitoid density across varying ecological and seasonal conditions (Tougeron and Tena, 2020); given its 0.8% contribution, its effect

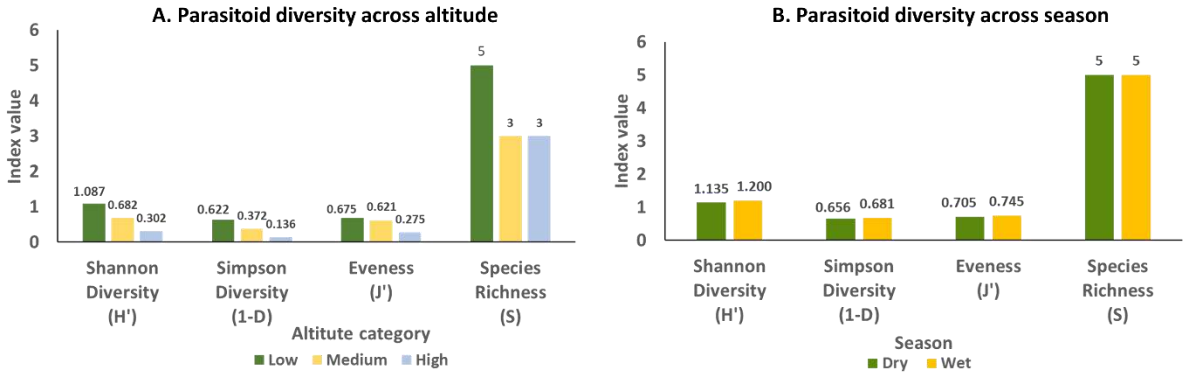

Fig. 2: Parasitoid diversity metrics across (A) elevation categories and (B) seasons. Metrics shown: Shannon index (H'), Simpson index (1-D), Pielou's evenness (J'), and species richness (S)

Table 3: Species diversity metrics for armored scale insects (Diaspididae) and parasitoid wasps (Aphelinidae) recorded across eight East Java citrus agroecosystem sites

Diversity Metric	Hosts (Diaspididae)	Parasitoids (Aphelinidae)
Species richness (S)	5	5
Shannon diversity index (H')	1.283 (95% CI: 0.811–1.319)	1.149 (95% CI: 0.788–1.200)
Simpson diversity index (1–D)	0.699 (95% CI: 0.455–0.718)	0.661 (95% CI: 0.469–0.677)
Pielou's evenness (J')	0.797 (95% CI: 0.529–0.942)	0.714 (95% CI: 0.550–0.927)
Berger-Parker Dominance (D)	0.398 (95% CI: 0.336–0.698)	0.406 (95% CI: 0.348–0.692)

Note: Bootstrap confidence intervals were computed by resampling sites (n = 8) with replacement over 999 iterations. Species richness (S) confidence intervals are not reported as S represents a fixed count based on all specimens identified across sites.

on parasitism estimates is considered negligible. Bipartite network analysis yielded moderate specialization (H2' = 0.35). No model analysis indicated that the observed value deviated significantly from random expectation (mean null H2' = 0.21 ± 0.04; $p < 0.05$), with 14 of 25 links realized (56%) (Table 4, and Fig. 3 and Fig. 4). The observed network specialization value (H2' = 0.35) aligns with typical values reported for simplified agroecosystem networks (Derocles *et al.,* 2020). However, given the small network dimensions (5 × 5 taxa) and the high probability of cryptic diversity within the *Encarsia* genus, this value should be interpreted as a preliminary characterization rather than definitive evidence of a stable ecological organization (Qin *et al.,* 2018). The 44% unrealized links may be associated with host specificity constraints, spatial organ segregation, and insufficient sampling to detect rare interactions. Parasitism differed significantly among host species: *A. aurantii* (10.48%) and *P. ziziphi* (10.00%) received the highest parasitism, *L. beckii* intermediate (8.57%), and *L. gloveri* and *P. aspidistrae* the lowest (1.90% each). Plant organ was a strong and significant determinant (Kruskal-Wallis H = 29.04, $p < 0.001$): fruits (11.14%) > leaves (7.43%) > branches (1.14%; Fig. 5). Four host species showed peak parasitism on fruits (4.3–17.1%); *P. ziziphi* peaked on leaves (18.6%). This nearly ten-fold fruit-to-branch gradient may be attributable to microclimate differences, differential host accessibility (Hoffmann and Frodsham, 1993), organ-specific metabolite profiles (Tena and García-Marí, 2011b), and HIPV-mediated attraction (Abdala-Roberts *et al.,* 2019), though none were directly measured. Scale populations on branches experienced a markedly lower parasitism rate (1.14%), indicating reduced parasitoid regulation in branch tissues; complementary management interventions, such as pruning or selective biorational applications, are highly recommended to suppress branch-associated refugia, regardless of parasitoid, to improve overall biological control efficiency.

Table 4: Host (armored scale insects) and the parasitoid specialization in citrus plants

Species	d' Value	Classification
Host		
Aonidiella aurantii	0.4945	Moderate
Lepidosaphes beckii	0.2621	Generalist
Lepidosaphes gloveri	0.4109	Moderate
Parlatoria ziziphi	0.2464	Generalist
Pinnaspis aspidistrae	0.4927	Moderate
Parasitoid		
Aphytis melinus	0.2275	Generalist (5 hosts)
Encarsia perniciosi	0.2424	Generalist (5 hosts)
Encarsia suzanae	0.6756	Specialist (1 hosts)
Encarsia sp.	0.5439	Specialist (1 hosts)
Marietta sp.	0.5317	Specialist (1 hosts)

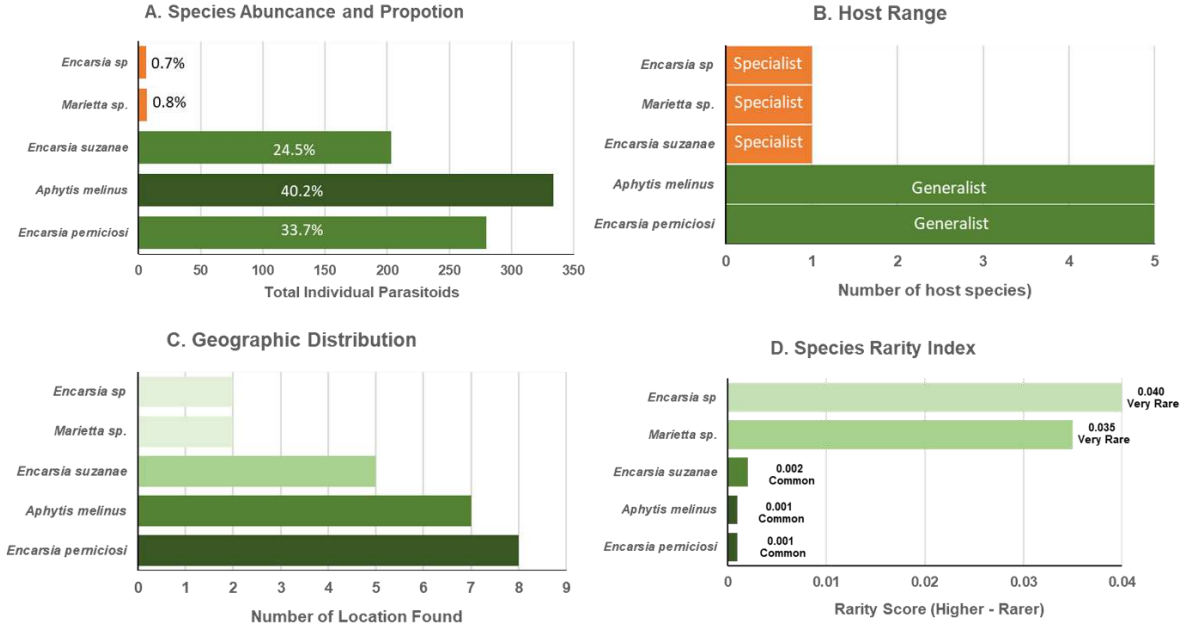

Fig. 3: Ecological characteristics of the five parasitoid species. (A) Total abundance and species composition; (B) Host range breadth; (C) Geographic distribution across sampling locations; (D) Species rarity index

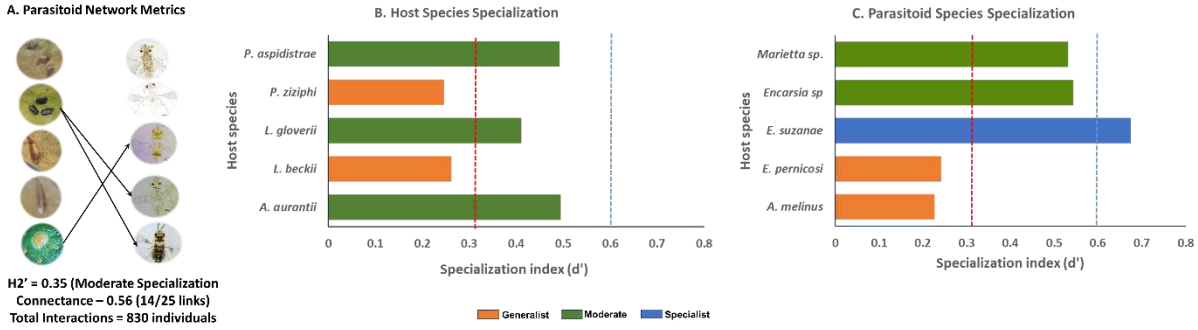

Fig. 4: Host–parasitoid interaction network and species-level specialization. (A) Bipartite network diagram; line thickness represents interaction strength. (B) Species-level specialization indices (d') for hosts and parasitoids; colors denote generalists (d' < 0.3), moderate specialists (0.3 ≤ d' < 0.6), and specialists (d' ≥ 0.6)

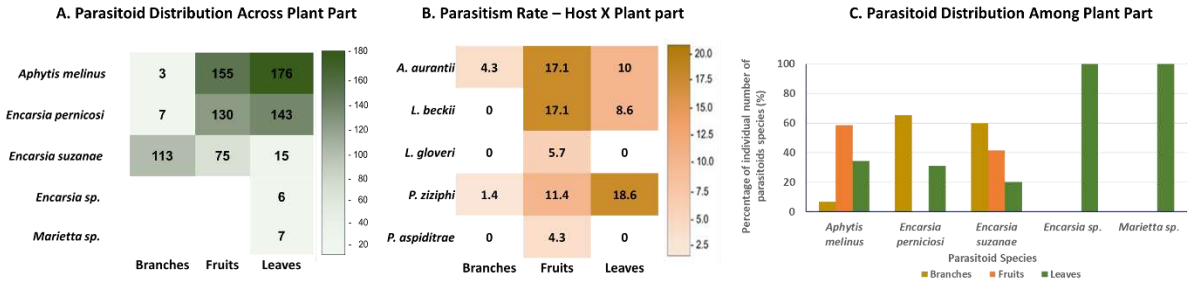

Fig. 5: Spatial distribution of parasitoid-host interactions across plant parts. (A) Parasitoid abundance by plant part; (B) Host parasitism rates showing parasitoids preferring patterns; (C) Parasitoid microhabitat partitioning on plant parts

release strategy deployed. Multi-criteria assessment yielded *A. melinus* (BPS = 0.85), *E. perniciosi* (BPS = 0.78), and *E. suzanae* (BPS = 0.75) as high-priority candidates (Fig. 6), with rankings robust across all 30 weight combinations (BPS ranges: 0.750–0.893, 0.738–0.891, and 0.411–0.571, respectively). Both *Encarsia* sp. and *Marietta* sp. scored below 0.20 on the composite index. Notably, in the case of *Marietta* sp., its presumed obligate hyperparasitoid status would fundamentally preclude its utility as a biological control agent, irrespective of its numerical score. *A. melinus* exhibited the broadest host range, highest abundance, and widest geographic distribution. *E. perniciosi* may be associated with an extended parasitism window through younger-instar preference. *E. suzanae* warrants targeted deployment against *A. aurantii* given its specialist efficiency. Effective implementation requires organ-specific targeting: fruit-focused releases are recommended for *A. aurantii*, *L. beckii*, and *L. gloveri*; leaf-targeted releases for *P. ziziphi*; and horticultural mineral oil or selective insecticides for branch populations. Drawing from comparable citrus systems, achieving meaningful biological control in this region will require a multi-faceted management framework. First, selective pesticide protocols must be implemented to preserve extant natural enemies, alongside targeted interventions to disrupt ant–scale mutualisms (Calabuig *et al.,* 2014). Second, given the pressures of global warming, incorporating endoparasitoids with broader thermal tolerances could provide a vital, climate-resilient complement to Aphytis populations (Furlong and Zalucki, 2017; Shah *et al.,* 2025). Ultimately, the efficacy of these combined strategies awaits definitive field validation under East Java conditions. Three findings merit particular attention. First, documentation of five Aphelinidae species in East Java citrus addresses a gap in the regional literature, an observation consistent with an extension of known distributions to a previously undocumented agroecosystem. Second, bipartite network analysis indicated moderate specialization (H2' = 0.35) with generalist resilience and specialist efficiency, a configuration consistent with community resilience against host population fluctuations, though constrained by small network size (5 × 5 taxa). Third, plant organs emerged as the primary spatial determinant of parasitism. The ten-fold fruit-to-branch gradient observed here represents one of the most pronounced microhabitat effects documented to date in Diaspididae-parasitoid systems. Future priorities include implementing molecular barcoding across all parasitoid taxa, conducting manipulative microhabitat experiments, and executing field trials for organ-targeted augmentative release programs under diverse agroecological and climatic conditions.

CONCLUSION

The present study provides the first systematic documentation of Aphelinidae parasitoid communities associated with Diaspididae in Indonesian citrus agroecosystems, filling a critical gap in tropical biological control knowledge and practice, where no comparable quantitative

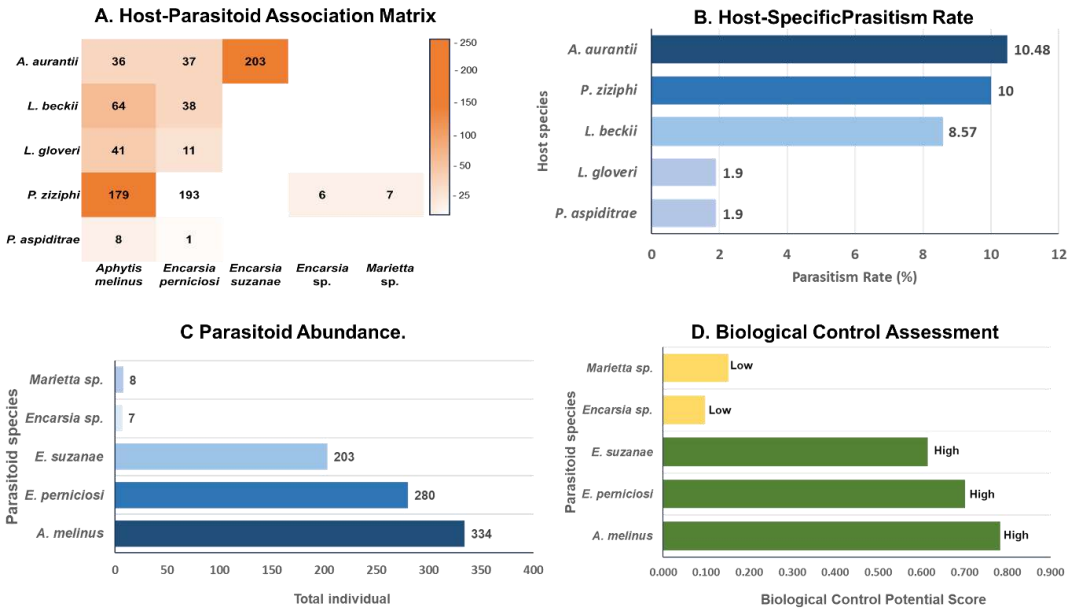

Fig. 6: Host-parasitoid associations and biological control assessment. (A) Association matrix showing parasitoid abundance per host-parasitoid pair; (B) Host-specific parasitism rates; (C) Total parasitoid abundance; (D) Biological control potential scores integrating multiple efficacy metrics

inventory existed in the regional literature. The five parasitoid species exhibited a functionally complementary community structure, with dominant generalists (*A. melinus* and *E. perniciosi*) consistent with community resilience and specialist *E. suzanae* associated with targeted suppression of *A. aurantii*. Community composition was stable across elevation zones and seasons, suggesting persistent parasitoid activity throughout the study period. This stability implies that conservation biological control strategies may be uniformly applied without season-specific management adjustments, although this approach awaits confirmation through higher-frequency temporal sampling. Plant organ emerged as the primary spatial determinant of host–parasitoid interaction structure, with parasitism differing nearly tenfold between fruits and branches — among the strongest microhabitat effects documented in any Diaspididae system. This organ-level gradient is likely driven by multiple interacting mechanisms, including microclimate variations, differential host accessibility, and organ-specific volatile profiles. Although these individual factors were not directly quantified in the present study, they provide compelling hypotheses for future mechanistic investigation. Effective biological control in structurally complex citrus canopies is therefore dependent on organ-specific rather than uniform canopy-wide release strategies. Branch-dwelling populations, experience substantially lower parasitism rates (below 5%), thereby evading effective natural regulation by parasitoids. Consequently, supplementary management interventions—utilizing either horticultural mineral oil or selective systemic insecticides—are required, irrespective of the specific parasitoid release strategy implemented. *A. melinus* (BPS = 0.85), *E. perniciosi* (BPS = 0.78), and *E. suzanae* (BPS = 0.75) were ranked as high-priority augmentative biological control candidates, with rankings robust through sensitivity analysis across 30 weight combinations. These three species exhibited high field abundance, extensive host utilization, and broad geographic distribution — attributes that align with the criteria for effective augmentative biological control agents. The

classification of *Marietta* sp. as a putative hyperparasitoid necessitates strict caution; if validated, its overall impact on biological control efficacy would be detrimental. Consequently, this taxon should be excluded from management recommendations until its trophic position is verified via dissection. The 6.57 percent parasitism rate represents a natural unmanaged baseline; although relatively modest modest, improvement is biologically plausible under optimized conditions, including selective pesticide protocols and ant–scale mutualism management. Several host–parasitoid associations documented in this study, including *E. perniciosi* parasitizing *L. gloveri*, *P. ziziphi*, and *P. aspidistrae*, and the occurrence of *E. suzanae* and *Marietta* sp. in East Java, represent putative new records for Indonesia, the significance of which is contingent on molecular verification. Exclusive reliance on morphological identification is acknowledged as a limitation; all identifications constitute a recognized limitation of this study; consequently, all taxonomic designations are best considered morphospecies-level assignments pending molecular barcoding to definitive verify species boundaries. The documented occurrence of cryptic species within *Aphytis* and *Encarsia* suggests that the true diversity of interacting taxa may be higher than reported, an observation with potential implications for network specialization estimates and biological control potential assessments. Collectively, these findings establish a preliminary ecological framework for the integration of indigenous parasitoid communities into spatially targeted integrated pest management programs in East Java citrus agroecosystems. Future research initiatives should prioritize the molecular barcoding of all five parasitoid taxa, alongside manipulative microhabitat experiments to elucidate the mechanisms driving organ-level parasitism gradients. Furthermore, characterizing the thermal performance profiles of *E. perniciosi* and *E. suzanae* under East Java conditions, paired with field trials of organ-targeted augmentative release programs is essential to quantify empirical biological control efficacy. Pending independent field validation, these findings establish a scientifically rigorous baseline for the development of low-input IPM strategies within complex tropical citrus agroecosystems. Furthermore, this predictive model possesses broader utility, with potential scalability to ecologically analogous tropical citrus systems characterized by comparable host–parasitoid assemblages.

AUTHOR CONTRIBUTIONS

D.A. Sunarto developed the study concept, designed the experiment, conducted the fieldwork, interpreted the findings, and prepared the initial draft of the manuscript. Nurindah contributed to the conceptualization and design of the study, performed data analysis and interpretation, revised the manuscript, and served as the corresponding author. B.T. Raharjo supervised the work and contributed to writing and editing the manuscript. H. Tarno assisted in the interpretation of data analysis, manuscript revision, and supervision. A. Afandhi contributed to writing and editing the manuscript. All authors reviewed and approved the final version of the manuscript prior to submission.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors. Ethical clearance for field collection was obtained through the institutional review process under the RIIM Competitive Research Scheme Batch 3 (LPDP). Field sampling was conducted with permission from orchard owners at all sites.

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ABBREVIATIONS

%	Percent
^oC	Degree Celsius
AICc	Akaike information criterion corrected (for small sample sizes)
asl	above sea level
BPS	Biocontrol potential score(s)
BRIN	Badan Riset dan Inovasi Nasional (National Research and Innovation Agency of Indonesia)
CI	Confidence interval
d'	species-level specialization index (bipartite network)
DHARMa	Residual diagnostics for hierarchical models
DNA	Deoxyribonucleic acid
GLMMs	Generalized linear mixed models
GPS	Global positioning system
H'	Shannon Diversity Index
H2'	network-level specialization index (bipartite networks)
HIPVs	Herbivore-induced plant volatiles
iNEXT	Interpolation and EXTrapolation
IPB	Institut Pertanian Bogor (Bogor Agricultural University)
IPM	Integrated pest management
J'	Pielou's Evenness Index
KOH	Potassium hydroxide
MCDA	Multi-criteria decision analysis
mm	millimeters
MZB	Museum Zoologicum Bogoriense
RH	Relative humidity

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ORIGINAL RESEARCH ARTICLE

Urban environmental visibility factors from street-view imagery using fine-tuned deep learning

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ABSTRACT

BACKGROUND AND OBJECTIVES: Street-level urban view factors are important indicators for assessing urban form. Environmental conditions and greenery exposure ultimately dictate residents' quality of life; however, robust evaluation frameworks for assessing these determinants are still limited. This limitation is primarily due to the challenges in collecting extensive field data across large urban areas. To address this limitation, the objectives of this study were to leverage existing street-view imagery. This approach can be a cost-effective and widely available data source for urban environmental assessment. This study introduces an evaluative framework for quantifying building, tree, and sky view factors through the application of advanced deep learning models.

METHODS: A DeepLabV3+ model, pre-trained on the Cityscapes dataset, was selected for this study. To identify critical urban landscape features (buildings, trees, and sky), the model underwent localized fine-tuning aimed at enhancing predictive performance. In the fine-tuning process, manually annotated street-view images collected directly from the study area were used. The historic city center of Chiang Mai, Thailand, was selected as the research site. Street-view images were collected using the Google Street View Static application programming interface. To enhance segmentation performance under local urban conditions, several data augmentation strategies were examined and benchmarked against a baseline model.

FINDINGS: The site-specific fine-tuning significantly enhanced model performance. The results demonstrated that combining various data augmentation strategies provides greater robustness than single-method approaches. The multi-augmentation model achieved an optimal mean intersection over union of 0.908. This metric reflected robust performance in the segmentation of buildings, trees, and sky features. Statistical analysis revealed a strong negative correlation between building view factor and tree view factor (ρ= -0.71, $p < 0.001$). This inverse relation reflects both urban spatial arrangements and intrinsic compositional class limitations.

CONCLUSION: This study demonstrates the effectiveness of combining localized fine-tuning and multiple data-augmentation techniques to adapt DeepLabV3+ to the complex urban environment of Chiang Mai. The model improves urban view factor extraction accuracy. This study systematically evaluates localized fine-tuning and data-augmentation strategies and demonstrates that a relatively small, locally labelled dataset can effectively improve the performance of a pretrained model in a site-specific urban context.

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INTRODUCTION

Rapid and unmanaged urban expansion widely undermines the quality of life and long-term livability in urban environments. This environmental challenge is particularly pronounced in developing nations. In this global context, Thailand serves as a highly vulnerable area (Prakaisak *et al.,* 2026). Critical environmental challenges driven by urban heat island (UHI) phenomena and escalating heatwaves demand rigorous climate and infrastructure adaptation strategies (Gabrian *et al.,* 2025). Concurrently, the physical urban environment is recognized as an important determinant of psychological well-being. Specifically, these surroundings play a key role in improving mental health and reducing stress (Reid *et al.,* 2022; Wedyan and Saeidi-Rizi, 2024; Suppakittpaisarn *et al.,* 2025). Furthermore, access to urban green spaces is recognized as a vital component in promoting the well-being of urban populations (Egbosimba, 2025). Emerging evidence indicates that sufficient exposure to green spaces confers substantial psychological health benefits (Jiang *et al.*, 2025). Outdoor thermal comfort (OTC) is also recognized as a primary determinant of pedestrian route choice and walking behavior (Suwanmanee *et al.*, 2024). Due to inherent budgetary and personnel constraints, traditional urban element surveys frequently present significant challenges (Iamtrakul *et al.*, 2024); consequently, convolutional neural networks (CNNs) have been widely adopted for street-level image classification. These models primarily leverage Google street view (GSV) data. Urban morphology studies increasingly validate GSV as a reliable proxy for field surveys. This approach effectively quantifies key urban indices. These indices include the building view factor (BVF), sky view factor (SVF), and tree view factor (TVF) (Gong *et al.*, 2018). Conceptually, TVF shares a similar scope with the green view index (GVI); while the former broadly encompasses total vegetation including trees and grass, GVI specifically denotes the overall proportion of visible greenery from the observer's perspective (Liu *et al.*, 2023). Extending these conceptual foundations, this investigation seeks to capture pedestrian-level visual perspectives. Rather than converting planar street-view imagery into hemispherical projections, this study directly examines planar GSV data, ensuring that the quantified proportions of building, vegetation, and sky reflect an eye-level observer's visual field. To reflect this perspective, the terms visible building view factor (VBVF), Visible tree view factor (VTVF), and visible sky view factor (VSVF) are used in this study. Rather than serving as mere environmental metrics, these factors describe key visual characteristics of the urban environment. Collectively, these visual characteristics dictate residents' perceptions of urban density and overall psychological health (Sabir *et al.*, 2025). However, the efficacy of models trained on global datasets remains questionable when applied to other cityscapes with distinct characteristics (Thitisiriwech *et al.*, 2022). Furthermore, object occlusion in street-level imagery, caused by obstacles like dense foliage, introduces significant distortions into the calculation of urban physical indices (Yan *et al.*, 2025). The application of deep learning (DL) is proposed to identify these obstructions and enhance the accuracy of urban spatial modeling (Wang *et al.*, 2022). Model fine-tuning and data augmentation serve as pivotal approaches to resolve classification difficulties (Tsuchiya *et al.*, 2019). These techniques are crucial for complex urban environments with high object diversity. DL has significantly advanced the semantic segmentation of urban elements in geographical and street-level imagery. Nevertheless, the scarcity of appropriate training datasets continues to present a significant hurdle, particularly for municipalities exhibiting distinct urban profiles absent in standard benchmark datasets. Consequently, image data augmentation is employed as a pivotal process to address the scarcity of labeled data and to reduce statistical imbalances within datasets (Shorten and Khoshgoftaar, 2019). Appropriate augmentation strategies, including color adjustment, rotation, horizontal flipping, and Gaussian blurring, were

adopted to maximize semantic segmentation efficacy and control for overfitting (Tsuchiya *et al.*, 2019). Regarding architectural models, DeepLabV3+ integrates Atrous Convolution and Atrous Spatial Pyramid Pooling (ASPP) with an encoder-decoder structure, effectively addressing the loss of spatial detail during downsampling (Chen *et al.*, 2018; Hao, 2025). This framework excels at extracting multi-scale contextual features from complex urban environments while maintaining high segmentation accuracy. Furthermore, DeepLabV3+ provides a reliable benchmark for streetscape evaluation, combining structural robustness, ease of implementation, and modest hardware demands—making it well-suited for fine-tuning on localized datasets and wider urban deployments (Alokasi and Ahmad, 2022). The DeepLabV3+ architecture with a ResNet-101 backbone was selected for its strong transfer learning capabilities and feature extraction performance. This combination effectively balances precision and computational efficiency when segmenting complex urban elements from streetscape imagery. Accordingly, this study focuses on implementing DeepLabV3+ for localized urban fine-tuning to ensure compatibility with standardized city datasets. Model robustness to noise in street-level imagery remains critical for semantic segmentation architectures. This robustness directly affects the reliability of empirical results. Consequently, training processes must account for environmental factors such as cast shadows, vegetation occlusion, and illumination variations (Kamann and Rother, 2020). Research within Thailand using the Bangkok Urbanscapes dataset underscores the importance of localized fine-tuning (Thitisiriwech *et al.*, 2022). This process significantly improves semantic segmentation performance for models pre-trained on standard datasets like Cityscapes (Cordts *et al.*, 2016). Such targeted adaptation can significantly improve semantic segmentation performance for identifying locally distinctive urban features. Notable examples include Thai-style roofs, utility poles, and municipal signage. The integration of artificial intelligence (AI) with street-view imagery has received increasing attention in recent years. This combination serves to quantify physical urban indicators. Recent studies increasingly rely on automated computational approaches to evaluate building coverage as a core metric for characterizing urban morphology (Gong *et al.*, 2018). Similarly, visible urban greenery represents a key indicator of urban livability from the observer's perspective (Liu *et al.*, 2023). Additionally, sky openness indicators such as VSVF are widely recognized as a key indicator of OTC (Middel *et al.*, 2017). The validity of these metrics in modern, densely populated environments—typified by Hong Kong—was previously established by foundational studies such as Gong *et al.* (2018). However, significant challenges remain when transferring these models to different spatial contexts. Historic tropical urban environments present a substantial domain shift. Distinct vernacular architecture, complex tree canopy occlusions, and severe illumination fluctuations degrade the performance of models pre-trained on global or modern urban datasets. To overcome existing methodological constraints, we advance traditional view-factor extraction methods by developing a specialized, location-specific fine-tuning approach. By systematically evaluating multiple data augmentation strategies tailored to tropical streetscape conditions, this approach resolves local feature classification ambiguities and improves spatial model generalization in historic urban settings. The measurement of sky openness (evaluated as VSVF in this study) and visible greenery (evaluated as VTVF) is essential, as both parameters represent critical variables in urban microclimate analysis (Suwanmanee *et al.*, 2024; Solanki *et al.*, 2025). For this reason, low VSVF in areas with dense vegetation can indicate favorable conditions for maintaining OTC during the day. These urban indicators derived from semantic segmentation models can be integrated into a web-based geographic information system (WebGIS) platform to support urban analysis and planning (Varras *et al.*, 2016; Grêt-Regamey *et al.*, 2017;

Gebetsroither-Geringer *et al.*, 2018). However, the literature reveals a significant research gap. Specifically, challenges arise when applying semantic segmentation to street-level imagery within highly complex urban environments. The integration of data augmentation techniques and systematic image filtering procedures is essential. This approach serves to improve data quality and enhance model robustness (Hartley, 2025). This study aims to develop a site-specific fine-tuning approach for semantic segmentation of urban street-level imagery to estimate VBVF, VTVF, and VSVF. The study is conducted in Chiang Mai, Thailand, with data collected via the application programming interface (API) of GSV service in 2025.

MATERIALS AND METHODS

Methodologically, the workflow is divided into seven core phases: defining study area characterization, local streetscape data collection, dataset preparation, semantic segmentation modeling, implementation details and setup, urban view factor analysis, and model performance indicators. The details of each part are described in the following subsections.

Study area characterization

The study area is the Old City of Chiang Mai, located in Chiang Mai province in northern Thailand (Fig. 1). This region is centered at approximately 18.78° N, 98.99° E, covering an area of approximately 4.56 square kilometers (km^2). As a historic urban center in a tropical environment, the study area features diverse architectural styles and low-rise urban buildings. These settings are characterized by narrow streets, abundant roadside vegetation, and complex streetscapes. The dense arrangement of buildings and vegetation also creates frequent visual occlusions, while tropical illumination introduces additional visual variability. By comparison to the study area, the Cityscapes dataset predominantly captures modern European urban morphology—environments distinguished by wider street networks, clear roadway markings, consistent building alignments, and highly organized spatial elements (Fig. 2). Consequently, the specific characteristics of the study area are not fully represented in such common datasets. This difference creates a domain gap and limits model generalizability. Therefore, the study area serves as an appropriate testbed for assessing the effectiveness of localized model adaptation and fine-tuning strategies.

Local streetscape data collection

Street-level imagery was collected using GSV to quantify urban view factors within the study area. Sampling locations were generated in QGIS Software. This process generated 2,640 valid sample locations at 30 meters (m) intervals across the road network, with corresponding street-view images retrieved via the GSV Static API in 2025. The actual acquisition dates ranged from 2011 to 2024. The dataset is predominantly composed of recent imagery, with 2024 representing the largest proportion (1,422 sample points), whereas earlier years such as 2014, 2018, and 2021 accounted for the fewest representations, with 1 sample point each. Dataset quality control involved automated screening during API retrieval to eliminate locations with incomplete metadata or unavailable street view imagery, substituting each with the closest structurally compliant sampling locations along the road network. Additionally, a visual quality check was conducted on the retrieved imagery to verify that no severe artifacts, extreme blurring, or blocking occlusions hindered the identification of the three target urban elements. Following the methodology of Liu *et al.* (2023), four images were acquired at headings of 0°, 90°, 180°, and 270° (at pitch = 0°) for each sampling location to capture the surrounding streetscape closer to the pedestrian perspective. This configuration is considered appropriate because each captured frame features a 90° horizontal field of view (FOV). However, despite this comprehensive spatial coverage, perspective distortion at the image periphery may slightly reduce the accuracy of the derived view factors. Overall, this process resulted

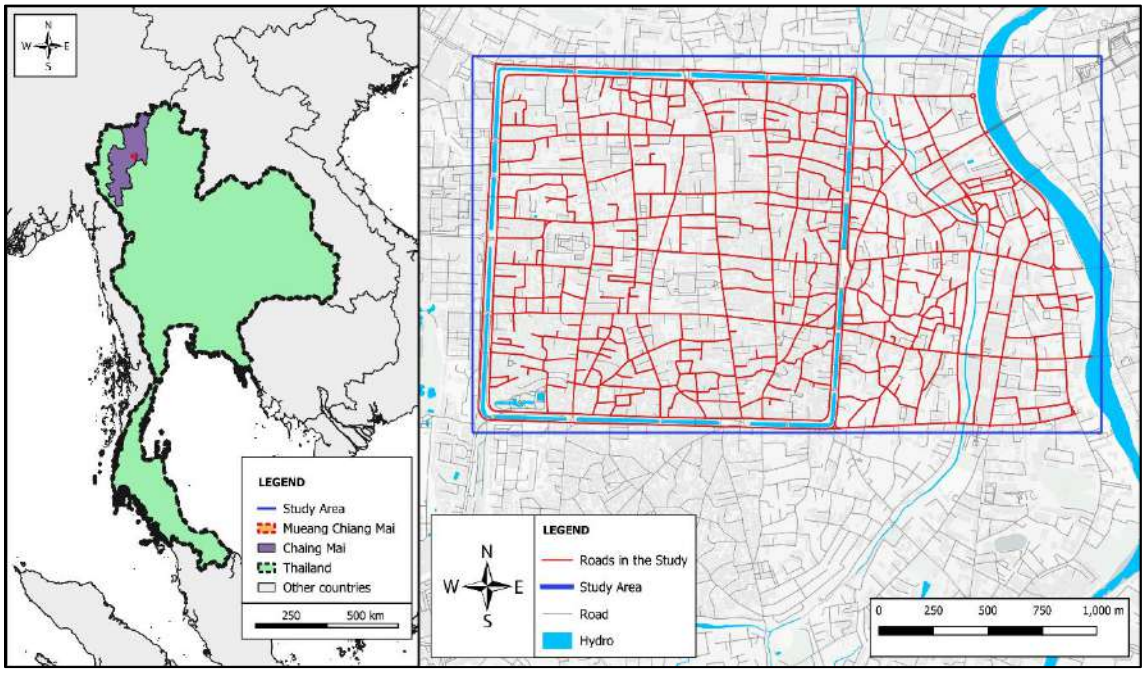

Fig. 1: Geographical location of the study area in Chiang Mai, Thailand



(a) (b)

Fig. 2: Comparison of representative street-view environments between (a) the Cityscapes dataset and (b) the study area

in a dataset of 10,560 images across 2,640 sampling locations. Averaging the four directional view factors at each point eliminates directional bias. This averaging approach ensures that the urban environmental indicators derived remain both reliable and spatially representative at each sample location (Gong *et al.*, 2018; Li *et al.*, 2017).

Dataset preparation

The Cityscapes dataset was employed as the primary training dataset for developing the semantic segmentation model. The imagery used in this study was acquired at a resolution of 640 × 640 pixels. This resolution has been widely adopted in previous urban morphology studies. This setting serves to capture critical architectural details and urban elements required for high-accuracy semantic segmentation (Han *et al.*, 2022; Nguyen *et al.*, 2020). To improve model applicability to the local urban context, a subset of 100 locally collected street-view images was selected for model fine-tuning. To reduce the risk of spatial data leakage, a spatially separated stratified sampling approach was used for image selection. A subset of 100 images was collected to represent diverse urban typologies, characterized by varying proportions of structural elements, vegetation cover, and sky visibility. Based on the sampling process in the previous section, a minimum distance of 30 m was maintained between sampling locations. Within the scope of this study, this distance interval effectively captures localized streetscape heterogeneity while ensuring statistical independence among samples. Furthermore, restricting the selection to a single image per sampling point minimizes visual scene overlaps, redundant camera headings, and shared background structures. This strategy guarantees that the test set provides a robust measure of model transferability across varied spatial environments. Following image selection, the 100 street-view images were manually annotated. This dataset was prepared using the computer vision annotation tool (CVAT) for localized fine-tuning. This study focuses specifically on three classes: building, vegetation, and sky. However, all 19 semantic classes from the Cityscapes dataset were manually annotated. This approach maintains full consistency with original label definitions. Retaining all classes preserves vital spatial context and pre-trained feature representation during localized fine-tuning. It also prevents object boundary confusion along overlapping streetscape elements. For view-factor quantification, target outputs were mapped directly to their corresponding semantic classes. The building class was used to derive VBVF. The vegetation class, encompassing trees and hedges, was used for the VTVF. The sky class was used for the VSVF. Although the manually labeled dataset is limited in size, systematic augmentation techniques were applied. These methods serve to increase data diversity and improve model generalization. The augmentation methods included color adjustment, Gaussian blur, image flipping, and image rotation. Color adjustment modifies the image's color properties. Gaussian blur smooths the image. Image flipping changes the image orientation. Image rotation changes the viewing angle. These augmentation methods are illustrated in Fig. 3.

Semantic segmentation modeling

This study employs DeepLabV3+ pre-trained on the Cityscapes dataset as the primary architecture for semantic segmentation. As a widely adopted benchmark, Cityscapes feature diverse urban streetscapes and semantic classes standard for training segmentation models (Cordts *et al.*, 2016). As illustrated in Fig. 4, DeepLabV3+ utilizes an encoder-decoder architecture to capture spatial and contextual information effectively. The encoder leverages Atrous Convolution and Atrous Spatial Pyramid Pooling (ASPP) to extract multi-scale contextual features without losing spatial resolution during down sampling. To maintain structural fidelity during semantic parsing, the decoder synthesizes global contextual cues with fine-grained spatial representations, thereby optimizing boundary delineation for street-level urban data. To improve performance, a localized fine-tuning process was implemented.



Fig. 3: Examples of data augmentation techniques applied to GSV images, to enhance the diversity and representativeness of the training dataset

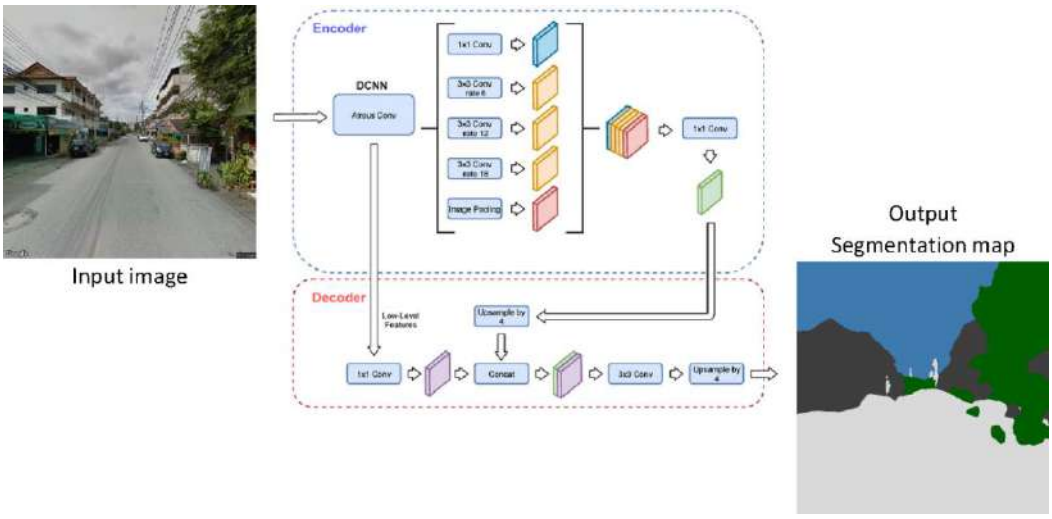

Fig. 4: Architecture diagram of DeepLabV3+

This process involved adjusting model weights with a local image dataset. ResNet-101 serves as the backbone network due to proven effectiveness in urban scene segmentation (Chen *et al.*, 2018). The study area encompasses a compact spatial extent characterized by high morphological homogeneity across urban streetscapes. To preserve sample diversity and prevent spatial redundancy, a manually annotated local dataset of 100 images was partitioned into training with 70 percent (%), validation (15%), and testing (15%) sets using a stratified selection strategy. This approach ensured that key urban features, including varying building densities, tree canopy cover, and open sky, were proportionally distributed across all subsets while preventing spatial redundancy. The training set was utilized for localized fine-tuning. Meanwhile, the validation and testing sets remained unchanged throughout all experiments. Seven experimental cases were established to evaluate the effects of different data augmentation strategies, as shown in Table 1. These cases include the pre-trained baseline model and six localized fine-tuning models with different augmentation strategies. The base training set of 70 images was utilized directly for Case-01 un-augmented fine-tuning and Case-06. For Cases-02 through Case-05, offline augmentation was applied exclusively to the 70 training images. Each technique generated 70 additional images, expanding the training subset to 140 images. These single-technique augmentations included color adjustment with a saturation factor of 1.5, Gaussian blur with a radius of 1.5 pixels, horizontal flipping, and random rotation between -15° to 15° at 1° steps.

Table 1: Configuration of experimental settings for model training and evaluation

Name	Training dataset (images)		Augmentation technique applied to local dataset	Augmented dataset
	Cityscape dataset	Local dataset		
Baseline model	2,795	0	None	0
Case-01	2,795	70	None	0
Case-02	2,795	70	Color adjustment	70
Case-03	2,795	70	Gaussian Blur	70
Case-04	2,795	70	Horizontal Flip	70
Case-05	2,795	70	Rotate	70
Case-06	2,795	70	Multi-augmentation	70

Additionally, Case-06 evaluated a dynamic multi-augmentation strategy applied on-the-fly during training to the 70 training images. Within this pipeline, multiple transformations were applied continuously per batch: random horizontal flipping (p = 0.5), random rotation between -15° and 15° (p = 1.0), random brightness and contrast adjustments within a [0.8, 1.2] factor range, and Gaussian blur with a 3×3 kernel size. This dynamic approach introduced variability across training epochs while avoiding dataset over-expansion. Furthermore, a previous study by Kamann and Rother (2020) demonstrated that ResNet-101 architecture possesses strong intrinsic robustness against noise and environmental variations. Integrating this foundational backbone within the architectural framework enhances robustness in handling real-world variations in illumination and shadows across streetscape imagery.

Implementation details and setup

All experiments and localized fine-tuning models were developed using Python (v3.12.3) and the PyTorch deep learning framework with CUDA acceleration. A fixed random seed of 42 was employed across all parameter initialization and data splitting routines to ensure the reproducibility of the experiments. Training and evaluation were executed on a hardware setup equipped with an AMD Ryzen 7 2700X CPU, 32 GB of RAM, and an NVIDIA GeForce RTX 3090 GPU (24 GB VRAM). The DeepLabV3+ architecture with a ResNet-101 backbone was initialized using pre-trained weights from the Cityscapes dataset. A full fine-tuning strategy was implemented, permitting the iterative update of all constituent network layers. All experimental configurations were trained using the Adam optimizer with a learning rate of 10^{-4}, a batch size of 4, and 250 training epochs. Pixel-level prediction errors were calculated using the categorical cross-entropy loss function. Model checkpoints were saved based on the highest validation mIoU. To prevent data leakage, the independent test set was strictly held out during training. It was evaluated only after the best model was selected.

Urban view factor analysis

Following semantic segmentation, three urban view factors were derived from the segmented GSV images: VBVF, VTVF, and VSVF. These indicators represent the proportion of image pixels classified as buildings, vegetation, and sky, respectively, relative to the total number of pixels in each image. The calculations of urban view factors, specifically VBVF, VTVF, and VSVF are defined using Eqs. 1 to 3 (Middel *et al.*, 2017):

$$VBVF = \frac{P_{build}}{P_{total}} \quad (1)$$

$$VTVF = \frac{P_{veg}}{P_{total}} \quad (2)$$

$$VSVF = \frac{P_{sky}}{P_{total}} \quad (3)$$

Where:

P_{build} = Total number of building pixels

P_{veg} = Total number of vegetation pixels

P_{sky} = Total number of sky pixels

P_{total} = Total number of pixels in the entire image frame

Therefore, the cumulative sum of VBVF, VTVF, and VSVF is naturally less than or equal to 1.0 (VBVF + VTVF + VSVF ≤ 1.0). For each sampling location, metrics extracted from the four-directional street-view images were averaged to derive a composite index representing the overall visual composition of the surrounding urban environment. The relationships between VBVF, VTVF, and VSVF were examined using Spearman's rank correlation coefficient (ρ). Spearman's correlation was selected over Pearson's correlation because normality assumptions were violated, with VBVF (skewness = 0.68) and VTVF (skewness = 0.66) exhibiting moderate right-skewness. The correlation analysis was conducted to assess the magnitude and direction of pairwise associations among the extracted visible view factors across the study area.

Model performance indicators

Model performance was evaluated using mean intersection over union (mIoU) and pixel accuracy (PA) for the three target classes: building, vegetation, and sky. The mIoU metric was calculated as the average intersection over union (IoU) across the three classes. In contrast, PA quantifies the overall proportion of correctly classified pixels across the entire image. Among the evaluated metrics, mIoU was adopted as the primary performance indicator, as it assesses class-specific segmentation accuracy individually and exhibits greater resilience to class imbalance than PA, thereby providing a more reliable, comprehensive, and robust evaluation of segmentation performance across diverse urban scenes.

RESULTS AND DISCUSSION

The results are presented in four sections: model performance evaluation, spatial distribution of urban view factors, urban view factor correlation analysis, and study limitations.

Model performance evaluation

Table 2 contrasts the experimental outcomes across the seven distinct configurations, demonstrating that localized fine-tuning considerably enhances the accuracy of the DeepLabV3+ model within the study area. The mIoU improved after localized fine-tuning with street-view imagery collected from the study area. This site-specific fine-tuning with local data aligns with the findings of Gong *et al.* (2018). This approach is crucial for bridging the gap between global datasets and actual spatial contexts. The quantitative evaluation metrics for all seven experimental setups are detailed in Table 2. Localized fine-tuning improved segmentation performance compared to the baseline model trained solely on Cityscapes. Among all configurations, Case-06 (multi-augmentation) achieved the highest numerical scores, reaching an mIoU of 0.908, pixel accuracy (PA) of 0.967, and F1-score of 0.951, which were closely comparable to Case-02 (mIoU of 0.906). These results demonstrate that both color-based modifications and multi-augmentation strategies achieved high segmentation accuracy, with Case-06 providing an optimal balance that facilitated robust model generalization across heterogeneous streetscape components. Fig. 5 illustrates the distribution of class-wise IoU values across the experiments. Across all fine-tuned cases, Sky consistently yielded high IoU values with low variability, peaking at 0.990 in Case-02. This indicates that color adjustment effectively stabilized sky segmentation under varying illumination conditions. Vegetation-IoU reached its maximum of 0.915 in Case-01, where the distribution showed a higher median value compared to the baseline model. This finding indicates that model fine-tuning conducted in the absence of spatial transformations contributed to the preservation of boundary delineation in tree canopies. In contrast, the building class exhibited higher variance across most cases due to diverse architectural styles and irregular urban patterns. Compared to the baseline DeepLabV3+ model, the

Table 2: Overall performance metrics across experimental cases

Name	mIoU	PA	Precision	Recall	F1-score
Baseline model	0.759	0.882	0.859	0.884	0.862
Case-01	0.897	0.958	0.938	0.952	0.945
Case-02	0.906	0.965	0.937	0.961	0.949
Case-03	0.899	0.958	0.937	0.953	0.945
Case-04	0.882	0.956	0.924	0.948	0.936
Case-05	0.862	0.945	0.911	0.935	0.923
Case-06	0.908	0.967	0.938	0.963	0.951

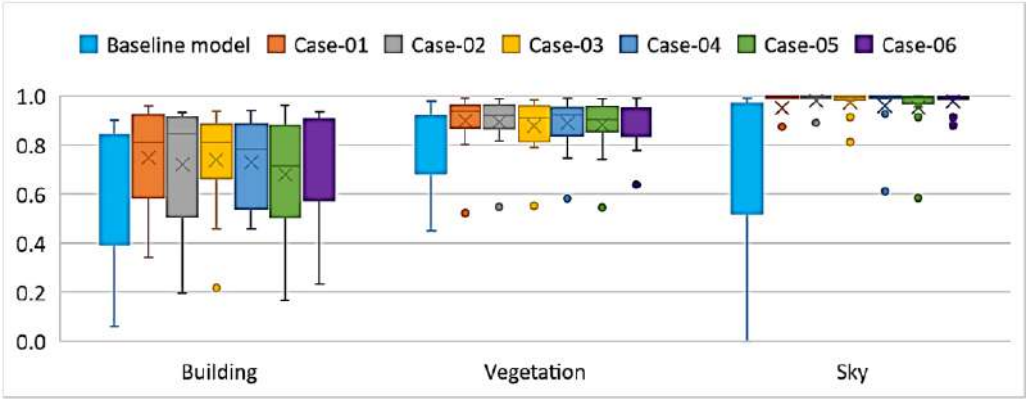

Fig. 5: The distribution of image-level IoU scores for each urban element under different data augmentation strategies (n = 15 test images)

fine-tuned multi-augmented model (Case-06) achieved substantial accuracy gains across all target classes, increasing Building IoU from 0.710 to 0.829, Vegetation IoU from 0.790 to 0.907, and Sky IoU from 0.777 to 0.988, yielding an overall mIoU improvement from 0.759 to 0.908. However, Case-06 also markedly reduced performance variability for the building class. The enhanced efficacy observed in the multi-augmentation configuration (Case-06) is attributable to its capacity to emulate the varied perspective distortions and illumination fluctuations characteristic of high-density tropical streetscapes. While color-based transformations alone (Case-02) stabilized Sky segmentation by accommodating exposure shifts, spatial and geometric augmentations were crucial for disentangling complex, overlapping features such as tree branches, utility poles, and fragmented building facades. These findings indicate that amplifying data variability via multi-augmentation strategies enables the model to effectively accommodate the intricate physical characteristics of the study area. Furthermore, visual inspection of the classification results presented in Fig. 6 demonstrates a clear improvement. Specifically, the model was fine-tuned with locally collected data using the multi-augmentation technique. Compared to the baseline configuration, the proposed model delineated building and vegetation boundaries with enhanced precision, most pronounced in urban microenvironments characterized by intricate infrastructure such as utility poles and overhead power lines.Additionally, this approach handles roadside vegetation, which is commonly found throughout the study area. The confusion matrix analysis is presented in Fig. 7. This Fig. 7 demonstrates substantial improvements achieved by the fine-tuned model using the multi-augmentation technique. For the sky class, the baseline model correctly classified only 79.49%,

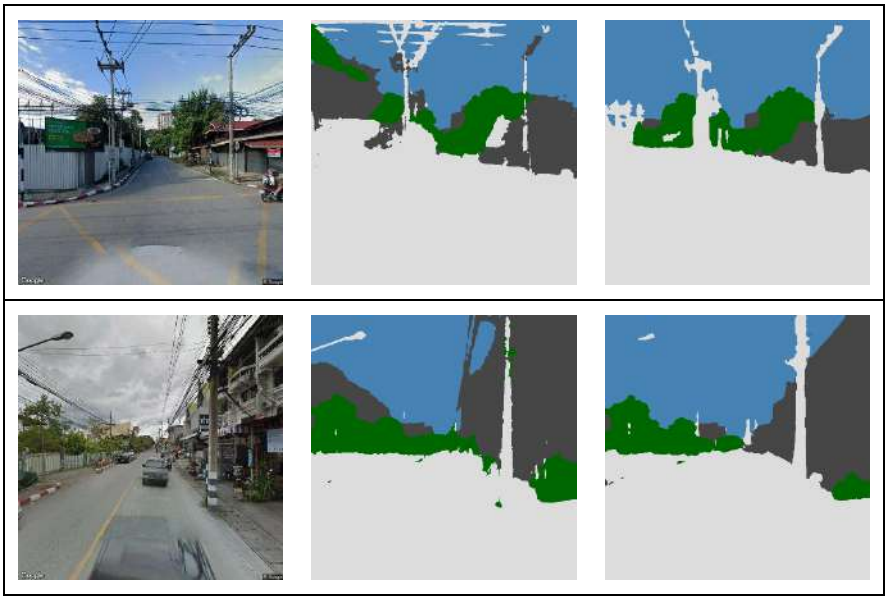

Fig. 6: Visual comparison of semantic segmentation results: (left) original street-view image, (middle) segmentation result from the baseline model, and (right) segmentation result from the model fine-tuned with local data using the multi-augmentation technique

	Predicted Building	Predicted Vegetation	Predicted Sky
Actual Building	95.61	4.28	0.12
Actual Vegetation	0.35	99.63	0.02
Actual Sky	15.29	5.22	79.49

(a)

	Predicted Building	Predicted Vegetation	Predicted Sky
Actual Building	97.83	1.47	0.71
Actual Vegetation	1.00	98.90	0.10
Actual Sky	0.20	0.19	99.61

(b)

Fig. 7: Confusion matrices of semantic segmentation results normalized by true class (%) for (a) the baseline case and (b) Case-06

and 15.29% were misclassified as buildings. In contrast, the multi-augmentation model elevated sky classification accuracy to 99.61% while decreasing the misclassification rate to 0.20%. These findings suggest the multi-augmentation technique improves the model's ability to distinguish classes under urban conditions. This observation is consistent with previous studies showing improved model accuracy is essential for semantic segmentation in complex and heterogeneous urban environments under varying conditions (Wang *et al.*, 2022).

Spatial distribution of urban view factors

This section presents the spatial distribution maps of VBVF, VTVF, and VSVF (Figs. 8 to 10(visually overlaid on the official urban land-use zoning map provided by the Department of Public Works and Town and Country Planning (DPT) via web map service (WMS). Across all maps, chromatic gradation corresponds to data magnitude, where lighter color intensities denote lower values and darker intensities indicate higher values. While vector feature data were unavailable for direct numerical attribute

extraction per polygon, the visual spatial overlay provides an official reference for contextualizing the distribution patterns across municipal land-use zones. Specifically, the VBVF distribution map (Fig. 8) shows that high values are mainly found in designated Commercial and Medium-Density Residential zones. These zones feature densely arranged buildings that form continuous street frontages. Conversely, the historic district and areas zoned for religious or open space purposes exhibit lower VBVF values, driven by higher spatial openness and more abundant roadside vegetation. This spatial distribution highlights underlying variations in urban morphology across the study area. Fig. 9 shows the spatial distribution of VTVF. Elevated VTVF values are primarily concentrated within the historic district, educational institution zones, and residential neighborhoods characterized by mature canopy trees and dense vegetation. Conversely, commercial and hospitality areas demonstrate significantly lower VTVF magnitudes. These lower values occur because buildings and other built surfaces occupy most of these spaces. This pattern highlights the important role of vegetation in the tropical urban landscape. High VSVF values are mainly observed in open areas (Fig. 10). These high VSVF areas are generally located outside zones with high VBVF or VTVF values. Representative instances comprise open roadway segments, agricultural conservation zones, and communal spaces characterized by minimal overhead obstructions. In contrast, streets lined with continuous buildings and tree canopies show lower VSVF values. These lower values occur because the surrounding features obstruct the sky view. The variations of these three maps align directly with the urban landscape of the study area and correspond to official land-use designations. These patterns reflect the diversity of urban structures and land cover. However, the spatial distribution maps alone do not explicitly reveal the underlying interrelationships among the visible view factors. Consequently, a quantitative correlation analysis is undertaken in the subsequent section to further evaluate these associations across the study area.

Urban view factor correlation analysis

The relationships among the VBVF, VTVF, and VSVF were further examined using Spearman's rank correlation analysis (Table 3). The analysis revealed a strong negative correlation between VBVF and VTVF ($\rho = -0.71$, $p < 0.001$). This inverse relation reflects urban spatial patterns and compositional class constraints within the streetscape environment, highlighting a fundamental physical constraint in street-canyon geometry and visual enclosure effects. Specifically, this inverse relationship is governed by urban morphology and municipal planning policies: compact street canyons featuring restricted building setbacks and narrow sidewalks physically hinder roadside vegetation planting, whereas thoroughfares with wider rights-of-way and lower building coverage furnish adequate spatial envelopes for tree canopy development. Across the entire study area (n = 2,640), the overall mean values for VBVF, VTVF, and VSVF were 0.2151 ±0.1288, 0.1916 ±0.1277, and 0.1891 ±0.0674, respectively. High building density severely suppresses vegetation visibility in dense street canyons like Hong Kong, keeping mean TVF at 0.14 with predominant values below 0.10 (Gong *et al.*, 2018). Conversely, historic and residential districts within Chiang Mai demonstrate markedly elevated VTVF levels, attributed to extensive roadside tree canopies that effectively offset the spatial dominance of building massing. Furthermore, sky visibility in extreme high-rise cores is heavily constrained by high-rise building clusters. For instance, Manhattan shows an average SVF of 0.23, and downtown Phoenix

Table 3: Inter-variable relationships among VBVF, VTVF, and VSVF (n = 2,640)

Correlation	ρ	p-value
VBVF-VTVF	-0.71	<0.001
VBVF-VSVF	-0.26	<0.001
VTVF-VSVF	-0.25	<0.001



Fig. 8: Spatial distribution of VBVF in the study area overlaid on the official land-use zoning map (DPT)

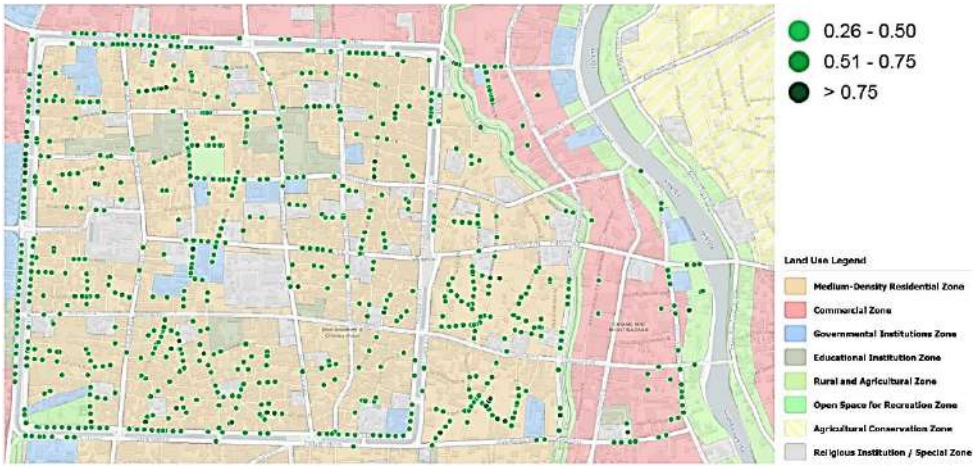

Fig. 9: Spatial distribution of VTVF in the study area overlaid on the official land-use zoning map (DPT)

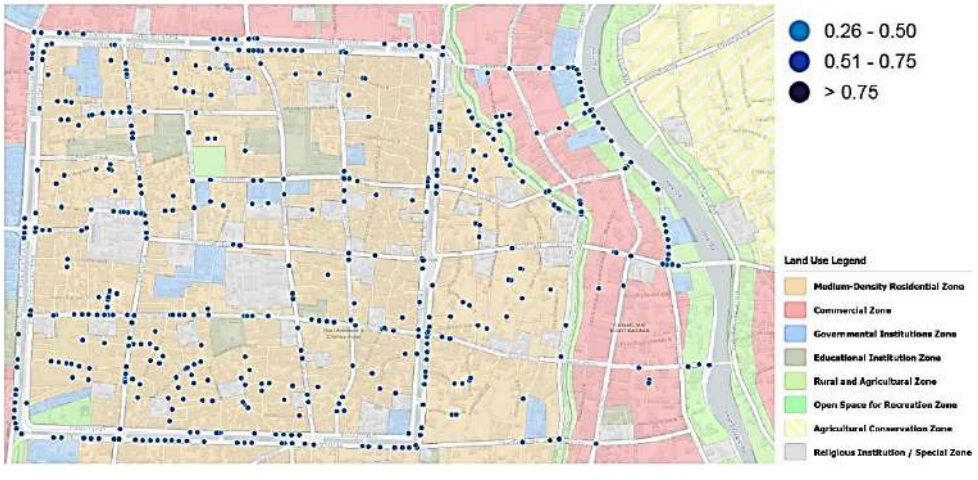

Fig. 10: Spatial distribution of VSVF in the study area overlaid on the official land-use zoning map (DPT)

generally, exhibits SVF values below 0.40 (Middel *et al.*, 2017). In Chiang Mai, overall sky visibility is lower (mean VSVF = 0.1891) with low spatial variability (SD = 0.0674), indicating that sky exposure is continuously dictated by a dual obstruction of low-to-mid-rise building density and overlapping tree canopies rather than sheer architectural height alone. Additionally, weak negative correlations were observed between VBVF and VSVF (ρ = -0.26) and between VTVF and VSVF (ρ = -0.25). These metrics indicate that sky visibility is modulated by a combination of determinants, including building density, street geometry, and vegetation canopy cover. Overall, building-dominated streetscapes generally provide less visible vegetation. Meanwhile, sky visibility is controlled by multiple urban landscape elements rather than a single factor. The observed relationships are consistent with the spatial distribution patterns shown in the previous section.

In summary, the experimental results demonstrate the effectiveness of localized fine-tuning in reducing the domain gap between the Cityscapes dataset and the local urban environment, thereby improving semantic segmentation performance for building, tree, and sky classes. The generated view factors revealed meaningful spatial distribution patterns, and their quantitative relationships were consistent with the physical characteristics of the study area. These findings indicate that the proposed framework provides dependable street-level urban metrics for subsequent environmental analyses and can be applied to other urban areas with similar streetscape characteristics through localized fine-tuning using a targeted dataset of at least 100–200 annotated images. Applicable environments include diverse architectural styles, narrow streets, utility poles, overhead wires, and abundant roadside vegetation that are underrepresented in the Cityscapes dataset. Beyond technical evaluation, the derived view factors provide actionable spatial design metrics for municipal policy and decision-making. High VBVF mapping identifies dense street canyons requiring building bulk regulation and airflow corridor preservation, while VTVF distributions identify canopy-deficient street segments for targeted urban forestry and green infrastructure investments. Integrating VSVF and VTVF enables delineation of localized microclimatic heat vulnerability zones to support targeted shade provision and climate adaptation strategies for reducing pedestrian thermal stress. Incorporating these metrics into WebGIS or spatial dashboards further provides an automated decision-support framework for GIS-based smart city monitoring.

Study limitations

Although the proposed framework demonstrates high performance for street-level view factor analysis, several limitations should be acknowledged: First, regarding data and annotation constraints, the fine-tuning was based on a relatively small locally annotated dataset (n = 100). While this sample size proved sufficient for localized domain adaptation, manual annotation inherently involves minor uncertainties. This limitation is particularly evident along complex boundaries of roadside vegetation, overhead utility wires, and distant objects beyond approximately 30 m, where feature resolution degrades regardless of whether objects are overlapping or distinct. Second, regarding imagery properties, GSV data carry inherent temporal and spatial dependencies. Images are captured across varying seasons and times of day, which may introduce lighting variations and seasonal vegetation fluctuations. Furthermore, adjacent sampling locations situated along the street network may demonstrate notable spatial autocorrelation. Furthermore, GSV imagery is spatially restricted to vehicle-accessible public roads, thereby excluding pedestrianized alleys, private courtyards, and interior green spaces. The imagery also inherently captures transient elements, such as moving or parked vehicles, buses, and temporary construction setups, which

can briefly obscure static building facades and lower roadside vegetation. Third, with respect to geometric perspective, the derivation of view factors from planar perspective imagery yields an eye-level approximation. Additionally, the standardized mounting height of GSV cameras on vehicle roofs (approx. 2.0–2.5 m) is slightly higher than human eye level (approx. 1.5–1.6 m), which may marginally affect the perspective of low-lying street elements. This representation naturally introduces minor geometric deviations compared to full 180° hemispherical fisheye projections traditionally used in urban microclimate studies. Fourth, regarding computational demands, executing city-scale batch processing necessitates high-bandwidth image retrieval pipelines and mid-range GPU hardware with at least 6–8 GB VRAM for efficient semantic segmentation. Finally, regarding generalizability, this research represents a single-city case study focusing on Chiang Mai. Due to the absence of external-city validation, transferring the trained model to alternative geographic settings characterized by divergent architectural typologies or streetscape geometries would require localized fine-tuning using targeted regional images.

CONCLUSION

This study demonstrates the successful application of DeepLabV3+ with localized fine-tuning. This approach effectively analyzes complex urban environments in the Old City of Chiang Mai. Out of all experimental settings, the multi-augmentation technique paired with local street-view imagery yielded superior segmentation performance. This setup outperformed models trained solely on the benchmark dataset. These preliminary findings underscore the critical necessity of utilizing locally representative training datasets. Incorporating such data successfully bridges the gap between benchmark datasets and site-specific urban contexts. Consequently, the resulting fine-tuning process directly enhances the extraction accuracy of urban view factors (VBVF, VTVF, and VSVF). This level of accuracy enables the compilation of high-quality spatial databases essential for quantitative analyses of urban morphology. Correlation analysis revealed a strong negative relationship between buildings and vegetation visibility (ρ = -0.71). Similarly, a weak negative relationship was observed between buildings and sky visibility (ρ = -0.26). These statistical findings reflect the high-density structure of the study area along with the significant interplay and occlusion among physical elements. These statistical insights provide quantitative evidence for understanding the spatial relationships between buildings and open spaces. Both factors represent fundamental components of urban studies. The proposed framework can serve as a practical approach for improving model performance. This application is particularly effective in urban environments with physical characteristics like those of the study area. To apply the proposed framework to other urban areas, fine-tuning with a small target-annotated dataset is required, allowing efficient model adaptation with minimal manual labeling effort. Appropriate augmentation strategies should also be considered based on the target streetscape characteristics. Additionally, this framework also provides a practical workflow for developing localized semantic segmentation models. For long-term monitoring, the framework can be executed on a 2-to-3-year cycle matching typical Google Street View updates or triggered on-demand following major municipal greening and redevelopment projects. To further advance this framework, future studies can incorporate additional urban elements (e.g., sidewalks, street furniture) and integrate multi-source spatial data, such as Light Detection and Ranging (LiDAR) point clouds and Unmanned Aerial Vehicle (UAV) imagery, to enhance three-dimensional (3D) volumetric accuracy. Furthermore, leveraging multi-temporal street-view datasets alongside microclimate sensor networks can enable direct modeling of UHI and pedestrian thermal comfort indicators. The established methodological framework produces dependable street-level

urban metrics designed to inform municipal planning and environmental evaluation.

AUTHOR CONTRIBUTIONS

W. Achariyaviriya conceived the research idea, drafted the paper, and contributed to the development of the methodology. C. Sundaranaga developed the semantic segmentation model with localized fine-tuning, performed data acquisition, processing and analysis. D. Rinchumphu supervised the first author and reviewed the paper draft. P. Suppakittpaisarn supervised the overall research methodology. P. Kantavat supervised the first author in collecting the dataset and reviewed the paper draft.

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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 author(s) have used Artificial Intelligence (AI) [Gemini and ChatGPT] to assist with language proofreading and refinement of the academic English phrasing of the manuscript. 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
3D	Three-dimension
AI	Artificial intelligence
API	Application programming interface
ASPP	Atrous spatial pyramid pooling
BVF	Building view factor
CNNs	Convolutional neural networks
CVAT	Computer vision annotation tool
DL	Deep learning
DPT	Department of Public Works and Town and Country Planning
FOV	Field of view
GSV	Google street view
GVI	Green view index
IoU	Intersection over union
km^2	Square kilometer
LiDAR	Light detection and ranging
m	Meter

mIoU	Mean intersection over union
OTC	Outdoor thermal comfort
PA	Pixel accuracy
QGIS	Quantum geographic information system
SVF	Sky view factor
TVF	Tree view factor
UAV	Unmanned aerial vehicle
UHI	Urban heat island
VBVF	Visible building view factor
VSVF	Visible sky view factor
VTVF	Visible tree view factor
WebGIS	Web-based geographic information system
WMS	Web Map Service

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CASE STUDY

Risk identification and assessment of passive roofs for rural housing in hot and dry regions using Delphi method

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ABSTRACT

BACKGROUND AND OBJECTIVES: Passive roofs are increasingly recognized as effective solutions for improving thermal performance and reducing energy consumption in buildings. Nevertheless, the execution of these measures in rural housing sectors is frequently compromised by a complex array of uncertainties, including those related to policy management, financial constraints, environmental factors, health and safety, and quality control. Existing studies mainly focus on roof performance and energy benefits, while systematic risk assessment remains limited, particularly in rural areas with constrained resources and technical capacity. The study objectives were to develop a structured framework to identify and assess the risks associated with passive roofs in the hot–dry regions of Southwest China.

METHODS: A two-round Delphi survey was conducted to evaluate impact and frequency, and consensus was tested using Kendall's W and interquartile range. Risk levels were subsequently evaluated through the application of a modified risk matrix featuring 0.8-interval classification.

FINDINGS: A total of 49 preliminary risk factors were identified through literature review and expert judgment. After screening using the content validity ratio, 47, 35, 48, and 42 risk factors were retained for blue roofs, cool roofs, green roofs, and ventilated roofs, respectively. The findings demonstrate that the highest cumulative risk levels are associated with green and blue roofing systems. Blue roofs contain 15 high-risk and 5 very high-risk factors, while green roofs contain 16 high-risk and 5 very high-risk factors. Cool roofing alternatives presents fewer extreme vulnerabilities but conversely generate the highest percentage of high-risk outcomes. Ventilated roofs show relatively lower overall risk levels, although several critical risks remain. Across all roof types, high-risk factors were primarily associated with construction quality, management capacity, maintenance requirements, and economic constraints. several low-consensus risks were observed, reflecting the site-specific constraints governing passive roofing systems in rural jurisdictions.

CONCLUSION: The findings indicate that risk levels are strongly associated with roof complexity, construction conditions, and maintenance requirements. This framework delivers a systematic basis to guide risk-informed decisions regarding rural passive roofing installations.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
39	5	3

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INTRODUCTION

Improving the energy performance of rural housing has become an important issue under the "dual carbon" goals and rural revitalization strategies (Chang *et al.,* 2022; Qi *et al.,* 2023; Shao *et al.,* 2021; Wang *et al.,* 2023; Xiao *et al.,* 2024). Unlike urban buildings, rural dwellings typically lack comprehensive regulatory or technical oversight during design, execution, and operation, resulting in deficient envelope performance and elevated energy consumption (Shao *et al.,* 2021). Hot–dry regions of Southwest China are characterized by high temperatures, strong solar radiation, and large diurnal temperature variations. Together with the high roof-to-floor ratio of low-rise buildings, these characteristics make roofs a critical factor influencing indoor thermal conditions and energy consumption (Athmani, *et al.,* 2022; Dristy, *et al.,* 2020). Passive roofing systems—encompassing green roofs (GRs), blue roofs (BRs), cool roofs (CRs), and ventilated roofs (VRs)—mitigate environmental impacts by leveraging inherent physical mechanisms such as insulation, reflection, evaporation, and ventilation (Shun *et al.,* 2025). However, their implementation in rural areas faces multiple challenges, such as limited technical capacity, weak management systems, insufficient maintenance, and cost constraints (Andenæs *et al.,* 2020; Mbua *et al.,* 2024; Rawat *et al.,* 2021). Such constraints introduce critical uncertainties regarding practical scalability; however, the established body of research focus is largely confined to engineering metrics, namely thermal performance, energy modeling, material synthesis, and structural design (Saber *et al.,* 2021; Yazdani and Baneshi, 2021; Zhao *et al.,* 2023). While these studies demonstrate the technical potential of passive roofs, they pay limited attention to risks during implementation. Moreover, risk assessments are often conducted in urban or well-regulated environments, overlooking the complexities of rural construction contexts. In rural regions, roof application involves not only technical feasibility but also management, financial, environmental, and operational factors. Without systematic risk identification and classification, the deployment of passive roofing technologies may yield suboptimal outcomes or precipitate novel safety and operational hazards. These studies generally focus on single roof technologies, urban contexts, or lifecycle management issues (Gerzhova *et al.,* 2022; Säwén *et al.,* 2022; Tabatabaee *et al.,* 2022). Consequently, there is a lack of systematic frameworks that cover multiple passive roof types and address both technical and non-technical risks under resource-constrained conditions. Owing to its capacity for establishing expert consensus amidst high levels of uncertainty, the Delphi method has seen extensive application within construction and sustainability research (Abdul Rahman *et al.,* 2022; Tabatabaee *et al.,* 2022). By conducting multiple rounds of anonymous evaluation, it improves the reliability of subjective judgments, making it particularly suitable for risk assessment in data-scarce contexts (Hussain *et al.,* 2024; Khosravi *et al.,* 2020). As a visual classification framework, the risk matrix (RM) maps severity and frequency into intuitive risk thresholds, thereby facilitating strategic decision-making (Anthony Cox, 2008). Integrating Delphi with RM enables both quantitative assessment and clear visualization of risks. It develops a systematic framework for risk identification and assessment of passive roofs. The contributions are threefold. First, this study shifts the research paradigm from localized technical performance toward a comprehensive, system-level risk assessment. Second, it establishes an integrated methodological framework that sequentially synthesizes a literature review, the content validity ratio (CVR) screening, Delphi evaluation, and risk matrix (RM) classification. Third, it provides practical support for decision-making in rural passive roof applications. The aims are: 1) To establish risk factor lists through literature review and expert judgment; 2) To quantify impact and

occurrence frequency using Delphi surveys; 3) To classify risk levels using a modified RM method and identify high-risk and low-consensus risks. This study has been carried out in Panzhihua City in Sichuan, China a hot–dry region in 2025 and 2026.

MATERIALS AND METHODS

The study area

Panzhihua sits at the geographic border of Sichuan and Yunnan Provinces, representing a textbook sub-hot-dry climate in Southwest China (SPDHURD, 2022; Szokolay, 1980). The region experiences a distinct climatic dichotomy characterized by pronounced wet and dry seasons, high evaporation rates, and an annual mean temperature of 20.7 degrees Celsius (°C) (People's Government of Panzhihua Municipality, 2025). Within its rural territories, the building fabric is overwhelmingly dominated by single- or two-story low-rise houses. In such microclimates, the roof envelope rather than vertical walls acts as the primary conduit for intense solar heat entry (Saurabh and Madhura, 2023). Crucially, while the regional "Technical Standard for Application of Energy-saving Technology for Civil Buildings in Panxi"- 2022, officially endorses passive roofs, its generic guidelines lack actionable, risk-oriented execution paths. This institutional oversight constrains rural residents to rely on unstandardized and inherently vulnerable roofing practices during autonomous construction. Panzhihua's collision of climate stress and rural resource bottlenecks makes it an irreplaceable empirical case to dissect implementation risks.

Literature search and identification of risk factors

To identify potential risk factors associated with passive roofing systems in rural housing, this study employed a structured literature review coupled with qualitative content analysis. Considering that the study area is located in the hot–dry regions of Southwest China, where local codes and practical experience are often documented in Chinese, both English and Chinese sources were included to ensure comprehensive coverage. ScienceDirect and China National Knowledge Infrastructure (CNKI) were selected as the primary databases. ScienceDirect was used to retrieve English journal articles, while CNKI was used to identify Chinese studies and roof-related technical codes (Shun *et al.,* 2025). To guarantee data timeliness, the temporal scope of the literature search was restricted to the 2016–2025 period. Furthermore, in contrast to keyword- or abstract-based queries, a title-based retrieval strategy was implemented to yield more precise and highly topic-focused results (Lu *et al.,* 2025). Accordingly, a title-based search strategy was adopted using terms such as "passive roof", "blue roof", "cool roof", "green roof", "ventilated roof", "double roof", "pond roof", and "roofing code". Crucially, to counteract the potential omission risks inherent in title-only filtering, a systematic manual backward snowballing strategy was subsequently executed. This involved a meticulous manual screening of the reference lists from the fully reviewed articles and prominent review papers. For example, although the technical code for roof engineering (GB 50345–2012) issued by MOHURD, (2012) falls outside the selected timeframe, it remains the current governing standard in the study region and was therefore included as a key reference. Following the literature screening process, 88 studies met the inclusion criteria and were selected for subsequent risk identification and analysis (Fig. 1). Content analysis was used to code and categorize risk-related information from the selected literature (Elo *et al.,* 2014). Similar or overlapping risk descriptions were merged and standardized, and then classified according to their characteristics. To ensure comprehensiveness, particularly within rural contexts, the initial risk framework was supplemented with operational risk factors derived from professional expertise and subsequently validated against contemporary literature. This process resulted in a preliminary

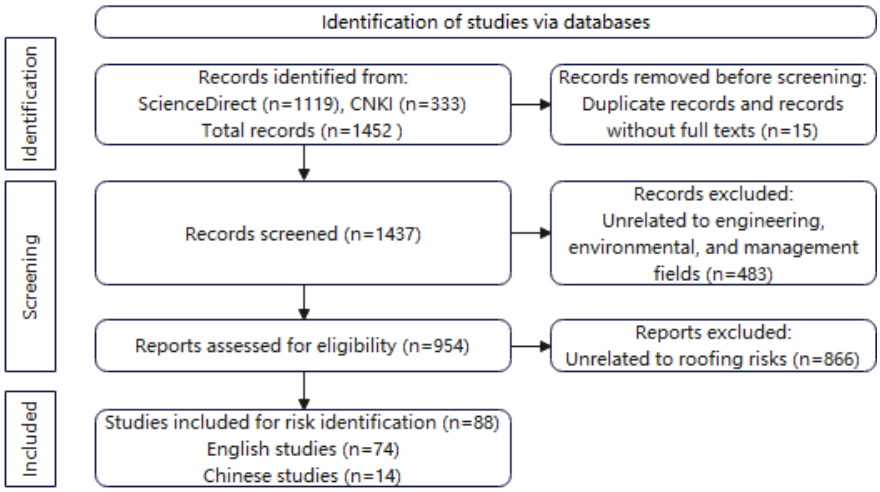

Fig. 1: Flow diagram of the literature screening process (Adapted from the preferred reporting items for systematic reviews and meta-analyses)

risk list comprising five categories: management and policy risks, financial risks, environmental risks, health and safety risks, and quality risks. This list formed the basis for subsequent expert screening and the Delphi survey.

Overall research framework

The overall research framework is illustrated in Fig. 2 and comprises five main stages. A preliminary risk list was initially generated by conducting a systematic literature review targeted at identifying the diverse risk factors associated with passive roofing applications. Experts were then recruited through purposive sampling based on predefined selection criteria, and the preliminary risk list was screened to establish the final risk lists for the four roof types. Delphi surveys were subsequently conducted to evaluate the impact index (II) and frequency index (FI) of each risk factor. The initial phase centered on the elicitation of expert ratings, which were subsequently subjected to descriptive statistical analysis and consistency testing. Statistical feedback from the first round was then provided to the experts to support a second round of evaluation and further improve consensus. After the predefined consistency criteria had been satisfied, the mean II and FI values were calculated. In the final stage, the risk factors were projected onto the RM to categorize critical and severe threats, providing a structured foundation for the ensuing evaluation and discussion.

Expert selection criteria

To ensure the rigor of the results, explicit expert selection criteria were established (Table 1), covering professional experience, project involvement, expertise, and contextual familiarity. To qualify for selection, panel experts were required to possess a minimum of five years of professional experience in architectural design, construction, or management. Additionally, eligible candidates must have participated in at least five roof-related initiatives and demonstrate familiarity with hot–dry climates or rural construction practices. To ensure relevance, this study employed purposive sampling based on specific criteria and considerations (Rama *et al.*, 2023). The resulting panel comprised architects, engineers, researchers, government officials, contractors, and material suppliers, thereby enhancing the overall representativeness of the cohort. Considering that Delphi studies typically involve 15–20 experts, and given the limited availability of qualified participants, 15 experts were ultimately selected (Khosravi *et al.*, 2020).

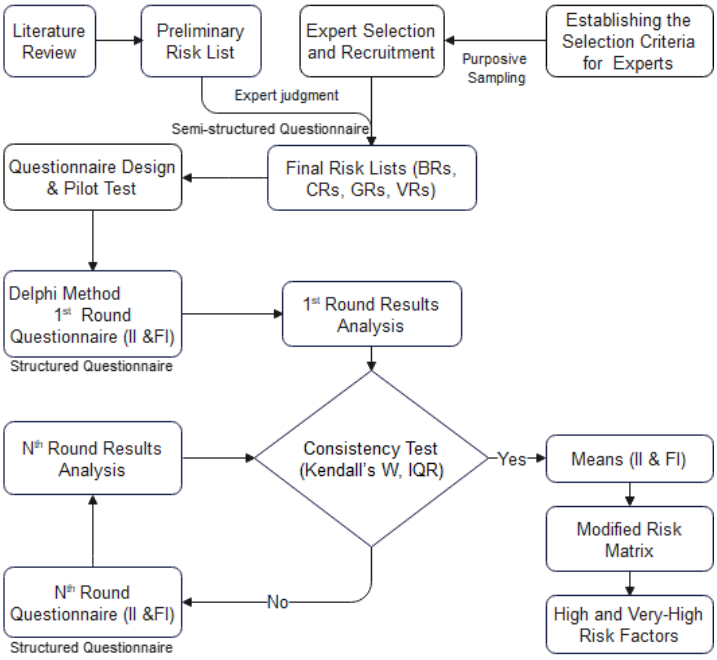

Fig. 2: The study framework for risk identification and assessment Note: BRs = blue roofs; CRs = cool roofs; FI = frequency index; GRs = green roofs; II = impact index; IQR = interquartile range; Kendall's W = Kendall's coefficient of concordance; VRs = ventilated roofs

Table 1: Expert selection criteria for the Delphi survey

Criterion	Description
Professional experience	Professional or research experience ≥5 years related to building design, construction, or management
Project involvement	Participation in roof-related projects ≥5
Professional background	Architect, engineer, researcher, government official, contractor, or building material supplier
Relevant expertise	Experience in passive building design, roof systems, rural housing, or building risk management
Context familiarity	Familiarity with hot–dry climatic conditions or rural construction practices in Southwest China or similar regions

Experts were recruited through multiple channels, including industry associations, engineering projects, official documents, and professional recommendations. To maintain strict confidentiality, all panel participants remained completely anonymized throughout the evaluation process.

Risk identification

A triangulation approach combining literature analysis and expert judgment was adopted to improve validity (Abdul Rahman *et al.,* 2022). The preliminary risk inventory was distributed to the 15-member expert panel, who evaluated the practical applicability of each factor across the four designated roofing typologies. The questionnaire was semi-structured, allowing experts not only to classify risks but also to suggest additional factors based on their experience. This step ensured alignment between literature-derived risks and real-world conditions. The CVR was used to determine risk retention (Lawshe, 1975). In accordance with the content validity thresholds established by Ayre and Scally (2014), a minimum of 12 panel endorsements from the 15 participating experts was required for a risk factor to be retained. Any risks falling below this consensus benchmark were systematically excluded, yielding the final risk inventory for subsequent analysis and prioritization.

Delphi questionnaire design

A structured questionnaire was developed, including instructions, risk categories, codes, descriptions, II, and FI. II and FI were measured using a five-point Likert scale. II ranged from 1 (low risk) to 5 (very high risk), while FI ranged from 1 (very rare) to 5 (very frequent). The questionnaire was distributed via email and online using a quick response code. To enhance the clarity and comprehensibility of the instrument, a pilot test was conducted with a tripartite expert panel comprising a researcher, an engineer, and a government official. Based on feedback, adjustments were made to layout, format (Excel preferred), and risk descriptions. The first Delphi round then collected expert ratings for II and FI.

Data analysis methods

Data analysis included three steps: descriptive statistics, consistency testing, and RM mapping. After each Delphi round, data were analyzed using statistical package for the social sciences (SPSS). To assess the distribution of the data, the mean values and interquartile ranges (IQRs) were determined for each individual risk factor (Hussain *et al.,* 2024). The mean reflects overall evaluation, while the IQR indicates consensus. An IQR ≤ 1.0 suggests agreement, whereas values > 1.0 indicate low consensus. Kendall's coefficient of concordance (W) was used to assess ranking consistency, with significance tested using p-values (Chen *et al.,* 2024; Dong *et al.,* 2025). A value of $W \geq 0.5$ with $p < 0.001$ indicates acceptable agreement; otherwise, an additional Delphi round is required (Ashrafi *et al.,* 2025). Once consensus was achieved, mean II and FI values were calculated. To maintain consistency between expert ratings and risk-level interpretations, the 0.8-interval classification was established by segmenting the 1–5 Likert scale range into five equal categories (Table 2). Compared with numerical tables, the RM provides a clearer visualization of risk levels and their relative positions (Anthony Cox, 2008). The mean II and FI values were mapped onto a 5 × 5 RM, where the vertical axis represents impact and the horizontal axis represents frequency. Risk severity escalates from the lower-left to the upper-right quadrant of the matrix, facilitating the clear delineation of high-risk and critical zones. Furthermore, risk factors characterized by a low expert consensus were explicitly retained for closer examination. A modified RM was used to map these risks, allowing both their risk levels and divergence to be visualized. Fig. 3 presents the distribution of risk levels and low-consensus risks across the four roof types.

RESULTS AND DISCUSSION

Risk identification results

Through a systematic literature review, an initial risk inventory for passive roofing systems in rural dwellings within hot–dry regions was established, comprising 49 distinct risk factors classified into five primary categories (Table 3). To enhance practical relevance, expert screening was conducted. A total of 32 experts were invited, and 15 participated, including researchers, architects, engineers, government officials, contractors, and a materials supplier. Using the CVR threshold, risk factors were screened separately for each roof type, resulting in 47, 35, 48, and 42 risks for BRs, CRs, GRs, and VRs, respectively. Such differences reflect divergent levels of technical complexity alongside distinct operational and application environments. Overall, synthesizing the literature review and expert judgment ensured both comprehensiveness and validity of the research framework. The CVR-based screening improved reliability, forming a robust foundation for subsequent Delphi-based assessment, while minimizing the inclusion of irrelevant variables and enhancing the methodological rigor, consistency, and credibility of the identified risk inventory across different rooftop farming system configurations examined.

Table 2: Likert scale for the mean II and mean FI

The range of mean II/mean FI	Index	Level
1.0000 – 1.7999	1	Very Low
1.8000 – 2.5999	2	Low
2.6000 – 3.3999	3	Moderate
3.4000 – 4.1999	4	High
4.2000 – 5.0000	5	Very High

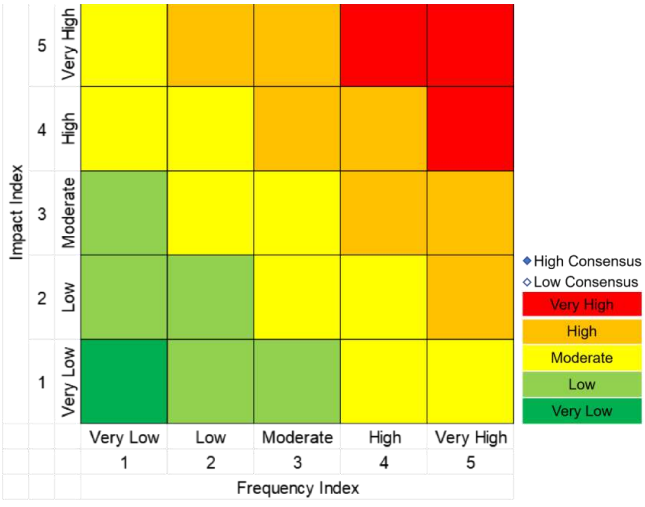

Fig. 3: Distribution of risks in the modified RM for passive roofs

Table 3: Preliminary risk list for passive roofs

Risk clusters	Code	Risk factors	Risk clusters	Code	Risk factors
Management and Policy risks	M1	Non-compliant construction practices	Health and safety risks	H4	Mould contamination
	M2	Incongruous architectural style		H5	Microbial contamination
	M3	Adoption of non-standard technical solutions		H6	Light pollution
	M4	Breach of contract		H7	Mosquito breeding
	M5	Underestimation of required maintenance		H8	Fire risk
	M6	Construction workers lack technical experience	Quality risks	Q1	Low resistance to strong winds
	M7	Lack of policies and guidance		Q2	Degraded thermal insulation performance
	M8	Supply chain vulnerability		Q3	Substandard thermal insulation performance
	M9	Lack of collaboration among stakeholders		Q4	Material corrosion
	M10	Insufficient contractor awareness level		Q5	Material aging or deterioration
	M11	Insufficient owner awareness level		Q6	Noise Intrusion
	M12	Insufficient architect awareness level		Q7	Roof leakage
	M13	Incentive policy uncertainty		Q8	Difficulty in detecting leak points
Financial risks	F1	Initial construction cost exceeds expectations		Q9	Overloading
	F2	Unexpectedly high maintenance costs		Q10	Horizontal displacement of roof components
	F3	Underestimated the high operating costs		Q11	Lightning strike
	F4	Unsatisfactory cost-effectiveness		Q12	Condensation risk
Environmental risks	E1	Water or soil contamination		Q13	Moisture risk
	E2	Animal infestation and pests		Q14	Material deformation
	E3	Odor generation		Q15	Insulation flotation
	E4	Drought risk		Q16	Drain blockage
	E5	Causing an increase in carbon emissions		Q17	Spatial impact
Health & safety risks	H1	Construction injuries		Q18	Incompatible building details
	H2	Tripping hazards		Q19	Insulation board failure
	H3	Fall hazards			

Delphi round 1 results

The first Delphi round evaluated expert agreement on II and FI using IQR and W. Overall, statistically significant agreement was achieved across all roofing typologies ($p < 0.001$), although the level of consensus exhibited considerable variation. For BRs, W reached 0.588 for II and 0.720 for FI, indicating moderate to high agreement among experts. Most risks exhibited IQR values ≤ 1, with only six risks in each category showing relatively low consensus. CRs showed comparatively lower agreement in II assessment (W = 0.430), while FI assessment demonstrated improved consistency (W = 0.612). Several risks factors maintained IQR values of 2, indicating a degree of divergence in expert consensus. Notably, GRs demonstrated the most pronounced variance in expert opinions during II assessment. Two risks showed an IQR of 3 and 20 risks exhibited an IQR of 2, indicating substantial disagreement regarding impact severity. By contrast, FI assessment achieved higher consistency (W = 0.682), with a reduced number of risk factors demonstrating low consensus. For VRs, W values were 0.553 for II and 0.547 for FI, reflecting moderate agreement among experts. Although most risks achieved IQR values ≤ 1, several risks still demonstrated limited consensus, particularly in FI assessment. Overall, while the initial Delphi round yielded an acceptable level of consensus, the convergence of expert opinions remained incomplete, necessitating a subsequent round to enhance consistency and stabilize risk assessments.

Delphi round 2 results and consistency analysis

Delphi round 2 substantially improved expert consensus across all passive roof types. For BRs, W increased to 0.685 for II and 0.798 for FI. All II assessments achieved IQR values ≤ 1, while only one FI risk (Q14) exhibited an IQR > 1. For CRs, W reached 0.643 for II and 0.817 for FI. All II and FI assessments exhibited IQR values ≤ 1, indicating full convergence of expert opinions. For GRs, W increased to 0.691 for II and 0.846 for FI. All II assessments achieved IQR values ≤ 1, whereas only one FI risk (H3) showed an IQR > 1. For VRs, W reached 0.708 for II and 0.737 for FI. All II assessments exhibited IQR values ≤ 1, while three FI risks (E2, H3, and Q9) exhibited IQR values > 1. Compared with the first Delphi round, IQR values generally decreased and W increased for both II and FI, suggesting improved stability and consistency in expert judgment. To ensure a comprehensive evaluation, risk factors exhibiting persistent disagreement were not discarded; instead, they were classified as low-consensus risks and subjected to further scrutiny in the RM framework and discussion.

RM and risk level classification

Upon achieving panel consensus, the finalized risk levels were classified using the RM method. The RM distribution for passive roofs is presented in Fig. 4. Among the identified risks of BRs, 5 were classified as very low risk, 10 as low risk, 12 as medium risk, 15 as high risk, and 5 as very high risk. Among the identified risks of CRs, 2 were classified as very low risk, 10 as low risk, 6 as medium risk, 14 as high risk, and 3 as very high risk. An analysis of the risks associated with GRs revealed that the 49 identified factors spanned a broad spectrum: 4 were classified as very low risk, 13 as low risk, 10 as medium risk, 16 as high risk, and 5 as very high risk. Among the identified risks of VRs, 6 were classified as very low risk, 13 as low risk, 10 as medium risk, 9 as high risk, and 4 as very high risk. The results reveal: Clear differences in risk distribution across roof types; GRs and BRs have higher overall risk levels; CRs and VRs show relatively lower or more concentrated risks. High-risk and very high-risk factors are primarily concentrated within the management and quality control dimensions. In addition, a few risks (H3,

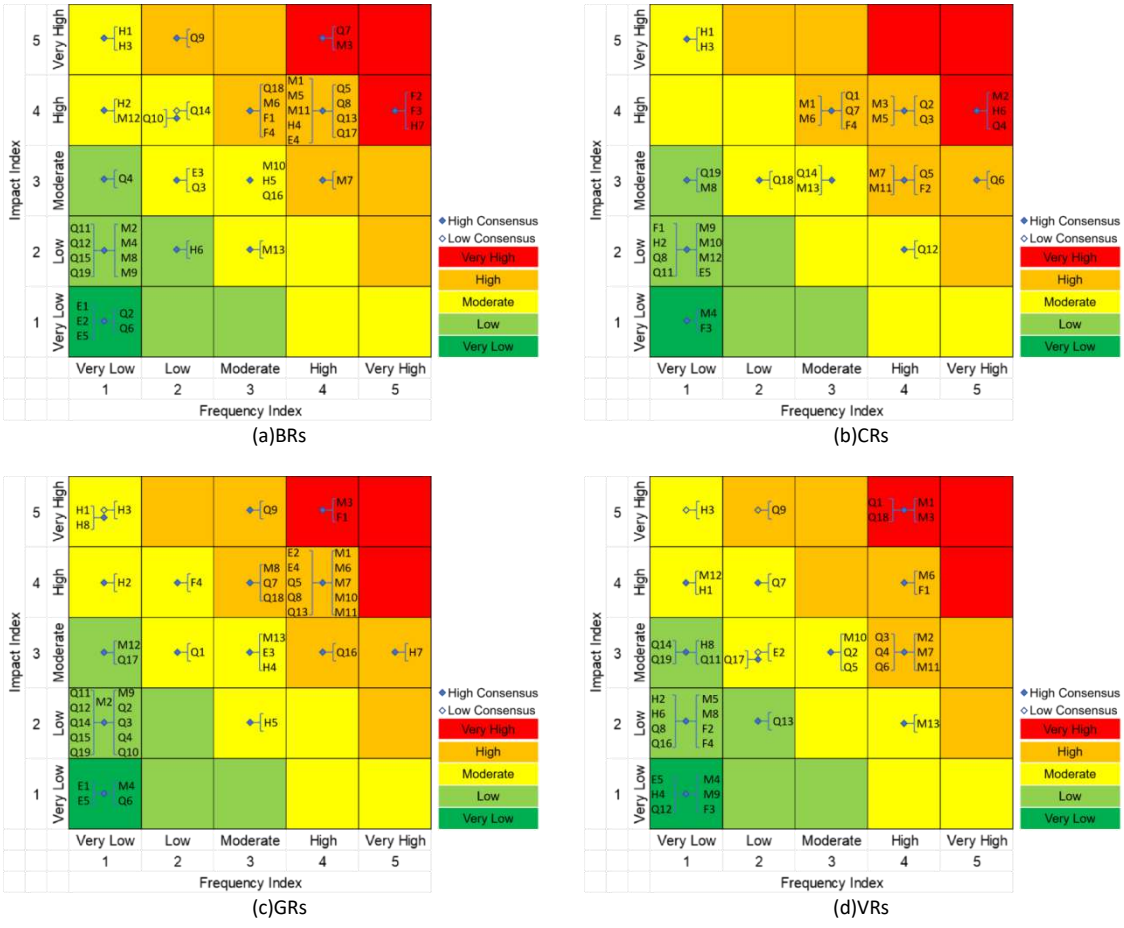

Fig. 4: Distribution of risks in the modified RM for passive roofs

E2, Q14) were identified as a low-consensus risks, located in the medium-risk zone. While these factors fell short of the high-risk classification threshold, the observed panel dissension underscores an inherent ambiguity in expert consensus, thereby justifying closer scrutiny during empirical deployment and subsequent analysis.

Comparative analysis of risk levels among four passive roofs

The four passive roofing typologies exhibit pronounced variations regarding their respective risk volumes, their spatial distribution within the RM, and their primary risk categories. As shown in Fig. 5, GRs contain the largest number of high-risk and very high-risk factors, followed by BRs, whereas VRs present the lowest overall risk level. Although CRs exhibit fewer high and very high-risk factors in absolute terms, they represent a greater proportion of the system's total risk profile. These differences are largely associated with variations in structural complexity, dependence on construction quality, and maintenance intensity. GRs involve multi-layer systems—including vegetation, drainage, waterproofing, and substrate layers—resulting in high structural and functional complexity (Abdul Rahman *et al.,* 2022). In rural environments, constrained technical capacity and deficient quality control measures frequently introduce systemic flaws across various project phases, ultimately escalating the

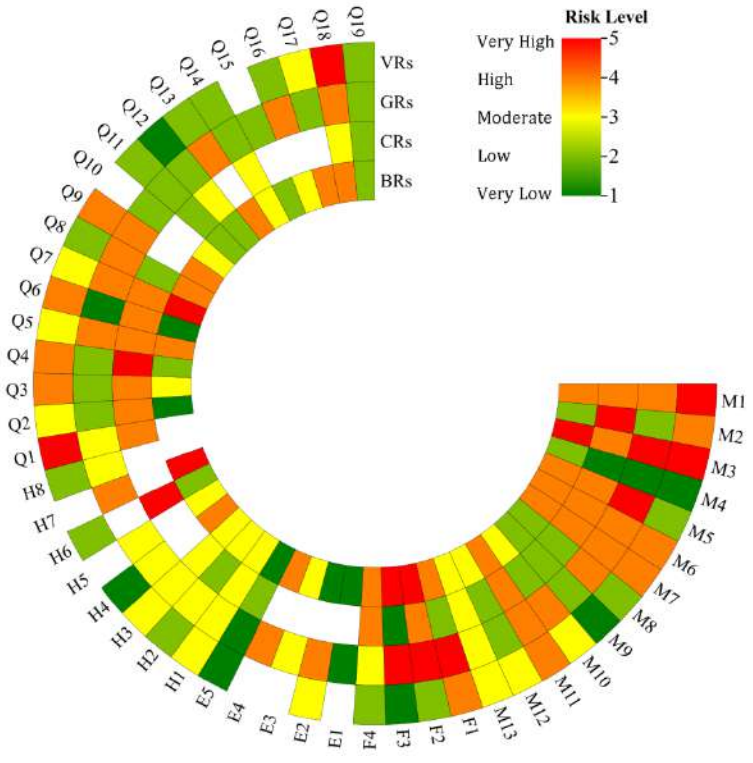

Fig. 5: Risk level of risk factors for the four passive roofs

cumulative risk profile. In addition, GRs rely heavily on post-installation maintenance, such as irrigation and vegetation management, which further increases uncertainty. Their relatively limited adoption, combined with insufficient technical guidance, also contributes to elevated risks. Notwithstanding these challenges, GRs exhibit distinct advantages in thermal performance, illustrating a fundamental trade-off between operational benefits and implementation risks. BRs also exhibit relatively high-risk levels. While they provide benefits in stormwater management and thermal regulation, the inclusion of water storage and drainage systems introduces additional risks related to waterproofing, structural loads, and operational management. In rural houses, these risks are amplified by limited maintenance capacity. CRs rank third in terms of high-risk and very high-risk factors. T Their comparatively uncomplicated design, ease of assembly, and lower capital requirements collectively foster a highly manageable risk profile (Athmani *et al.,* 2022). However, reliance on high-reflectivity materials may introduce specific risks, including surface degradation, glare, and potential impacts on visual comfort and building aesthetics. VRs exhibit the lowest overall risk level. The strong dependence of these systems on proper technical execution is evidenced by the concentration of high-risk factors within design detailing, construction quality, and structural performance parameters. Compared with GRs and BRs, VRs have advantages in reduced maintenance requirements and long-term stability. Overall, risk levels are closely linked to structural complexity, construction dependency, and maintenance requirements. Roofing typologies characterized by structural simplicity and minimal maintenance requirements typically exhibit a lower prevalence of high-risk

factors, whereas structurally complex systems encounter significantly greater risk exposure.

Causes of high-risk, very high-risk, and low-consensus risks

This study shows that high-risk and low-consensus risks are shaped not only by technical factors but also by the broader rural context. From a construction perspective, high-risk factors are mainly associated with construction management, quality control, and structural safety. Residential construction practices within rural contexts are predominantly governed by empirical, generationally transmitted knowledge as opposed to standardized engineering protocols. Limited technical expertise, inadequate supervision, and insufficient training may increase the likelihood of construction deviations and compromise implementation quality (Kaushik *et al.,* 2024). In addition, the outflow of skilled labor further reduces construction quality. Consequently, even structurally sound passive roofing systems may fall short of anticipated performance benchmarks, thereby exacerbating operational risks. Economic constraints are another critical factor. Rural households are highly sensitive to initial costs. When passive roofs—especially GRs, BRs, and VRs—require additional investment, cost pressures may lead to simplified designs, lower-quality materials, or inadequate maintenance. Such cost-driven compromises can significantly increase long-term risks. The hot–dry climate is defined by intense solar radiation, pronounced diurnal temperature fluctuations, and elevated rates of evaporation. These conditions may accelerate the degradation of reflective coatings and insulation materials, increase water-related operational challenges, and contribute to greater implementation and performance risks. Low-consensus risks reflect variability in expert judgment, an outcome attributable to multiple distinct sources: 1) Differences in professional background and involvement across project stages lead experts to emphasize different aspects of risk. For instance, while engineers prioritize structural load-bearing capacity and public safety, regulatory compliance and environmental impacts command the attention of government officials; concurrently, architects concentrate heavily on the conceptual design stage, whereas contractors emphasize execution and long-term maintenance. 2) Practical experience varies considerably across regions. Some experts have limited exposure to rural houses and therefore assess risks based on urban project experience, whereas actual rural conditions are often more complex. 3) Some risks are context-dependent, with their frequency of occurrence and level of impact varying substantially under different village and township conditions. Collectively, these findings indicate that both high-risk factors and low-consensus variations originate from a combination of technical complications and broader systemic impediments, most notably institutional capacity limitations, management practices, and economic constraints.

Comparison with existing research

The findings of this study both align with and extend existing research. Consistent with previous studies, construction quality, structural capacity, and long-term maintenance are identified as key risk factors for GRs and CRs (Perivoliotis *et al.,* 2023). These elements are similarly categorized as high or very high risk within the present study, underscoring their role as fundamental diverse challenges across contexts. However, differences emerge when comparing rural and urban settings. Existing studies tend to emphasize technical performance, such as thermal efficiency and material optimization, while paying less attention to implementation risks (Chen *et al.,* 2024; Saber *et al.,* 2021; Zhao *et al.,* 2023). In contrast, this study highlights the importance of management

and institutional risks in rural houses. This implies that within resource-constrained settings, successful deployment hinges not merely on technical efficacy but equally on managerial capabilities and institutional support. In such contexts, non-technical factors may play a more decisive role. In addition, several low-consensus risks identified in this study have received limited attention in previous research, indicating that existing studies may not fully capture the uncertainties of rural applications. By incorporating expert judgment and iterative consensus-building, this study provides a more context-sensitive understanding of risk. Overall, this study expands the scope of passive roofing literature by transitioning from a performance-centric analysis to a multidimensional framework integrating management, economic, environmental, safety, and quality considerations.

Implications for practice

Risk management should extend beyond technical design. Many high-risk factors are linked to construction practices and institutional capacity. Strengthening training, technical guidance, and supervision mechanisms is therefore essential. Particular attention should also be given to low-consensus risks. Given that these risks are frequently context-dependent and subject to geographical variation, localized, site-specific assessments are imperative prior to deployment rather than relying exclusively on generalized frameworks. In this sense, low-consensus risks provide a complementary perspective to conventional risk assessment. The RM developed in this study can further support decision-making during project planning and design. While high- and very high-risk factors necessitate immediate, prioritized intervention, moderate- and low-level risks can typically be mitigated through routine administrative controls. Shcherbak *et al.* (2024) reported similar findings and highlighted the role of systematic assessment approaches in supporting environmental sustainability and strengthening environmental management practices in rural areas. Beyond the practical findings, the methodological framework adopted in this study, integrating a comprehensive literature review, expert judgment, Delphi consensus, and RM mapping, provides a transparent and systematic approach that may serve as a valuable reference for future risk assessment studies in rural, resource-constrained, and data-scarce settings across diverse infrastructure and sustainability applications.

CONCLUSION

This study investigated the risks associated with passive roofs in rural housing located in the hot–dry regions of Southwest China. By integrating a comprehensive literature review, CVR-based expert screening, a dual-round Delphi survey, and RM analysis, a robust and systematic assessment framework was successfully developed. Through this process, the impact, occurrence frequency, and overall risk level of passive roof applications were evaluated for GRs, BRs, CRs, and VRs. The findings show clear differences among the four roof types. GRs and BRs were associated with the largest numbers of high-risk and very high-risk factors, whereas VRs presented the lowest overall risk level. CRs occupied an intermediate position, with fewer very high-risk factors but a relatively large proportion of high-risk factors. These variations appear to be intimately linked to structural complexity, construction specifications, and subsequent maintenance demands. Roofs involving additional structural layers, water management components, or intensive maintenance tended to exhibit greater risk exposure than relatively simple roof configurations. The evaluation also demonstrates that numerous critical risks stem from systemic

factors lying outside the domain of formal engineering design. Structural performance, waterproofing, and construction quality remain important concerns. However, management capacity, financial limitations, policy support, and long-term maintenance were repeatedly identified as major sources of risk. This finding holds particular relevance for rural regions, where technical resources, professional oversight, and financial investments are frequently constrained. Under such conditions, implementation challenges may become as important as technical performance in determining project success. Several risks remained characterized by relatively low consensus even after two Delphi rounds. Differences in professional background, practical experience, and familiarity with rural construction conditions may partly explain this outcome. Furthermore, certain risks are heavily contingent upon localized environmental and socio-economic dynamics, complicating uniform assessment across divergent spatial scales. The presence of these low-consensus risks highlights the importance of considering local context when applying passive roof technologies. Overall, this study extends current passive-roof research from a predominantly performance-oriented perspective to a broader consideration of implementation risks. The proposed framework offers a practical screening mechanism for planners and practitioners, enabling the proactive identification of critical risks prior to the implementation of passive roofing systems. This may facilitate more informed decision-making, particularly in regions with limited empirical data. Several limitations should be acknowledged. Although the equal-interval classification facilitates interpretation and comparison, it may introduce boundary effects. The findings are based on expert judgments obtained through purposive sampling and may therefore be influenced by subjective bias. The current iteration of the framework centers exclusively on risk identification and evaluation metrics, omitting empirical validation via case studies or field-level data. In addition, advanced statistical analyses and mitigation strategies were beyond the scope of this study. Furthermore, because the framework was designed specifically around rural housing in China's hot–dry zones, extending its direct applicability to alternative climatic, socio-economic, or institutional environments requires careful qualification. Further sstufies are required to operationalize these identified risks into actionable, concrete mitigation strategies. Developing a structured risk response framework would support more effective implementation of passive roofs in rural houses by facilitating systematic decision-making, optimizing resource allocation, improving stakeholder coordination, ensuring long-term sustainability, and enhancing project resilience.

AUTHOR CONTRIBUTIONS

S. Li, the first author, contributed to the conceptualization of the study, methodology development, data collection, data analysis, and manuscript preparation. S.N.Z. Abidin, the corresponding author, contributed to the methodology development, data collection, supervision of the research, and manuscript review. M.A. Kamarazaly contributed to the methodology development and data analysis. All authors read and approved the final manuscript prior to journal submission.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The Delphi survey collected anonymous professional opinions from experts on passive roof risks. Participation was voluntary, and no personal, medical, or sensitive information was collected. The study adhered to good research practices. The authors consulted the University's Human Ethics Committee regarding this study and were informed that retrospective ethics approval cannot be issued after data collection has been completed. In addition, the authors confirm that all ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been fully observed.

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ABBREVIATIONS

<	Less than
≤	Less than or equal to
>	Greater than
≥	Greater than or equal to
=	Equal sign
oC	Degree Celsius
BRs	Blue roofs
CNKI	China national knowledge infrastructure
CRs	Cool roofs
CVR	Content validity ratio
e.g.	Exempli gratia
FI	Frequency index
Fig.	Figure
GRs	Green roofs
IQR	Interquartile range
II	Impact index
MOHURD	Ministry of housing and urban-rural development of the people's republic of China
p	p-value
RM	Risk matrix
SPSS	Statistical package for the social sciences
VRs	Ventilated roofs
W	Kendall's coefficient of concordance

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ORIGINAL RESEARCH ARTICLE

Eco-friendly and net-zero emission implementation strategies for sustainable urban tourism

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ABSTRACT

BACKGROUND AND OBJECTIVES: The tourism sector is confronted with an increasing number of challenges that are associated with the reduction of carbon emissions and climate change. As a major source of greenhouse gas emissions, the tourism sector requires robust decarbonization frameworks to fulfill global sustainable development goals and net-zero commitments. Despite their critical importance, the linkages connecting sustainable tourism, destination management, resilience, and net-zero targets remain virtually unexplored. The objectives of this study were to assess destination initiatives in urban tourism by employing a resilience-based framework to facilitate the attainment of net-zero emissions.

METHODS: The study was conducted at six heritage tourism destinations in Medan City, Indonesia, namely Al-Mashun Grand Mosque, Maimun Palace, Tjong A Fie House, Velangkani Temple, Medan Zoo, and the Crocodile Breeding Center. A systematic questionnaire was provided to 200 visitors of the cultural heritage area to obtain insights into their perspectives on developed and implemented resilience initiatives. This study utilizes a comprehensive evaluation strategy, encompassing internal and external strategies, performance measurement, and corrective actions—to examine pathways toward net-zero emissions, positioning a resilience-based framework as a critical intervening variable. Data were analyzed using structural equation modeling–partial least squares.

FINDINGS: The measurement model met the required validity and reliability criteria. Structural model analysis revealed that internal and external strategies significantly influenced net zero emissions ($\beta = 0.215$; $p = 0.005$) and destination resilience ($\beta = 0.331$; $p < 0.001$). Performance measurement positively affected net zero emissions ($\beta = 0.239$; $p = 0.001$) but showed no significant effect on resilience. The resilience-based framework exerted the strongest influence on net zero emissions ($\beta = 0.400$; $p < 0.001$) and significantly mediated the relationship between strategy and net zero emissions achievement. Conversely, corrective action did not exert a statistically significant effect on net-zero emissions. Overall, the empirical model accounted for 44.9 percent of the variance in net zero emissions ($R^2 = 0.449$).

CONCLUSION: The empirical insights provide practical frameworks for heritage site administrators and institutional stakeholders to bolster systemic resilience, promote social cohesion, and safeguard the economic sustainability of the cultural tourism sector amidst environmental and market volatility.

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INTRODUCTION

Climate change has emerged as the defining systemic challenge of the twenty-first century, placing unprecedented pressure on carbon-intensive economic sectors to fundamentally restructure their development pathways. As one of the global economy's largest sectors, tourism occupies a critical intersection between macroeconomic growth and environmental stewardship. The sector currently accounts for approximately 8–11 percent (%) of global greenhouse gas (GHG) emissions, equivalent to 4.0 gigatons of carbon dioxide equivalent ($GtCO_2e$) annually a figure encompassing transportation, accommodation, and destination-level activities (Lenzen *et al.*, 2018; UNWTO, 2023). The urgency of this challenge has intensified following the 2022 Glasgow Declaration on Climate Action in Tourism, endorsed by over 700 signatories, which committed the global tourism sector to halving emissions by 2030 and achieving net-zero emissions (NZE) before 2050 (UNWTO, 2023). Achieving these benchmarks requires systemic transformations in destination governance and management rather than marginal efficiency gains to ensure long-term climate resilience (Gössling *et al.*, 2024; Peeters and Papp, 2024). Indonesia presents a particularly compelling case for investigating the governance dimensions of this transformation. As the world's fourth most populous country and the largest archipelagic state, Indonesia has committed to achieving NZE by 2060 or sooner under its long-term strategy for low carbon and climate resilience submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2021, with this commitment structurally embedded in the Seventh National Development Plan (RPJPN 2025–2045) mandating green and low-carbon sectoral restructuring (KLHKRI, 2021; Bappenas, 2025). Yet, Indonesia's NZE trajectory is rated 'Critically Insufficient' (Muslim and Hastuti, 2024), reflecting a structural governance gap between ambitious national commitments and the constrained implementation capacity of sub-national administrations. Accounting for 5.1% of GDP, 12.5 million jobs, and 13.9 million international arrivals in 2024, Indonesia's travel and tourism sector represents a macroeconomic heavyweight that can no longer be omitted from the nation's decarbonization strategy (BPS, 2025a). The challenge, therefore, is not whether tourism must transition to NZE, but how this transition can be realistically governed at the destination level. The academic literature on sustainable tourism governance has advanced considerably over the past two decades, yielding three converging streams of inquiry. First, the sustainable tourism governance stream posits that destination management should be guided by the normative principles of economic viability, socio-cultural equity, and ecological integrity (Bramwell *et al.*, 2017; Sharpley, 2021). Second, the destination resilience stream conceptualizes tourism destinations as complex adaptive systems capable of absorbing disturbances, reorganizing, and sustaining their essential functions in the face of climate variability, economic shocks, and public health crises (Cheer and Lew, 2017; Becken *et al.*, 2020; Hall *et al.*, 2024). Studies in this stream posits that destination management should be guided by the normative principles of economic viability, socio-cultural equity, and ecological integrity (Bangwayo-Skeete and Skeete, 2022; Azzaz and Elshaer, 2024). Third, the net-zero tourism transition stream focuses on decarbonization strategies, including carbon emission accounting, renewable energy adoption, and low-carbon mobility solutions, as the operational pathways toward sector-level emission neutrality (Gössling and Higham, 2021; Scott and Gössling, 2022; Peeters and Papp, 2024). Within this stream, performance measurement systems encompassing energy efficiency monitoring, waste reduction tracking, and carbon footprint assessment have been identified as critical instruments for evidence-based NZE governance (Becken *et al.*, 2020; Becken and

Scott, 2024). Furthermore, destination resilience research demonstrates that the capacity to withstand, adapt to, and recover from systemic shocks is inherently embedded within of institutional, economic, social, and ecological interdependencies (Conefrey *et al.*, 2024; Falk *et al.*, 2024). Innovative climate governance frameworks call for decentralized, multi-actor approaches that integrate stakeholder participation across city and destination administrative levels (Shtjefni *et al.*, 2024). Complementary work in carbon-neutral city governance (Huovila *et al.*, 2022) and tourism resilience theory (Ritchie and Jiang, 2019) further underscores that neither institutional adaptation nor technical decarbonization alone is sufficient their integration is required for durable sustainability outcomes. Despite recent progress, the separate literatures on sustainability governance, destination resilience, and NZE pathways remain siloed, without a cohesive empirical framework evaluating their structural interdependencies. However, four major theoretical and empirical gaps persist in the existing literature. First, the resilience-NZE nexus has not been empirically tested within a single, comprehensive quantitative framework. Although literature posits that reactive corrective actions fall short of achieving NZE targets and underscores the vital role of resilience-based adaptive capacity (Gössling and Higham, 2021), this theoretical assertion lacks empirical verification through structural modeling in a tourism destination context. Most prior studies examine these constructs in partial combinations resilience and governance, or governance and NZE, but not all three simultaneously leaving system-level dynamics and mediation mechanisms unexplored. Second, existing empirical models fail to disentangle how distinct management strategy components—such as internal and external actions, performance measurement, and corrective steps—individually influence resilience outcomes and NZE targets. Third, greenwashing risks and measurement validity in NZE governance studies have been insufficiently addressed: the absence of standardized carbon monitoring infrastructure in developing-country tourism destinations means that sustainability assessments frequently rely on perceptual proxies rather than verified emission data, creating an important methodological gap (Fahmi and Nuraini, 2024). Fourth, the interaction between cultural heritage conservation requirements and the implementation of low-carbon infrastructure remains theoretically underspecified in the current literature. Heritage conservation regulations typically restrict structural modification of protected sites, constraining the retrofitting of renewable energy installations and energy-efficient mechanical systems a dimension absent from existing NZE tourism models. To address these gaps, this study proposes and empirically tests an integrated Resilience–sustainability–net-zero emissions (RSNZE) framework. Within this model, destination resilience is operationalized as a dynamic mediating construct translating strategic management inputs into concrete NZE outcomes. Unlike prior studies that treat resilience, sustainability, and net-zero transition as separate theoretical constructs, this framework conceptualizes their interaction as a system: sustainability provides the normative governance foundation; resilience provides the adaptive institutional mechanism; and NZE constitutes the strategic decarbonization target. This framework is operationalized through structural equation modeling–partial least squares (SEM-PLS), allowing for the simultaneous estimation of direct path effects, mediation pathways, and predictive power. Three theoretical advances distinguish this study from prior work: 1) empirical validation of the resilience-to-NZE mediation pathway in a tourism destination context, addressing Gössling and Higham's (2021) unverified theoretical claim; 2) the first quantitative investigation of the RSNZE nexus in a multicultural urban heritage tourism

setting; and 3) contextualization of the framework within a mid-tier developing-country city characterized by constrained governance capacity and heritage conservation constraints a governance archetype shared by a large class of destinations across Southeast Asia, South Asia, and Sub-Saharan Africa for which generalizable empirical evidence is currently lacking. This study was carried out at six principal heritage tourism destinations in Medan City, North Sumatra, Indonesia Al-Mashun Grand Mosque, Maimun Palace, Tjong A Fie House, Velangkani Temple, Medan Zoo, and the Crocodile Breeding Center in 2024. Grounded in this framework, the study addresses three distinct objectives: 1) to examine how internal and external destination strategies drive destination resilience and NZE outcomes; 2) to evaluate the empirical relationships connecting environmental performance metrics with NZE pathways and adaptive resilience capacity, thus offering fresh insights into the scholarly debate regarding whether monitoring systems alone are sufficient for fostering destination resilience; and 3) to examine the association between corrective action and NZE or resilience outcomes, testing the theoretical proposition that reactive management approaches are insufficient for the transformative change required by net-zero tourism transition. This study has been carried out in heritage tourism in Medan those were Al-Mashun Grand Mosque, Maimun Palace, Tjong a Fie House, Velangkani Temple, Medan Zoo, and Crocodile Breeding Center in 2024.

MATERIALS AND METHODS

Study area

The study was conducted in Medan City, North Sumatra, Indonesia. Medan City serves as the primary administrative and economic hub of western Indonesia and its fourth-largest municipality, making it an ideal study area for three substantive reasons: 1) the city serves as the primary urban heritage tourism hub within the western Indonesian region, offering a highly concentrated cluster of historical assets that reflect diverse civilizational influences; 2) its urban tourism governance exhibits structural vulnerabilities typical of secondary cities in developing nations, characterized by limited sub-national climate governance capacity, inadequate carbon monitoring infrastructure, and a heritage conservation agenda that has historically been decoupled from low-carbon development planning; and 3) the city's trajectory of rapid tourism growth, with North Sumatra recording a 27.37% increase in international arrivals between January and November 2024 (BPS, 2025b), creates an empirically relevant context for testing the associations between destination management strategies, resilience, and NZE achievement. Data collection was executed across six preeminent heritage tourism destinations, which collectively reflect the city's inter-civilizational tourism mosaic: Al-Mashun Grand Mosque, Maimun Palace, Tjong A Fie House, Velangkani Temple, Medan Zoo, and the Crocodile Breeding Center Sunggal (Fig. 1). Collectively reflecting Medan's multicultural urban heritage landscape, these six sites provide the diverse visitor profiles, management contexts, and heritage typologies required to empirically test the study's theoretical framework (Fig. 1). Al-Mashun Grand Mosque (built 1906), featuring Islamic Malay-Mughal architecture represents the Islamic heritage typology and attracted 52 respondents. Maimun Palace (built 1888), a royal Malay heritage contributed 38 respondents. Data collection also captured 28 respondents from the Tjong A Fie Mansion (built 1895), representing Chinese-colonial heritage, and 22 respondents from the Velangkanni Church pilgrimage site. Medan Zoo, a 30-hectare recreational and conservation facility established in 1953 catering primarily to family and educational visitors, provided 38 respondents. The Crocodile Breeding Center Sunggal, an ecotourism and wildlife conservation facility serving domestic tourists and educational groups—accounted for 22 respondents within the final sample. Together, the six destinations span Islamic, Malay royal, Chinese-colonial, Christian,

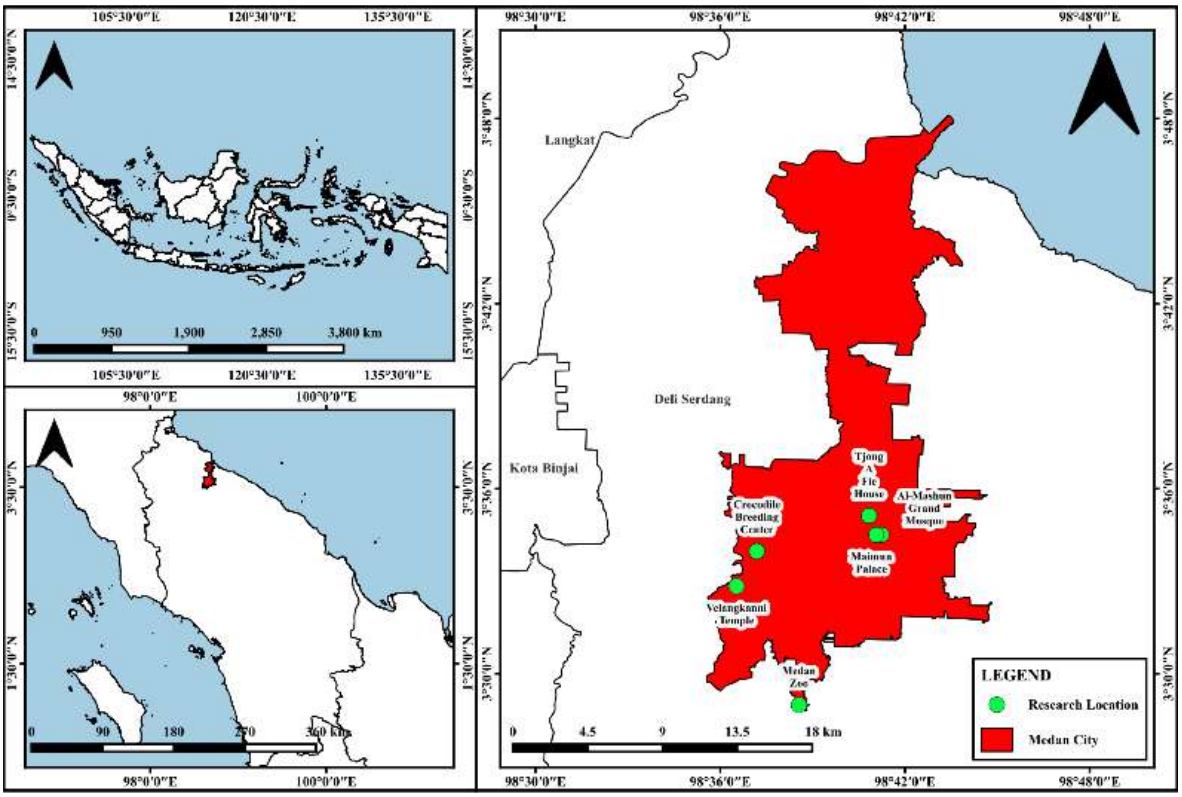

Fig. 1: Geographical location of the study area in Medan City, North Sumatra, in Indonesia

recreational, and ecological heritage typologies, providing the intra-city diversity of governance contexts and visitor profiles necessary for a robust cross-destination analysis of NZE governance perceptions.

Research design

This study employs a quantitative approach with an explanatory design to examine the causal inter-variable connections in the proposed conceptual model. This quantitative framework enables empirical hypothesis testing through rigorous statistical evaluation. The research model employed SEM-PLS due to its methodological advantages for complex models featuring several latent constructs, its effectiveness for medium sample sizes, and its suitability for data distributions that are not strictly normal. PLS-SEM was preferred over covariance-based SEM (CB-SEM) due to the model's emphasis on prediction and theoretical formulation, coupled with the integration of indicators that reflect each underlying construct. Furthermore, SEM-PLS offers greater flexibility regarding assumptions of data normality, which is appropriate for analyzing socio-economic contexts where data are frequently not normally distributed. This methodological choice carries an important interpretive boundary: SEM-PLS path coefficients are best understood as predictive associations identified within the proposed model rather than confirmatory causal estimates, and model adequacy is evaluated using prediction-oriented criteria (R^2, Q^2, SRMR) rather than the absolute fit indices conventionally reported in CB-SEM (e.g., CFI, RMSEA). Reflecting this epistemological boundary, the Results and Discussion section consistently utilizes associational rather than

causal terminology to describe the structural pathways revealed by the model.

Data collection

Primary data were collected through a questionnaire prepared and organized based on the study literature and adapted to the context of urban tourism destinations. Prior to distribution, the questionnaire materials were pre-tested to ensure item clarity and measurement consistency. Enumerators conducted data collection directly after receiving brief instruction on data entry procedures and research ethics. Respondents were briefed on the research objectives and provided with explicit assurances regarding data anonymity and confidentiality. The data collection procedure employed non-probability sampling, specifically incidental sampling, in which respondents were visitors encountered at the research site who were willing to complete the questionnaire. A sample size of 200 respondents met the minimum standard for SEM-PLS. Sample size determination was guided by the 10-times rule, which mandates a minimum sample equivalent to ten times the number of indicators associated with the model's largest structural component. Considering the complexity of the model, which involves several latent variables, a total of 200 respondents was considered sufficient to provide satisfactory outcomes.

Measurement instrument

This study employs five main latent constructs comprising 10 sub-variables and 20 reflective indicators, measured on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree), to investigate the factors influencing NZE achievement at the destination level. The first construct, internal and external strategy (X1), evaluates destination strategy encompassing operational efficiency management, renewable energy policy adoption, external stakeholder engagement, and sustainable procurement practices (Gössling *et al.*, 2023; Scott and Gössling, 2022). Environmental performance assessment within the second construct (X2) is evaluated through four primary dimensions: carbon emission monitoring systems, energy efficiency tracking, waste management indicators, and the assessment of visitor environmental impacts (Becken *et al.*, 2020; Becken and Scott, 2024). The third construct, corrective action (X3), evaluates reactive management interventions designed to modify policies and operational workflows. Specifically, it operationalizes these interventions through post-audit policy revisions, process adjustments following performance discrepancies, compliance training initiatives, and structural environmental remediation aimed at mitigating emissions and optimizing sustainability (Dredge, 2022; Peeters and Papp, 2024). The fourth construct, the resilience-based framework (Z), evaluates the adaptive capacity of the destination system to respond to a variety of external disturbances and ensure system durability amid change, measured through indicators of government green economy response, technological innovation capacity, local tourism manager adaptability, and consumer and employee environmental confidence (Cheer and Lew, 2017; Lew *et al.*, 2020; Azzaz and Elshaer, 2024). The fifth construct, NZE (Y), evaluates participant perceptions regarding the efficacy of carbon emission reduction initiatives and organizational alignment with NZE objectives. This variable is operationalized through four core metrics: commitment to energy reduction, adoption of sustainable products and services, enhancement of environmental conditions enhancement , and the attainment of carbon neutrality targets (Scott and Gössling, 2022; Peeters and Papp, 2024; UNWTO, 2023).

Data analysis

Data analysis was conducted using SmartPLS software, comprising two primary stages: evaluation of the measurement model (outer model) and evaluation of the structural model (inner model). To confirm the validity and reliability of the research model's latent variables,

an outer model evaluation was conducted. The constructs were benchmarked against conventional statistical criteria, requiring factor loadings ≥ 0.70, average variance extracted (AVE) ≥ 0.50, composite reliability (CR) ≥ 0.70, and Cronbach's Alpha ≥ 0.70. Discriminant validity was assessed using the Fornell-Larcker criterion. During model evaluation, indicators with a loading factor below 0.40 were excluded from the model, while indicators with loading factors between 0.40 and 0.70 were retained or removed depending on their impact on the AVE and CR values of each construct. Evaluation of the structural model (inner model) examines the relationships between constructs in the research model. This analytical approach evaluates path coefficients to ascertain the direction and magnitude of hypothesized relationships. Statistical significance is subsequently determined via t-statistics and p-values generated through a bootstrapping procedure utilizing 5,000 resamples. The model's capacity to explain endogenous variables was assessed using the coefficient of determination (R^2). A mediation analysis (indirect effect) was also conducted to examine the role of the resilience-based framework as an intervening mechanism in the relationships between management strategy variables and net zero emissions. Given $\alpha = 0.05$, a relationship between variables is considered significant if the p-value is below 0.05. To ascertain whether resilience serves as a mediating mechanism between management strategies and the achievement of NZE targets, the mediation effect was assessed by examining the statistical significance of the bootstrap-derived indirect effect.

Research design

This study adheres to academic ethical principles, ensuring that respondent participation was voluntary and that respondent identities remained confidential. All data collected were restricted strictly to the scope of this study and were not disseminated for external purposes.

RESULTS AND DISCUSSION

Measurement model evaluation

Assessment of the measurement model was conducted to ensure that the latent constructs employed in the study meet the criteria for validity and reliability. The latent constructs under examination were effectively operationalized by their respective indicators, all of which displayed factor loadings meeting the minimum retention criteria (Table 1). The average variance extracted (AVE) for all constructs exceeds the threshold of 0.50, indicating that each construct accounts for more than half of the variance in its indicators. Composite reliability values for all constructs exceed the recommended threshold of 0.70, indicating a high level of internal consistency. These findings demonstrate that the measurement model satisfies the established criteria for both convergent validity and internal consistency reliability. Discriminant validity, assessed using the Fornell-Larcker criterion, demonstrates that the square root of the AVE for each construct exceeds its correlation values with other constructs, confirming that each construct possesses adequate discriminant capability and that latent multicollinearity is not a concern in this research model.

Structural model and resilience-based pathways toward net zero emissions

Structural model assessment was executed via a bootstrapping procedure to evaluate the statistical significance of the hypothesized paths between the latent constructs. As shown in Table 2, internal and external strategy was significantly associated with NZE ($\beta = 0.215$, $p = 0.005$) and with the resilience-based framework ($\beta = 0.331$, $p < 0.001$). These results indicate that management strategies encompassing operational efficiency, resource management, and engagement with external stakeholders are associated with efforts to reduce carbon emissions at tourism destinations and demonstrate that competent

Table 1: Evaluation of measurement model

Construct	AVE	Composite reliability
Internal & External Strategy	0.685	0.813
Net Zero Emission	0.578	0.846
Performance Measurement	0.645	0.844
Resilience-Based Framework	0.547	0.780
Corrective Action	0.842	0.914

Table 2: Structural model path coefficients

Relationship	Path coefficient	p-value
Strategy → Net zero emissions	0.215	0.005
Strategy → Resilience	0.331	0.000
Performance measurement → Net zero emissions	0.239	0.001
Performance measurement → Resilience	0.026	0.804
Resilience → Net zero emissions	0.400	0.000
Corrective action → Net zero emissions	0.011	0.874

destination management plays an important role in facilitating the transition to low-carbon tourism. Within the paradigm of sustainable tourism, effective destination management necessitates the strategic integration of economic, socio-cultural, and environmental dimensions to secure enduring sustainability. Prior research indicates that destination approaches combining regulatory frameworks with clean energy innovation are associated with reduced carbon emissions and enhanced competitiveness among tourism destinations (Gössling *et al.,* 2023; Scott and Gössling, 2022). Tourism resilience refers to the capacity of a destination to withstand and recover from adverse events affecting the tourism system, to absorb disturbances, adapt to change, and sustain social and economic functions following a crisis (Cheer and Lew, 2017; Lew *et al.,* 2020). Prior studies demonstrate that community participation and institutional capacity are critical determinants of a destination's adaptive capacity, enabling tourism systems to mitigate climate vulnerabilities and sustain operations over time (Hall *et al.,* 2024). Performance measurement was significantly associated with NZE (β = 0.239, p = 0.001) but showed no significant association with resilience (β = 0.026, p = 0.804). This finding suggests that environmental monitoring and evaluation systems play an important role in supporting carbon emission reduction. While performance measurements encompassing energy efficiency, waste management, and carbon emission reduction provide precise data for climate change mitigation, prior research indicates that sector-specific systems, such as those in tourism, are particularly crucial instruments for identifying primary emission sources and devising effective decarbonization policies (Becken *et al.,* 2020; Becken and Scott, 2024; Gössling and Higham, 2024). However, the non-significant association between performance measurement and resilience suggests that environmental monitoring systems alone are currently insufficient to enhance destination resilience, which is a complex construct shaped by institutional capacity, human resources, and innovative capability (Dredge, 2022). Corrective action was not significantly associated with NZE (β = 0.011, p = 0.874) or with resilience. This finding demonstrates that reactive strategies possess limited efficacy in accelerating the tourism sector's transition toward a low-carbon economy. Achieving net-zero tourism requires systemic change involving technological innovation, shifts in visitor behavior, and multi-stakeholder engagement among government, industry actors, and local communities (Peeters and Papp, 2024). Among all constructs, the resilience-based framework exhibited the strongest association with NZE achievement (β = 0.400, p < 0.001). This

finding underscores destination resilience as a pivotal determinant of sectoral decarbonization, suggesting that highly resilient destinations possess superior capacity for implementing effective climate change adaptation and mitigation strategies (Scott *et al.,* 2024; Hall *et al.,* 2024). To further evaluate the explanatory power of the model, the coefficient of determination (R^2) was assessed (Table 3). The R^2 value for the NZE variable is 0.449, indicating that internal and external strategies, performance measurement, corrective action, and resilience collectively account for approximately 44.9% of the variation in NZE, which is classified as moderate. The structural model evaluation revealed an R^2 value of 0.167 for the resilience-based framework. This indicates that the combination of internal and external strategies, performance measurement, and corrective action account for approximately 16.7% of the variation in destination resilience.

Table 3: Coefficient of determination

Variable	R^2
Net zero emission	0.449
Resilience-based framework	0.167

Mediation analysis

The mediation test demonstrates that the resilience-based framework significantly mediates the relationship between internal and external strategy and NZE, with resilience accounting for 38.0% of the total strategy-NZE relationship (VAF = 38.0%). These findings demonstrate that resilience functions exclusively as a significant partial mediator within the strategy-NZE nexus. This empirically validates the theoretical proposition that resilience operates as a pivotal transmission mechanism through which strategic management capacity is translated into substantive emission reduction outcomes. No significant mediation was found for the performance measurement-NZE or corrective action-NZE relationships, consistent with the non-significant direct associations between these variables and resilience reported above (Table 4).

Theoretical implications: the resilience, sustainability, and net zero tourism triangle

This study contributes theoretically by integrating three primary perspectives in the sustainable tourism literature: tourism resilience, sustainable tourism governance, and net-zero tourism transition (Fig. 2). Most prior studies address these three perspectives separately. Prior research in sustainable tourism heavily emphasizes the alignment of systemic resource management, civic participation, and responsible governance structures (Bramwell *et al.,* 2017; Sharpley, 2021). Tourism resilience literature emphasizes the capacity of destinations to recover from crises such as natural disasters or pandemics (Cheer *et al.,* 2021; Hall *et al.,* 2024). Research on net-zero tourism, in contrast, emphasizes decarbonization techniques through carbon emission reduction, energy efficiency, and renewable energy utilization within the tourism sector (Gössling and Higham, 2024; Scott *et al.,* 2024). The theoretical triangle model (Fig. 2) illustrates that the attainment of Net-Zero Tourism (NZT) is intrinsically linked to a systemic transformation of the tourism sector, a process fundamentally underpinned by the twin pillars of resilience and sustainability. Sustainability serves as a normative foundation that emphasizes the balance of economic, environmental, and social considerations in destination tourism management. Resilience functions as an adaptive mechanism that enables tourism systems to respond to diverse external disturbances, such as climate change and global crises. The interaction between these two pillars strengthens the sustainability and robustness of the tourism sector, serving as a critical pathway toward a low-carbon framework and ultimate NZE achievement. This model confirms that attaining NZE is associated with the convergence of governance, sustainability, and destination resilience capabilities. The revised triangle framework (Fig. 2) is grounded in three theoretical traditions. First, sustainability serves as a normative foundation draws from Brundtland's intergenerational equity

Table 4: Mediation analysis results (bootstrapped indirect effects, 5,000 resamples)

Pathway	Indirect effect	SE	95% CI	p-value	Conclusion
Strategy → Resilience → NZE	0.132	0.047	[0.047, 0.231]	0.004	Significant partial mediation (VAF = 38.0%)
Performance Measurement → Resilience → NZE	0.010	0.015	[-0.018, 0.041]	0.481	Non-significant (no mediation)
Corrective Action → Resilience → NZE	0.004	0.012	[-0.019, 0.032]	0.743	Non-significant (no mediation)

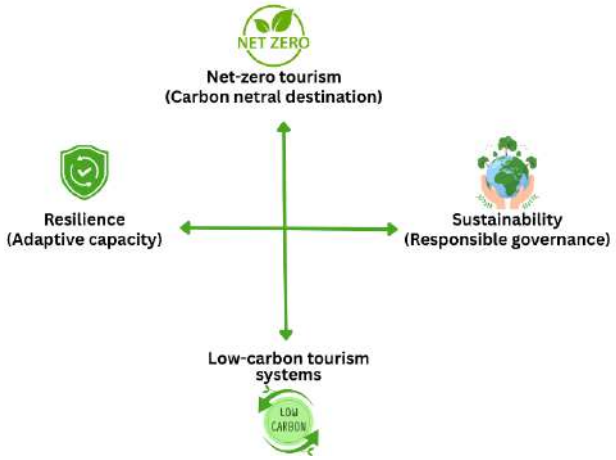

Fig. 2: The model of net zero tourism

principles operationalized through destination governance (Bramwell *et al.,* 2017). Second, resilience as an adaptive mechanism rooted in complex adaptive systems theory (Becken *et al.,* 2020) and socio-ecological resilience theory (Cheer and Lew, 2017). Finally, NZE is framed as a strategic transformation target, deriving from transition management theory (Peeters and Papp, 2024) and climate governance frameworks under the UNFCCC Paris Agreement. The revised figure incorporates the empirical path values obtained in this study (β = 0.400 for Resilience → NZE; β = 0.331 for Strategy → Resilience; β = 0.215 for the strategy → NZE direct path), the mediation pathway with its indirect effect value (0.132), R^2 values for the endogenous constructs, and ontological labels identifying sustainability as the normative foundation, resilience as the adaptive mechanism, and NZE as the strategic transformation target. The synergy among these three pillars establishes a theoretically robust and testable paradigm for executing sustainable transformation within the tourism sector. To clarify further how environmental, socio-economic, governance, heritage conservation, stakeholder participation, technological, and growth-pressure dimensions relate within this framework: sustainability establishes the normative foundation balancing environmental and socio-economic imperatives; resilience acts as the governance-driven adaptive mechanism; and NZE serves as the ultimate target toward which both pillars are oriented. Heritage conservation constraints (see earlier discussion), stakeholder equity and community participation, smart technology adoption, and the tension between visitor growth and emission intensity are best conceptualized as boundary conditions and moderating contextual factors that shape how strongly and how consistently the resilience-sustainability-NZE pathway operates in a given destination, rather than as additional empirically tested constructs within the present quantitative model. While the present study utilizes SEM-PLS

to validate the core strategy-resilience-NZE pathway, several avenues for future research remain. Specifically, subsequent empirical investigations should operationalize heritage conservation conflict, stakeholder equity, and technology adoption as distinct latent constructs. Furthermore, expanding the geographic and environmental scope beyond urban heritage settings would test the boundary conditions and generalizability of the proposed framework.

Findings indicate that establishing NZE in the tourism sector depends not only on policy and technical measures for carbon emission reduction but also on the capacity of adaptive systems to respond to varied external disturbances. Consequently, highly resilient tourism destinations are better positioned to adopt innovative technologies, integrate supportive policies, and implement sustainable management practices. This perspective is consistent with recent studies emphasizing that effective environmental governance, ecosystem resilience, and adaptive management are fundamental for achieving long-term sustainability outcomes across natural resource systems (Harahap *et al.,* 2025; Arthatiani *et al.,* 2026). Furthermore, socio-environmental and territorial governance mechanisms have been shown to strengthen institutional adaptability and improve the effectiveness of sustainable resource management, thereby supporting resilience-based transitions toward low-carbon development (Díaz-Ponce *et al.,* 2026). Therefore, the convergence of sustainability governance, adaptive resilience, and net-zero transitions constitutes a critical imperative for propelling the tourism industry toward a low-carbon paradigm. This study contributes to the development of an integrative resilience–sustainability–net-zero tourism model by linking the literature on sustainable tourism, resilient destinations, and climate change mitigation, while providing empirical evidence regarding the significant role of destination resilience in facilitating decarbonization within the tourism industry. The robust positive correlation between the resilience-based framework and NZE achievement (β = 0.400) aligns with a growing body of literature highlighting adaptive institutional capacity as a cornerstone of decarbonization governance and broader environmental resilience (Harahap *et al.,* 2025; Díaz-Ponce *et al.,* 2026; Arthatiani *et al.,* 2026). This synergy is evident across diverse geographical contexts, including Pacific Island destinations (Hall *et al*., 2024), European ski resorts (Scott *et al*., 2024), and New Zealand (Becken *et al*., 2020). The absence of a significant association between corrective action and NZE (β = 0.011) is theoretically consistent with Gössling and Higham (2021) critique of reactive management paradigms in tourism decarbonization, and empirically echoes Dredge (2022) finding that institutional corrective capacity alone is insufficient without foundational resilience infrastructure. Such an outcome may be attributed to the relative underdevelopment of structured corrective management mechanisms within Indonesia's urban tourism governance infrastructure (Fahmi and Nuraini, 2024; Shtjefni *et al.,* 2024). The non-significance of corrective action (β = 0.011, $p > 0.05$) aligns with the theoretical position advanced by Gössling and Higham (2021) that reactive management frameworks are structurally insufficient for net-zero transition, which demands systemic, anticipatory transformation rather than incremental post-hoc corrections. Peeters and Papp (2024) similarly argue that NZE achievement requires multi-stakeholder, technology-enabled transformations that transcend the scope of reactive corrective interventions. This evidence underscores a critical shift required in tourism governance, suggesting that sustainable destination management hinges on prioritizing anticipatory resilience and strategic decarbonization over traditional, reactive operational adjustments, thereby enhancing long-term adaptive capacity, climate resilience across destinations.

Practical implications

These findings carry significance for the formulation of sustainable tourism policy, particularly in supporting the transition to net-zero tourism. To address the substantial carbon footprint generated by tourist transit, literature underscores the need for regulatory bodies to mainstream climate mitigation policies into macro-level tourism development agendas. Effective governance in this domain requires a tripartite approach: incentivizing renewable energy adoption, optimizing sector-wide energy efficiency, and deploying sustainable transportation infrastructure (Peeters and Papp, 2024; Gössling *et al.,* 2023). Destination managers should strengthen resilience-based management within destination administration. Destination resilience can be enhanced through economic diversification in tourism, strengthened institutional capacity, and improved local public participation in tourism management (Lew *et al.,* 2020; Cheer *et al.,* 2021), helping to ensure that destinations remain adaptable to environmental changes and economic uncertainties. Government and tourism stakeholders should also develop monitoring and reporting systems for carbon emissions in the tourism sector, which can assist in identifying primary emission sources and evaluating the effectiveness of mitigation policies. Prior studies demonstrate that carbon emission measurement is a critical determinant of successful sectoral decarbonization initiatives across the tourism industry (Becken and Scott, 2024; Scott and Gössling, 2022). Multi-stakeholder collaboration among government, the corporate sector, local communities, and international organizations is a critical factor in reaching net zero tourism goals, advancing innovation policy, technology transfer, and the development of more sustainable tourism practices (Bramwell *et al.,* 2017; Hall *et al.,* 2024). The empirical evidence demonstrate that a resilience-based framework serves as the primary determinant of NZE success, highlighting systemic resilience as a critical prerequisite for sectoral decarbonization. In contrast, reactive operational adjustments fail to demonstrate a significant correlation with NZE targets or adaptive destination capacity. The development of a carbon emission monitoring system, together with certification for low-carbon tourism, may serve as an important instrument in advancing sustainability practices within the tourism business. Beyond the scope of the current perceptual scale, the authors highlight two distinct practical limitations requiring further investigation. First, disaggregated, source-level data distinguishing emission contributions from visitor mobility and transportation versus on-site operational activities at each destination were not collected; given that transportation is widely documented as a dominant emission source in tourism systems (Lenzen *et al.,* 2018; Scott and Gössling, 2022), it is recommended that future destination-level studies incorporate source-disaggregated carbon accounting validated against traffic counts, energy billing records, and waste audit data. Second, carbon offset mechanisms, carbon credit systems, and infrastructure lifecycle assessment, which are increasingly central to corporate and destination-level net-zero strategies globally (Peeters and Papp, 2024). Consequently, exploring these objective, non-perception-based pathways represents a critical avenue for future research to complement these findings. The financial sustainability of the resilience- and NZE-oriented initiatives discussed above, including cost-benefit analysis and funding mechanisms, was not evaluated in this study, as our model is perceptual and does not incorporate financial or budgetary data from destination management entities. These insights offer vital pragmatic direction for policymakers and destination administrators seeking to operationalize the study's empirical findings. Furthermore, the authors acknowledge several methodological limitations regarding stakeholder scope. Specifically, local community members were excluded from the survey sample, meaning that community participation and social equity were not evaluated as independent

constructs. Additionally, the internal/external strategy dimension relies on a single indicator for external stakeholder engagement, which was captured solely through the perceptual lens of the surveyed visitors. This is a notable limitation given that social equity and community participation are widely recognized as central pillars of sustainable tourism governance (Bramwell *et al.,* 2017; Sharpley, 2021). Relatedly, decarbonization strategies implemented without attention to distributional effects could plausibly affect informal vendors, small-scale tourism operators, or cultural practices reliant on existing infrastructure and visitor flow patterns at heritage sites. To align with a just-transition approach to tourism decarbonization, the future implementation of resilience-based NZE strategies should be accompanied by comprehensive social impact assessments. Such measures are vital to safeguarding local livelihoods and maintaining socio-cultural authenticity. Furthermore, future research designs must directly integrate community-level respondents to capture these socio-ecological dimensions empirically. Smart tourism technologies represent an important emerging lever for both resilience-building and emission reduction, including AI-based visitor flow optimization, IoT-enabled energy and waste monitoring, GIS-based spatial planning for carbon-efficient infrastructure, and digital real-time environmental monitoring dashboards. The evaluation of these specific technologies fell outside the scope of the present study, as the underlying measurement instrument was explicitly designed to assess constructs of management strategy, performance measurement, and corrective action constructs rather than specific digital technology adoption. This technology are a promising direction and recommend incorporating a dedicated digital and smart-technology adoption construct in future extensions of the proposed framework. In summary, the research offer the following stakeholder-differentiated recommendations. Collectively, the empirical insights yield distinct, stakeholder-specific recommendations. At the governance level, national and municipal governments should systematically integrate climate mitigation frameworks within comprehensive tourism planning strategies. This integration requires dismantling pervasive structural impediments, most notably the division of inter-agency jurisdictional authority and the budgetary limitations restricting municipal green-infrastructure investments. For destination managers: prioritize proactive resilience-building, encompassing economic diversification, institutional capacity, and local participation, over reactive corrective measures, consistent with our empirical finding on corrective action's non-significance. For heritage destination managers specifically: pursue non-invasive low-carbon interventions that respect conservation constraints, such as LED retrofitting and off-site renewable energy procurement, rather than structural retrofits.

Study limitations and future research

Although this study contributes important insight into the relationship between destination strategy, resilience, and net zero emissions, a number of limitations should be noted. Future research could also explore the role of digital technology and smart tourism in supporting carbon emission reduction in the tourism sector. As a cross-sectional survey study, causal directionality cannot be confirmed from these findings. Rather than demonstrating definitive causal mechanisms, the observed path coefficients reflect statistically significant relationships inherent to the proposed structural framework. Longitudinal research designs, quasi-experimental approaches, or natural experiments would be required to confirm causal mechanisms underlying the resilience-NZE relationship. The relatively modest R^2 for the resilience-based framework construct (R^2 = 0.167) indicates that the three management strategy variables, while statistically significant predictors, collectively explain only 16.7% of the variance in destination

resilience. This finding highlights the inherently multidimensional and complex nature of destination resilience (Dredge, 2022), which encompasses institutional, financial, ecological, human capital, and social dimensions beyond the scope of the current model. To enhance the predictive validity of destination resilience frameworks within the NZE paradigm, future empirical inquiries should integrate a broader array of determinants, namely governance quality metrics, climate vulnerability indices, fiscal capacity, community social capital, and digital technology adoption levels. Regarding geographic scope, this study was deliberately limited to Medan City because it represents a strategically important but understudied multicultural urban heritage tourism context within Indonesia's broader NZE 2060 commitment. The external validity of these outcomes is primarily confined to equivalent mid-tier, developing-nation urban heritage environments. Such destinations are typically characterized by comparable structural and regulatory impediments, most notably deficits in carbon accounting infrastructure and stringent heritage preservation mandates. Transferability to rural destinations, or to developed-country contexts with more mature carbon governance infrastructure, should be treated with caution, and a comparative cross-context replication are recommended as a priority direction for future research. Several critical trajectories for subsequent empirical study emerge from this review. First, transitioning toward longitudinal methodologies is essential to verify temporal precedence and overcome the structural, non-causal constraints of the present cross-sectional framework. Second, mixed-method approaches combining the current quantitative SEM-PLS framework with qualitative key-informant interviews. Engaging stakeholders such as municipal officials, destination managers, and community representatives would serve to empirically substantiate the governance, institutional, and equity dimensions that were explored conceptually in this study but remained unmeasured. Third, biodiversity and ecological indicators, particularly relevant for the Medan Zoo and Crocodile Breeding Center sites, were not incorporated into the current resilience construct and merit dedicated measurement. Fourth, carrying capacity analysis provides a mechanism to scrutinize the aforementioned friction between continued tourist expansion and the decoupling of emissions intensity. Finally, explicit alignment with the United Nations Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 8 (Decent Work and Economic Growth), would strengthen the policy relevance of future extensions of this study (UNWTO, 2023). Finally, the findings suggest that the resilience-sustainability-NZE triangle proposed in this study can serve as a basis for periodic destination-level assessment, using the performance measurement construct as an entry point for a standardized monitoring and reporting system, ideally combining recurring visitor perception surveys with objective carbon accounting per the recommendations above. Consequently, destination authorities should apply this framework longitudinally to enable a continuous trend analysis of resilience and NZE indicators, thereby upgrading the static, cross-sectional evaluation provided in this study into a dynamic monitoring tool. Findings indicate that achieving NZE requires a systemic strategy that integrates sustainable tourism governance, destination resilience capability, and decarbonization methods within the tourism sector. By strengthening cooperation among stakeholders, tourism destinations may contribute significantly to climate change mitigation efforts while supporting the long-term sustainability of the tourism sector. Intensifying pressures from the global climate crisis are compelling the tourism industry to transition toward sustainable and low-carbon business model. This shift requires the sector to balance its role as an engine of economic growth with an active commitment to global climate change mitigation. The transition to net

zero tourism should therefore be regarded as a fundamental component of the sustainable development agenda and of international commitments to carbon emission reduction.

CONCLUSION

This study offers empirical evidence that NZE achievement in the tourism sector is associated not only with the direct implementation of emission reduction strategies, but also with a destination's capacity to build adaptive, sustainable, and resilient management systems. The findings suggest that destination management strategies, environmental performance measures, and destination resilience are important factors underlying the transition toward low-carbon tourism. These results support the perspective that tourism decarbonization initiatives should be conceptualized as a core component of destination governance dedicated to long-term sustainability, rather than as a partial or incidental environmental program. Model analysis indicates that the resilience-based framework is the most influential factor associated with net zero emissions. This suggests that tourism destinations with high adaptive capacity, the ability to respond to environmental changes, and readiness to face external disturbances are better positioned to apply emission reduction strategies consistently and effectively. By embedding environmental, social, and economic parameters into governance frameworks, destination resilience enables stakeholders to reconcile the expansion of the tourism sector with rigorous environmental protection. Resilience is thus not only a risk mitigation mechanism but also an essential catalyst for accelerating the transition to a sustainable and carbon-neutral tourism system. Furthermore, the empirical evidence demonstrates that NZE attainment relies heavily on the dual contributions of internal and external destination management strategies. Tourism activities can lower their carbon emission intensity through internal strategies such as energy efficiency, use of renewable energy, waste management, and adoption of environmentally friendly operational practices. External strategies, such as engagement with government, the private sector, local communities, research institutions, and environmental organizations, are important in building capacity to implement sustainability programs. Stakeholder synergy plays a pivotal role in accelerating knowledge transfer, mobilizing green investments, and fostering policy frameworks that align with decarbonization targets within the tourism sector. The findings also emphasize the importance of environmental performance measurement and monitoring systems as effective control instruments. Precise tracking of sustainability metrics—including carbon emissions, energy consumption, resource utilization—enables destination administrators to evaluate policy efficacy and pinpoint areas for ongoing optimization. Ultimately, this quantitative baseline establishes a foundation for more data-driven, evidence-based decision making. Conversely, reactive corrective actions were not found to be significantly associated with NZE achievement. The outcomes suggest that post-hoc problem-solving mechanisms are insufficient for managing ecological impacts; conversely, preventive, strategic, and planned interventions yield significantly greater efficacy. The tourism sector therefore needs to shift its management orientation from reactive to proactive in pursuing emission mitigation and resilience building. Ultimately, these findings indicate that a successful transition to net-zero tourism cannot occur in isolation; rather, it demands a holistic approach combining effective governance and sustainable practices. Crucial enablers of this transition include institutional resilience, comprehensive environmental monitoring frameworks, and structured, long-term pathways for emission mitigation. The integration of these

elements will strengthen the tourism sector's capacity to support the sustainable development agenda, improve destination competitiveness, and contribute meaningfully to global climate change mitigation targets and future net zero emissions commitments.

AUTHOR CONTRIBUTIONS

M.A. Nasution, as first author and corresponding author, conceived the research idea, design, and conceptualization, conducted sample collection, and contributed to resources, methodology, analytical measurements, manuscript preparation, review and editing, and visualization. E. Revida supervised the first author, contributed to the conception of the research idea and design of the experiment, analytical measurements, review and editing, data validation, and resources. F.F. Noorikhsan supervised the first author, contributed to sample collection writing, review and editing, visualization, validation, resources, and data curation. All authors confirm being contributors to this article and have approved it for publication

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
AVE	Average variance extracted
BPS	Statistics Indonesia (Badan Pusat Statistik)
Bappenas	The Ministry of National Development Planning
CB-SEM	Covariance-based structural equation modeling
CMB	Common method bias
CR	Composite reliability
GDP	Gross domestic product
GHG	Greenhouse gas
$GtCO_2e$	Gigaton carbon dioxide equivalent

HTMT	Heterotrait-monotrait ratio
NZE	Net zero emissions
NZT	Net zero tourism
PLS	Partial least squares
Q^2	Predictive relevance
R^2	Coefficient of determination
RSNZE	Resilience–sustainability–net-zero emissions
RPJPN	Rencana Pembangunan Jangka Panjang Nasional
SEM	Structural equation modeling
SEM-PLS	Structural equation modeling–partial least squares
SRMR	Standardized root mean square residual
UNFCCC	United Nations Framework Convention on Climate Change
UNWTO	United Nations World Tourism Organization
VAF	Variance accounted for
VIF	Variance inflation factor

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ORIGINAL RESEARCH ARTICLE

Modeling streamflow dynamics under future land use scenarios using soil and water assessment tools

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ABSTRACT

BACKGROUND AND OBJECTIVES: Land use and land cover change is a major driver of hydrological change, particularly in mountainous basins where hydropower production depends on reliable streamflow. The Suki Kinari Hydropower Project on Pakistan's Kunhar River is a run-of-river facility that is highly sensitive to such variations. The primary objective of this study was to quantify how historical and simulated land use and land cover modifications influence streamflow, thereby providing actionable insights for watershed governance and sustainable hydropower operations.

METHODS: The soil and water assessment tool were employed to simulate streamflow dynamics under future land use scenarios. Model calibration and validation were performed against monthly discharge data from the Garhi Habibullah gauging station for the periods 2000–2011 and 2012–2016, respectively. Future land use and land cover projections for 2052 and 2082 were generated using a cellular Automata-Markov chain model based on historical transition probabilities from 1992, 2002, and 2012 satellite observations.

FINDINGS: The soil and water assessment tool model demonstrated acceptable performance for monthly simulations (Calibration: R^2 = 0.64, Nash–Sutcliffe Efficiency = 0.62; Validation: R^2 = 0.61, Nash–Sutcliffe Efficiency = 0.52). land use and land cover projections indicate a continuous expansion of urban areas (+400 percent by 2082), agricultural land (+72 percent), and barren land (+3.8 percent), driven by deforestation (-38 percent) and grassland degradation. Under these projected conditions, the mean monthly streamflow is simulated to increase by 2.64 percent and 7.54 percent by 2052 and 2082 respectively, accompanied by a temporal advance in peak runoff.

CONCLUSION: The study reveals that future land use and land cover changes will significantly increase streamflow and runoff in the Kunhar River Basin, posing potential risks of sedimentation and flooding for the Suki Kinari Hydropower Project. Consequently, these outcomes advocate for both an expanded hydro-meteorological monitoring infrastructure in the upper catchment and the systematic incorporation of scenario-based modeling into adaptive water allocation frameworks. Sustainable land management is essential to mitigate adverse hydrological impacts in mountainous basins.

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INTRODUCTION

The Urbanization is one of the most prevalent global trends, having profound effects on environmental systems (Gaur *et al.,* 2020; Gaur *et al.,* 2021). Over half of the world's population currently resides in urban areas, and trends indicate an additional 2.5 billion urban inhabitants between 2018 and 2050, with Asia and Africa accounting for most of this growth (Gaur *et al.,* 2021). Concurrently, this expansion has exacerbated anthropogenic drivers of environmental degradation, specifically accelerating deforestation, agricultural intensification, and infrastructure expansion within the region (Lamichhane and Shakya, 2019). These processes are the dominant drivers of land use and land cover (LULC) change, leading to widespread environmental transformations influencing Earth-atmosphere interactions and sustainable development (Turner, 2007; Turner, 1995). The compounding effects of climate change and LULC alterations exert significant control over coupled socio-ecological and hydrological processes, specifically impacting agricultural yields, catchment water balances, and hydropower potential (Akbar and Gheewala, 2020; Yesuph and Dagnew, 2019). The hydrological behavior of catchment is defined by complex interactions among soil characteristics, topography, climate, and LULC dynamics. These hydrological processes are inherently variable in both space and time and are especially sensitive to alterations in LULC. Numerous studies confirm that LULC change can substantially affect watershed hydrology (Afonso de Oliveira Serrão *et al.,* 2022). For instance, land conversion modifies streamflow magnitude, shifts the timing of peak flows and alters both peak and base flow regimes (Gessesse *et al.,* 2021). Climatic variability, characterized by pronounced fluctuations in precipitation and temperature, exacerbates stress on regional hydrological processes, thereby complicating water resource management (Samie, 2020). For the Kunhar River Basin, Ali and Shah (Syed Shahid Ali and Sayed Sanaullah Shah, 2015) applied the snowmelt runoff model (SRM) and projected a 20 percent (%) increase in precipitation and 2 degrees Celsius (°C) rise in temperature by the end of the twenty-first century. These climatic projections, coupled with widespread forest clearance and agricultural expansion, underscore the combined influence of atmospheric shifts and population-driven land-cover modifications in dictating basin-scale hydrological regimes (Nurdin *et al.,* 2019). The need for effective adaptation strategies integrating both land use and climate drivers is therefore evident for ensuring long-term water resource sustainability. In Pakistan, urbanization began soon after independence but accelerated markedly after 1971 (Adeel, 2015; Shahbaz *et al.,* 2017). According to the sixth national population census, approximately 36.4% of the country's population now resides in urban areas, with an overall density of 261 persons per square kilometer (PBS Pakistan Bureau of Statistics Government of Pakistan Islamabad (PBS, 2018)) and is expected to approach 50% by 2026 (Malik and Wahid, 2014). Accelerated urban expansion and intensifying demographic pressures have increasingly compromised the structural integrity of natural systems and the critical ecosystem services they provide. These include soil formation and protection, regulation of surface water, agricultural productivity, energy demand (Malik and Wahid, 2014; Niquisse *et al.,* 2017; Tolessa *et al.,* 2017; Salazar, 2015), as well as the quality (Lambin, 2011) and availability (Ewane and Lee, 2020) of freshwater resources. A large share of Pakistan's water originates in the northern mountainous regions, which function both as vital irrigation sources and as the core hydropower production zones. In response, the National Water Policy (NWP) highlights the strategic importance of these water resources, advocating for public-private partnerships (PPPs) to fully mobilize an estimated 60,000 megawatts (MW) of latent hydropower potential (Irfan *et al.,* 2019). With

rising population and energy demand, the country's power sector faces continuous pressure to expand capacity (UN DESA, 2017). Given that hydropower currently supplies about 17% of global electricity demand and is one of the most cost-effective renewable energy sources (Kuriqi, 2021), its development is a critical priority. Northern Pakistan occupies the unique triple junction of the Karakoram, Hindu Kush, and Himalaya Mountain ranges, an area defined by highly complex structural geology and heterogeneous hydrological regimes. Major rivers and tributaries originate here, providing favorable conditions for multiple hydropower projects. Several run-of-river plants are operational, with many more under construction or in planning. Among them is the Suki Kinari Hydropower Project (SKHPP), a run-of-river scheme under development on the Kunhar River in Mansehra District, Khyber Pakhtunkhwa Province (SK Hydro, 2025). The SKHPP represents one of the largest private-sector hydropower investments in Pakistan, with a design capacity of 884 MW and major infrastructure including a dam, spillway, water intake, headrace tunnel, underground powerhouse, and tailrace tunnels (Deng, 2020). Commissioned in mid-2023, the project incorporates a run-of-river design with negligible storage capacity, rendering its power generation highly sensitive to streamflow fluctuations. For effective watershed management and sustainable operation, it is essential to evaluate how climate and LULC changes will affect water resources. LULC shifts alter hydrological parameters such as surface runoff, lateral flow, infiltration, and evapotranspiration (Waikhom *et al.,* 2023), while climate change directly affects rainfall, atmospheric moisture, and soil water content (Wang, 2009). Elucidating these coupled processes necessitates robust hydrological modeling, particularly within data-scarce catchments. Run-of-river hydropower schemes, such as the SKHPP, require reliable streamflow predictions because of their lack of large storage buffers. Anticipating how LULC change affects flow variability is therefore critical. Among the available approaches, LULC modeling is widely used for forecasting urban expansion and associated land transitions (Leta *et al.,* 2021). These simulation frameworks elucidate LULC dynamics and broader urbanization processes, serving as critical decision-support systems for sustainable watershed management. Hydrological modeling frameworks further support such assessments. Semi-distributed models, which balance spatial detail with computational efficiency, are often preferred over fully distributed or lumped models (Jajarmizadeh, 2012). The soil and water assessment tool (SWAT) is a widely adopted, semi-distributed hydrological model that operates on a continuous daily time step to conduct long-term watershed simulations. SWAT has been used to evaluate agricultural watershed management (Moriasi *et al.* 2007), assess climate change impacts, establish water quality standards, and model surface–subsurface hydrology and sediment dynamics across diverse landscapes (Gassman *et al.,* 2014). Arc geographic information system extension for soil and water assessment tool, (ArcSWAT), has been applied in geographically diverse settings, including southern Australia (Shrestha *et al.,* 2016), South Asia (Shivhare, 2014), Africa (Baker and Miller, 2013), and Mediterranean Europe (Molina-Navarro *et al.,* 2014). Applications to reservoir catchments in China (Sellami *et al.,* 2016) and Pakistan (Wang and Xia, 2010; Ghoraba, 2015), further demonstrate its utility. Despite the widespread application of SWAT in LULC-hydrology studies, notable limitations persist. Specifically, the model frequently overlooks modifications to soil properties and terrain characteristics induced by land conversion (Shukla *et al*., 2023), even though hydrological responses to LULC change are intrinsically modulated by slope, vegetation dynamics, soil taxonomy, and localized management practices. In mountainous basins, escalating temperatures can accelerate snow and glaciers melt, alter evapotranspiration rates, and modify precipitation regimes, while

concurrent LULC dynamics dictate soil infiltration, runoff generation, and groundwater recharge. Within the Kunhar River Basin—a climatically sensitive and rapidly urbanizing catchment—this evolving hydrological behavior is explicitly driven by the compounding effects of both land-cover alterations and climate variability (Saifullah *et al.,* 2021). However, no comprehensive assessment has yet quantified how future LULC transitions will affect streamflow in this basin. This study addresses this gap by applying the SWAT model to evaluate the impacts of projected LULC change on streamflow in the Kunhar River Basin. This study presents a novel approach by combining SWAT modeling with CA–Markov projected LULC scenarios to assess future streamflow responses in the Kunhar River Basin, with specific consideration of the Suki Kinari Hydropower Project (884 MW). Future LULC scenarios for 2052 and 2082 were simulated using the Cellular Automata (CA)-Markov model, and their impacts on streamflow patterns relevant to hydropower operation were subsequently quantified. To isolate the precise drivers of hydrological change, baseline climate conditions were held constant across all simulations, thereby isolating LULC-induced dynamics as the sole source of streamflow variability. This approach is methodologically distinct from coupled climate–LULC studies and establishes a valuable baseline upon which future analyses integrating both climate and land use dynamics can be built. In contrast to prior regional assessments, these findings offer scenario-based projections capable of directly informing strategic watershed governance and sustainable hydropower planning. Conducted in the Kunhar River Basin of Kaghan Valley, Khyber Pakhtunkhwa Province, Pakistan, the methodology and outcomes of this study are transferable to similar data-scarce mountain catchments facing comparable land use and water resource management challenges. This study aims to assess the predictive performance and structural suitability of the SWAT model for simulating complex hydrological processes in a data-scarce, high-altitude basin. Future LULC scenarios for 2052 and 2082 were simulated using the CA-Markov model. This study has been contacted in Kunhar River Basin in the Kaghan Valley of Pakistan's Khyber Pakhtunkhwa Province in Pakistan 2025.

MATERIALS AND METHODS

Study area

The Kunhar River Basin (Fig. 1) extends between 33°3′ N–35°9′ north (N) and 73°8′ east (E)–75°35′ E, originating from Lake Lulusar in the Kaghan Valley of Pakistan's Khyber Pakhtunkhwa Province. The river flows for approximately 171 kilometers (km), passing through major towns including Jalkhand, Kaghan, Naran, Kwai, Balakot, Bata Kundi, and Garhi Habibullah, before merging with the Jhelum River at Rara. The basin covers about 2,630 square kilometers (km^2), with elevations ranging from 634 meters (m) to 5,214 m above sea level (Soomro *et al.,* 2021). The Suki Kinari Hydropower Project (SKHPP), located on the Kunhar River, is a major run-of-river hydropower scheme with a design capacity of 884 MW. Unlike many regional rivers, Kunhar is not connected to an irrigation network; hence, hydropower is the primary use of its water. The project accounts for approximately 5.22% of Pakistan's total installed hydropower capacity, while the Kunhar itself supplies nearly 11% of the total inflows into the Mangla Reservoir, highlighting its strategic role in the national water-energy nexus (Mahmood *et al.,* 2016). With regards to climate, Kunhar basin experiences cold winters and mild to warm summers under alpine conditions. Average annual maximum temperatures are 12.3 °C, at Naran, 24.9 °C at Balakot, and 28.4 °C, at Muzaffarabad, while minimum values are 3.2 °C, 12.4 °C, and 13.5 °C, respectively. Annual precipitation is high, with Balakot receiving about 1,531 mm and Muzaffarabad around 1,351 mmWinter snowfall serves as a primary cryospheric storage mechanism, functioning as a critical hydrological input that regulates seasonal streamflow during

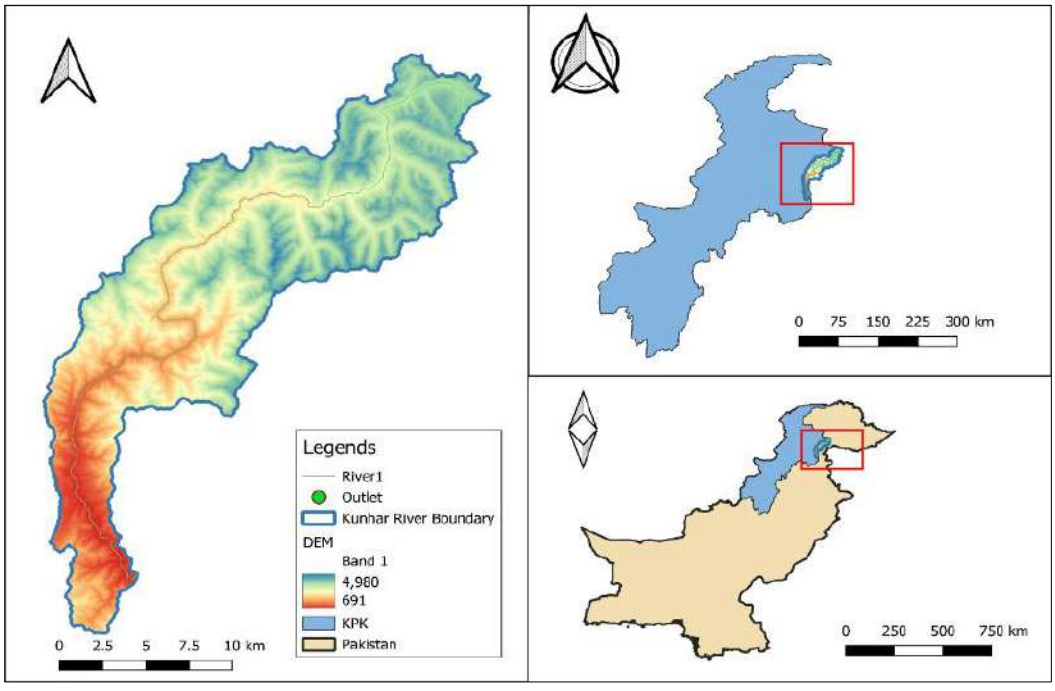

Fig. 1: Geographical location of the study area in Kaghan Valley of Pakistan's Khyber Pakhtunkhwa Province in Pakistan

the subsequent melt period (Saifullah *et al.,* 2021). Forests and grasslands, which play a critical role in regulating runoff and sustaining downstream water resources dominate the basin's mountainous topography. These geographic, hydrological, and climatic characteristics make the Kunhar Basin particularly sensitive to LULC change, highlighting the importance of evaluating its streamflow response in the context of hydropower development.

SWAT model explanation

SWAT is a robust, physically based ecohydrological framework designed to quantify the impacts of land use, soil properties, and terrain topography on the water balance and sediment yield within a watershed. Originating from the United State Department of Agriculture (USDA), the model is structured to work over large and complex catchments by dividing them into smaller sub-basins based on spatial variability in landscape features (Wang, 2019). Each sub-basin is further partitioned into Hydrological Response Units (HRUs), which lump together unique, coincidence combinations of land cover, soil type, and slope gradient. This method enables detailed spatial representation of land surface processes. SWAT can simulate key components of the hydrologic cycle, including snow accumulation and melt, infiltration, evapotranspiration, lateral flow, groundwater recharge, and streamflow routing. The structural framework and hydrological processes simulated by the SWAT model are illustrated in Fig. 2. The overall simulation framework is rooted in the principles of mass conservation, with the catchment water balance governed by Eq. 1 (Guevara Ochoa *et al.,* 2019):

Soil water content at time = initial water content; t = time = Daily precipitation = Surface runoff = evapotranspiration = Water percolated into the vadose zone = Return flow or contribution to shallow aquifer. (1)

Eq. 1 constitutes the mathematical foundation of SWAT's hydrological routine, enabling the

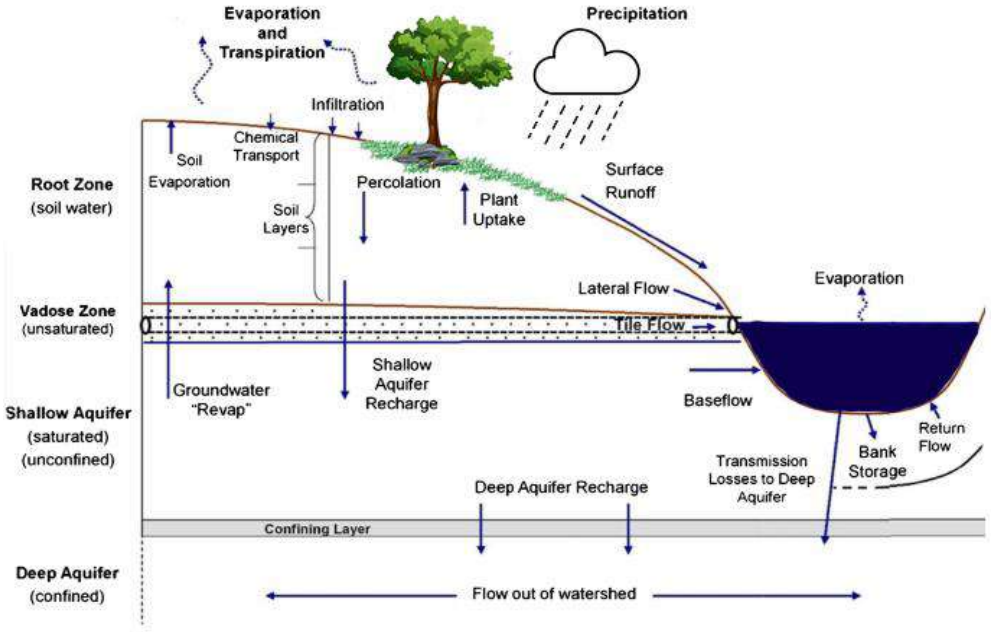

Fig. 2: Schematic representation of SWAT hydrological system

continuous, long-term quantification of water availability, streamflow dynamics, and anthropogenic land use impacts. The model incorporates two primary techniques for estimating surface runoff: the Green-Ampt infiltration model and the Curve Number (CN) method developed by the Soil Conservation Service (SCS) (Bauwe *et al.,* 2016). In this study, the Green-Ampt approach was omitted due to the absence of sub-daily rainfall data required for its parametrization. Instead, the SCS-CN method was adopted, as it is robustly suited for daily precipitation inputs and has proven reliable in data-scarce mountainous regions, as formulated in Eq. 2 (Weikel *et al.,* 2022):

$$Q_{surf} = \frac{(Q_{surf} - I_a)^2}{R_{day} - I_a + S} \quad (2)$$

Where: Q_{surf} is the surface runoff, R_{day} is the total daily rainfall depth (mm), S is the retention parameter, and I_a is the initial abstraction. The CN integrates land use, soil type, slope, and hydrologic condition into a single index ranging from 0 to 100, with higher values indicating higher runoff potential. To simulate lateral subsurface flow, SWAT employs a kinematic reservoir routing method based on saturated hydraulic conductivity, slope gradient, and slope length. In addition, SWAT explicitly partitions total evapotranspiration into independent soil evaporation and plant transpiration routines, yielding highly resolved estimates of catchment water balance components. Potential evapotranspiration (PET) in SWAT can be estimated using the Penman–Monteith, Priestley–Taylor, or Hargreaves equations. In this study, the Penman–Monteith approach was selected, as it aligns well with the availability and completeness of the meteorological data. This method necessitates input data for air temperature, solar radiation, relative humidity, and wind speed. Consequently, it offers a more physically rigorous parameterization than the temperature-dependent Hargreaves or radiation-driven Priestley–Taylor formulations, which operate under simplified, data-constrained assumption (Akumaga and Alderman, 2019).

Input and setup model

In this study, the ArcSWAT interface, an extension of the ArcGIS platform, was employed to execute the primary operations of the SWAT hydrological model. The initial modeling phase involved automated watershed delineation, utilizing a digital elevation model (DEM) to extract the drainage network, establish flow direction paths, and define topographic catchment boundaries. Based on topographic characteristics and outlet positions, the watershed was further divided into sub-basins, which were either automatically generated from natural stream confluences or manually defined by the user. To capture spatial heterogeneity across the watershed, thematic layers representing slope class, land use/land cover, and soil taxonomy were overlaid to partition each sub-basin into HRUs—discrete, homogeneous land segments with uniform physical characteristics. The core geospatial inputs required for model setup included DEM, soil classification maps, and LULC data. These layers were integrated within the ArcSWAT framework to provide a spatially distributed representation of hydrological processes. The overall GIS-based setup of the SWAT model for this study is illustrated in Fig. 3. In this study, for elevation data, the Shuttle Radar Topography Mission (SRTM) DEM Version 3.0 with a spatial resolution of 30 × 30 m was used, projected in WGS-84 geographic coordinates. Daily-resolution meteorological and hydrological data were obtained from the Pakistan Meteorological Department. Soil data were derived from the Food and Agriculture Organization (FAO) digital soil map at 1:5,000,000 scale, and LULC data from the United States Geological Survey (USGS); Earth Resources Observation and Science (EROS) Center with 30 m resolution. Table 1 summarizes the input data utilized in the study and their sources for geospatial analysis and soil erosion modeling.

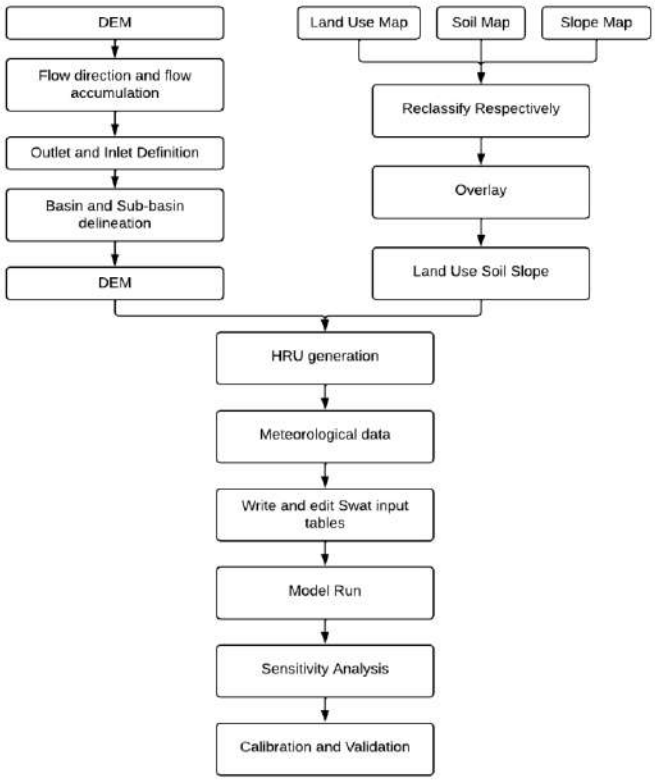

Fig. 3: The methodological framework of the current research study

Table 1: Source of the input data used in the study

Type of data	Source of data
DEM	USGS (EROS) Center (USGS 2025)
Soil data	Food and Agriculture Organization (FAO) of the United Nations (FAO 2025)
Land use land cover map	USGS (EROS) Center (USGS 2025)
Metrological data	Pakistan Meteorological Department (PMD 2025)

Topographic characterization and HRU delineation

Watershed delineation in SWAT followed five main procedures: i) preparation of the DEM, ii) identification of the stream network, iii) identification of inlets and outlets, iv) definition of watershed boundaries, and v) computation of sub-basin properties. The DEM was utilized to extract structural drainage networks, delineate stream channels, and calculate maximum flow-path lengths across both the main catchment and its constituent sub-basins. It also provided key topographic parameters, including channel slope, reach length, and terrain gradient. To ensure accuracy, enhanced SRTM data with a spatial resolution of 30 m were utilized. Based on this analysis, the Kunhar watershed was divided into three sub-basins (Fig. 4a) and classified into three slope categories (Fig. 4b). A critical threshold drainage area was defined to delineate the stream network and sub-basin boundaries, establishing the minimum upstream contributing area required to initiate channel development. HRUs represent unique combinations of land use, soil type, and slope within each sub-basin, enabling SWAT to capture spatial heterogeneity across the basin. HRU generation involves overlaying these three spatial layers, with threshold values applied to exclude minor classes and reduce model complexity. In this study, thresholds of 10% for land use, 12% for soil, and 12% for slope were adopted, resulting in the definition of 41 HRUs. Water balance components, including surface runoff, are simulated independently at the HRU scale; these individual outputs are subsequently aggregated at the sub-basin level and routed through the main channel network to quantify total catchment discharge. Appropriate threshold selection is essential for balancing computational efficiency with accurate representation of watershed conditions (Poblete *et al.* 2020).

Hydrological and metrological data

Accurate meteorological data form the basis of hydrological modeling in SWAT, as they drive the water balance simulation. The primary climatic variables incorporated into the model include daily precipitation, maximum and minimum air temperature, relative humidity, solar radiation, and wind speed. These meteorological parameters can be derived from empirical gauge records or simulated stochastically using SWAT's integrated weather generator, particularly in regions characterized by data scarcity. However, the use of generated data requires rigorous statistical validation to ensure reliability and consistency. In this study, daily precipitation and temperature data were directly obtained from observed station records. Other parameters, including relative humidity, solar radiation, and wind speed, were estimated using the model's weather generator or supplemented manually where available. Fig. 5 presents the precipitation data used for stations Naran, Astore, Murree, and Balakot. This integration of in-situ gauge measurements and stochastically generated inputs established the continuous meteorological forcing dataset required to simulate the complex alpine hydrological processes in the Kunhar watershed. SWAT incorporates a weather generator module (WXGEN) that can fill gaps in observational records or produce synthetic climate data. The module generates monthly statistical parameters, such as temperature, precipitation, solar radiation, wind speed, and relative humidity, from available daily observations for model simulations (Lee *et al.,* 2018).

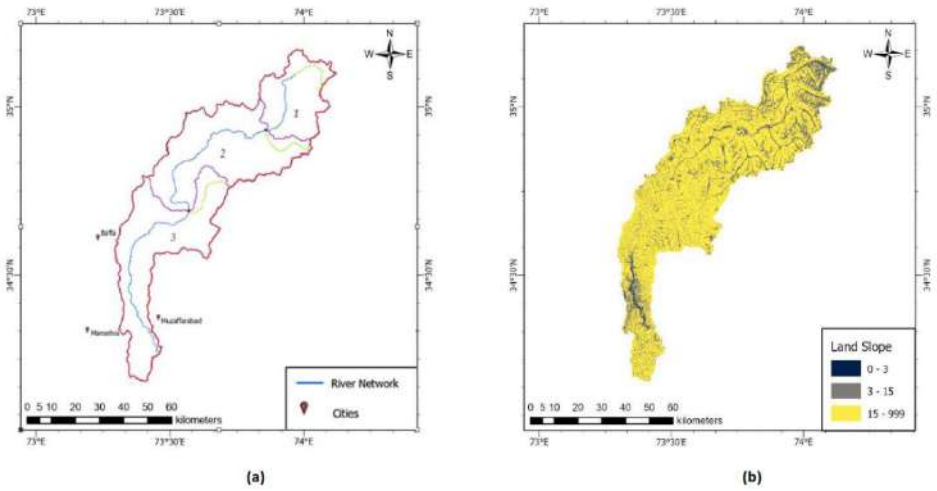

Fig. 4: (a) Sub-basins map; (b) Slope map

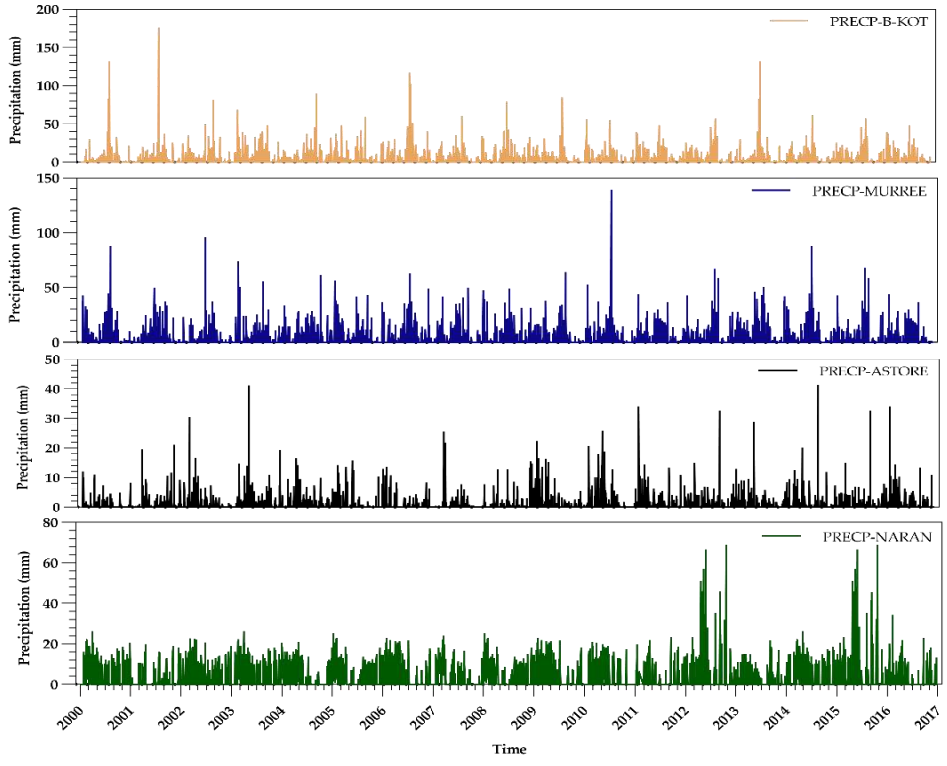

Fig. 5: Precipitation of the four-weather stations at Balakot, Murree, Astore, and Naran

These are then stored in a user-defined weather generator file ("User WGN") within the SWAT database. To minimize spatial uncertainty and capture localized elevation gradients, climatic records from multiple meteorological stations were integrated into the simulation framework. For this study, daily precipitation and temperature were obtained from four rain gauge stations: Astore, Balakot, Murree, and Naran. Since relative humidity, solar radiation, and wind speed were

unavailable at these stations, supplementary data for these variables were extracted from the NASA POWER (Prediction of Worldwide Energy Resources) database. Although SWAT can simulate basin hydrology under ungauged conditions, historical streamflow records were indispensable for parameter sensitivity analysis, ensuring robust and accurate predictions.

Soil classification and land use land cover map

The soil classification for the study area was developed using global soil data provided by FAO of the United Nations. This dataset, which includes detailed information on more than 5,000 soil types at a spatial resolution of 1:5 million, formed the basis for mapping soil characteristics within the watershed. Soil properties play a critical role in hydrological modeling, particularly in determining infiltration, water retention, and runoff behavior. The FAO dataset provides key attributes such as bulk density, organic carbon content, hydraulic conductivity, soil texture, and available water capacity. To facilitate integration into the ArcSWAT model, the selected parameters underwent evaluation and reformatting. This classification revealed that the Kunhar watershed is predominantly characterized by four soil categories: Fine Cambisols, Medium Cambisols, Medium, and Glacier soils (Fig. 6a). Accurate representation of these soils is essential for realistic simulation of surface and subsurface hydrological responses. LULC dynamics strongly influence runoff, evapotranspiration, and soil degradation within a watershed. In the Kunhar basin, land cover changes are mainly driven by urban expansion, agricultural intensification, and the development of irrigation networks. Temporal dynamics were captured by generating LULC maps from Landsat satellite imagery, which was retrieved from the USGS Earth Resources Observation and Science Center for 1992, 2014, and 2022. supervised maximum likelihood classification (MLC) was applied to Landsat Thematic Mapper, Enhanced Thematic Mapper Plus (ETM+, 2014), and operational land imager (OLI) imagery at 30 m spatial resolution. Training samples (with a minimum of 50 per class per image date) were collected using stratified random sampling, cross-referenced with high-resolution Google Earth imagery and ground-truth field observations. Subsequently, classification accuracy was evaluated utilizing 300 independent validation points per individual classification map. The 2022 classification achieved an Overall Accuracy of 86.4% and a Kappa Coefficient (κ = 0.84), confirming good to very good classification reliability. CA-Markov model prediction accuracy was validated by projecting the 2022 LULC map from 1992 and 2014 inputs and comparing it with the actual 2022 classified image, yielding a Figure of Merit of 0.71 and validation Kappa of 0.79. The spatial distribution of the six dominant LULC classes—forest, cropland, pasture, barren land, low-density built-up areas, and water bodies—is depicted in Fig. 6b.

Model simulation

After preparing and integrating all input datasets into the SWAT interface, the model was for hydrological simulation. The hydrological model was simulated over an 11-year period (2000–2011). A preliminary initialization (spin-up) run was conducted to perform parameter sensitivity analysis and quantify its impact on simulated outputs. Subsequently, model calibration was performed utilizing the definitive simulation runs. For the comparison study, the internal SWAT sensitivity analysis tool was applied, employing the Latin Hypercube One-Factor-At-A-Time method, which is effective for identifying parameters that have the greatest impact on model performance (Jajarmizadeh *et al.,* 2017).

Projection of future LULC maps

For projecting future LULC scenarios, the IDRISI software developed by Clark Labs was employed. This GIS and image-processing platform provides a variety of tools for environmental modeling and spatial analysis (Eastman, 2012). To model LULC dynamics, the land change modeler (LCM) module

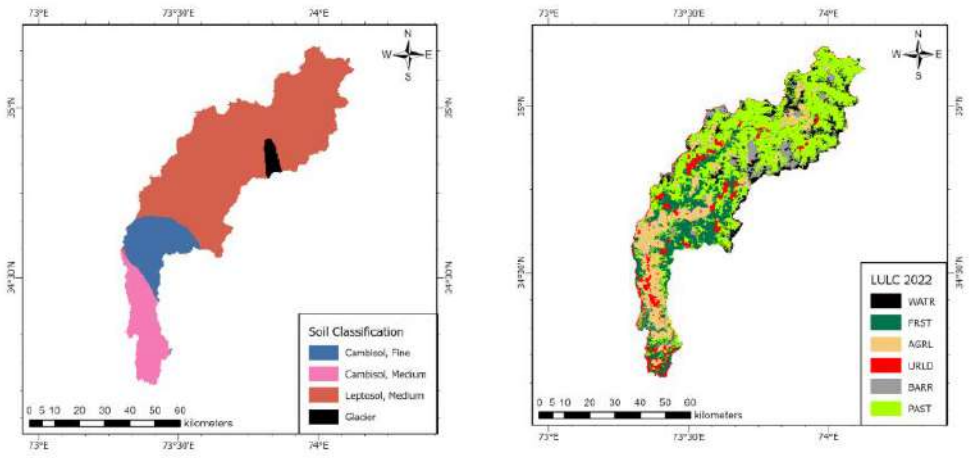

Fig. 6: (a) Soil classification map; (b) Land use land cover map

in IDRISI was deployed. This module enables a robust quantitative evaluation of land cover changes, mapping categorical transitions while accounting for concurrent gains and losses across the study area. Future projections were generated using a combination of the Markov chain transition matrix and Cellular Automata (CA) algorithms, which jointly capture spatial and temporal patterns of land use change. This integrated approach enhances the prediction of LULC transitions by quantifying the probability of change between classes over time (Eastman and He, 2020). Furthermore, transition suitability maps were generated within the CA-Markov framework to evaluate the spatial propensity of individual pixels to transition into alternative land cover class (Guan *et al.,* 2011). In this study, future climate variables were held constant across all simulated scenarios; this experimental design isolated the hydrological responses driven exclusively by LULC dynamics Accordingly, all projected variations in streamflow represent LULC-driven impacts only and do not incorporate the influence of future climate change. Consequently, the observed hydrological shifts can be confidently ascribed to land-use modifications rather than variations in climate. The future LULC was derived via a two-step process. The 2022 LULC pictures were first projected using maps from 1992 (Fig. 7a) and 2014 and then compared to the real 2022 image for validation until an acceptable level of accuracy was achieved (Fig. 7b). Second, 2052 pictures were projected using the LULC maps of 1992 and 2022 (Fig. 7c), and 2082 images were projected using the same 2022 and 2052 images, as shown in Fig. 7d. Socio-economic pressures—namely population growth, urban sprawl, and intensified agriculture—are the primary drivers behind both historical and future LULC dynamics. Increased settlement and cultivated land reflect rising demands for housing and food security, while deforestation for fuel and construction materials contributes to forest loss and soil exposure. These socio-economic drivers provide essential context for interpreting the hydrological impact observed in the basin.

Model efficiency

The efficiency of the model was evaluated by identifying and ranking the most sensitive hydrological parameters influencing streamflow. To identify the key variables governing surface runoff simulations, a preliminary sensitivity analysis was performed on 22 hydrology-related parameters frequently highlighted in SWAT documentation and existing literature. A global sensitivity analysis was then performed

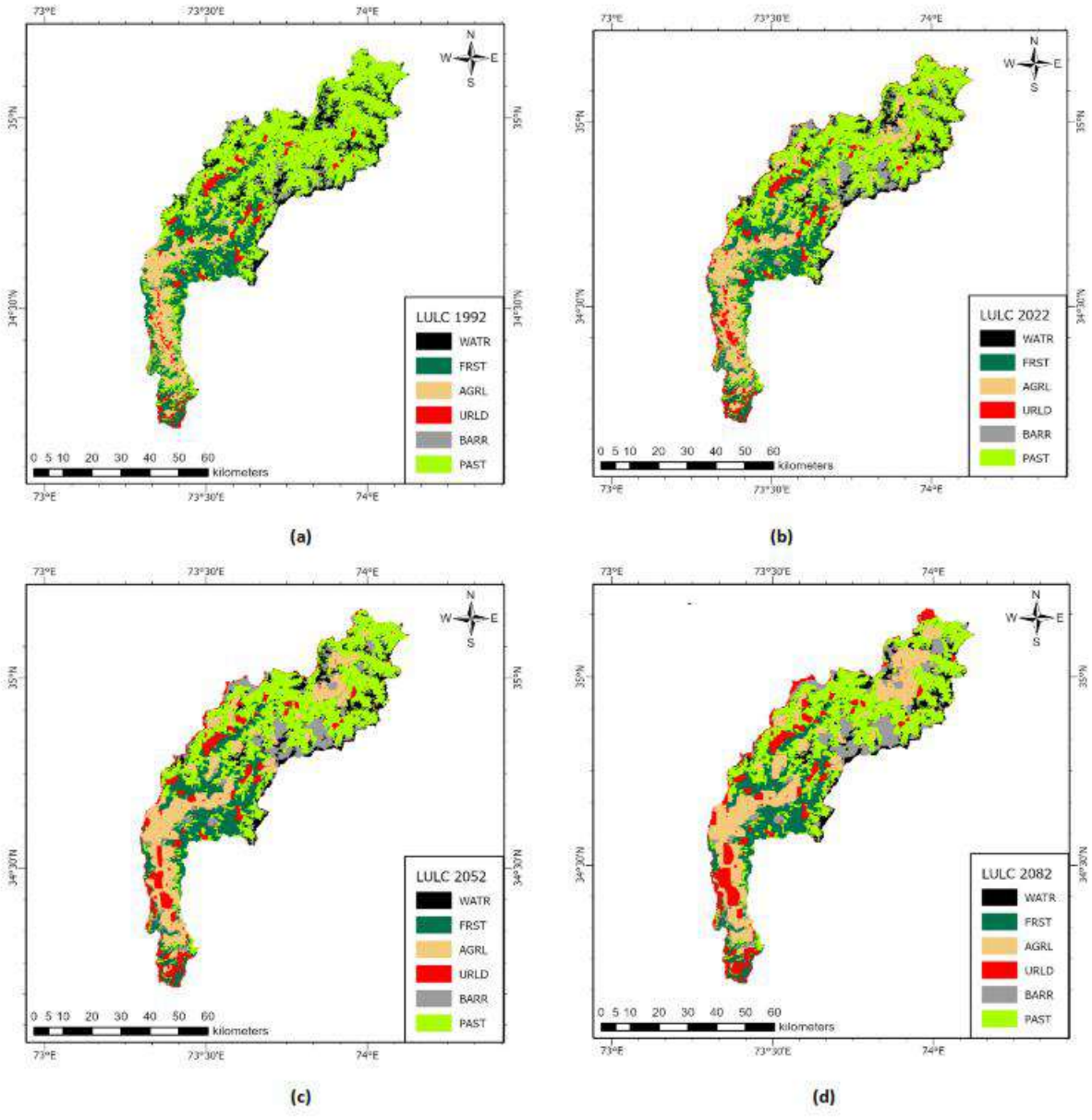

Fig. 7: Land use land cover maps for (a) 1992; (b) 2022; (c) 2052; (d) 2082

using the sequential uncertainty fitting (SUFI)-2 (Sequential Uncertainty Fitting) algorithm (Campolongo *et al.,* 2000), which relies on two statistical indicators: the t-statistic, reflecting the relative sensitivity of each parameter, and the p-value, indicating the statistical significance of that sensitivity in relation to the model's objective function. A total of 500 simulations were executed. Of these, 18 parameters exhibited a t-statistic exceeding 1 and were consequently identified as highly sensitive, making them the focus for calibrating surface runoff within the Kunhar River Basin. The t-test assessed sensitivity under the assumption of linearity while controlling interactions among parameters, whereas the p-value reflected confidence in each parameter's influence. The degree of parameter influence was determined by the magnitude of the statistics,

where higher absolute t-values and lower p-values indicated the strongest effects. This procedure follows the guidelines outlined by Swiss Federal Institute of Aquatic Science and Technology (EAWAG) (Abbaspour, 2014) for effective sensitivity analysis. The accuracy and predictive capability of the streamflow simulations were assessed using three key statistical criteria: the coefficient of determination (R^2), the Nash–Sutcliffe Efficiency (NSE), and percent bias (PBIAS).

Coefficient of determination (R^2)

R^2 quantifies how much of the variance in observed streamflow is captured by the model, serving as a measure of the linear correlation between simulated and measured data. Higher values reflect stronger agreement and lower variance error. In hydrological modeling, R^2 values greater than 0.50 are generally acceptable, with 1.0 indicating a perfect fit. R^2 can be expressed mathematically, using Eq. 3 (Islam *et al.,* 2017):

$$R^2 = \frac{[\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})]}{\sum_{i=1}^{n} [(O_i - \bar{O}) \sum_{i=1}^{n} (P_i - \bar{P})^2]} \quad (3)$$

Where: P_i is the ith observation (stream flow) and $\bar{P}$ is the mean observed value, O_i is the ith simulated value, $\bar{O}$ is the mean of observed value, and n is the total number of observations.

Nash–sutcliffe efficiency (NSE)

Nash-Sutcliffe Efficiency is a standardized statistical measure that determines the efficiency of simulated data (model output) with respect to observed data. It is defined by Nash and Sutcliffe, using Eq. 4 (Nash, 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (4)$$

Where: O_i is the ith simulated value, $\bar{O}$ is the mean of the observed data, P_i is the ith observation (stream flow), and n is the total number of observations. The NSE value ranges from −1 to 1, with 1 indicating perfect agreement between observed and simulated values. An NSE > 0.5 is generally considered acceptable for hydrological modeling, while values closer to 1 indicate high model accuracy. While the evaluation metrics (R^2 ≈ 0.64, NSE ≈ 0.62) demonstrate only moderate model alignment, they provide an adequate baseline for capturing how future LULC shifts will relatively affect streamflow trends. The model reliably reproduces seasonal flow dynamics, allowing for meaningful scenario-based analysis, even if peak flows are slightly underestimated.

Percent bias

The average propensity of the simulated values to be more or less than their observed ones is measured by PBIAS (Gupta *et al.,* 1999). This metric is constrained within a range of 10 to 10, where lower absolute magnitude values signify superior model simulation proficiency. An optimal Percent Bias (PBIAS) value is denoted by 0.0. Consistent with Eq. 5, positive values reflect model underestimation, whereas negative values characterize model overestimation (Gupta *et al.,* 1999):

$$PBIAS = [\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n} (Y_i^{obs})}] \quad (5)$$

Where: Y_i^{obs} is the observed value and Y_i^{sim} is the simulated value. Performance metrics such as R^2, NSE, PBIAS, and others along with their acceptable ranges were recommended by Moriasi *et al.* (2007) to help ensure effective calibration and model performance evaluation. It is critical to acknowledge that these specified ranges are derived exclusively from model simulations conducted at a monthly time step. Typically, when the time resolution is increased to a daily time step, the values of these test statistics tend to worsen. In the present study, simulations were executed at a monthly temporal resolution, utilizing the recommended ranges strictly as a baseline reference for evaluating model performance and calibration adequacy.

RESULTS AND DISCUSSION

Land use and land cover changes

Changes in LULC in the Kunhar Watershed were assessed using Landsat satellite imagery and supervised classification techniques for four time periods: 1992, 2022, 2052, and 2082. The selection of 2052 and 2082 was based on a two-step CA-Markov projection procedure: the 2052 LULC map was projected using the 1992 and 2022 base maps (representing a 30-year transition interval), and the 2082 map was projected from the 2022 and 2052 maps. Consistently adhering to the CA-Markov model's conceptual architecture, this stepwise approach derives transition probabilities dynamically, relying on the two most contemporary LULC datasets for each subsequent projection. The 30-year time step reflects a standard projection horizon commonly used in long-term watershed planning. The classification results were analyzed across six land cover classes in Fig. 8. Urban development expanded rapidly, increasing from 4.82% in 1992 to 12.25% in 2082. Extant literature attributes this expansion predominantly to the coupled effects of demographic growth and socioeconomic pressures (Niquisse *et al.,* 2017). Cultivated land and bare soil also nearly doubled over the same period, rising from 9.99% and 5.41% in 1992 to 19.79% and 11.22% in 2082, respectively. The expansion of built-up areas and irrigated agriculture is predominantly driven by the demographic demands for residential space and food security; conversely, the proliferation of bare soil is ostensibly accelerated by severe soil erosion along the steep terrain of the Kunhar watershed. In contrast, other land use classes declined significantly. Forest cover fell from 21.79% in 1992 to 16.26% in 2082, a net decrease of 5.52%, mainly due to conversion into agricultural and urban land. Pastureland also contracted sharply, with a net decline of 14.67% over the study period. Glacier and water body cover was projected to decrease by 2.85% between 1992 and 2082. The findings presented here are consistent with the previous analysis of the Himalayan watershed LULCC, which revealed an increase in cultivated areas, habitation, waterbodies, and sugarcane plantations. Consequently, these transitions precipitated a substantial contraction in the spatial extent of bare ground, wetlands, and forest land. Furthermore, Kumar *et al.* (2022) demonstrated that anthropogenic interventions—specifically reservoir construction and associated river training initiatives—exert a more immediate and pervasive influence on LULC dynamics than natural processes.

Calibration and validation

Niraula *et al.* (2015) emphasized that streamflow simulation results can vary considerably depending on whether the model is uncalibrated, calibrated at a single outlet, or spatially calibrated. To reliably assess the hydrological impacts of land use changes, it is therefore essential to employ spatially calibrated models. Prior to the calibration and validation of the SWAT model, a rigorous sensitivity analysis was conducted to identify the key parameters governing the watershed's hydrological response. Calibration was conducted at the watershed outlet using the Sequential Uncertainty Fitting algorithm (SUFI-2), implemented through the SWAT-CUP interface. (Tejaswini and Sathian, 2018) Observed monthly streamflow data for 2000–2011 were used in the calibration process. Model performance was evaluated with two statistical indicators: the coefficient of determination (R^2) and the Nash–Sutcliffe Efficiency (NSE). The calibration results showed that the SWAT model reasonably reproduced observed streamflow dynamics, achieving R^2 = 0.64 and NSE = 0.62. However, a slight underestimation of peak flows was observed in the simulated results (Fig. 9a). For model validation, the simulation spanned 2009–2016, wherein the initial three years served as a warm-up period and the subsequent years were utilized for validation. During calibration, percent error was 14.2%, NSE exceeded 0.5, and correlation

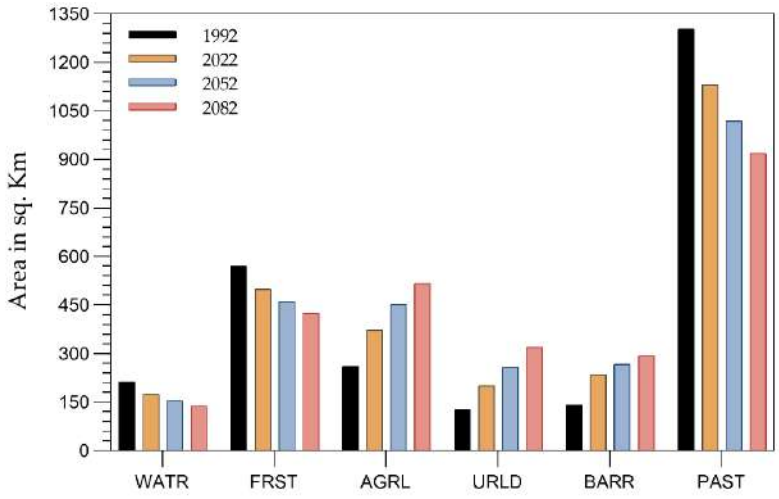

Fig. 8: Land use and land cover changes

between daily simulated and observed flows was greater than 0.6. During the validation phase, the model achieved a percent error of 16.5%, R^2 value of 0.61, and an NSE of 0.52, as illustrated in Fig. 9b and Fig. 9c. In hydrological modeling, he calibration performance (R^2 = 0.64, NSE = 0.62) and validation performance (R^2 = 0.61, NSE = 0.52) are within the range considered "satisfactory" for monthly streamflow simulation according to the widely cited guidelines of Moriasi *et al.* (2007), which define NSE > 0.5 as acceptable for watershed modeling. Percent bias (PBIAS) values of 14.2% and 16.5% were obtained during the calibration and validation phases, respectively, revealing a minor tendency to underestimate peak discharge. To quantify model uncertainty, the SUFI-2 algorithm generated 500 simulations to estimate the 95% prediction uncertainty band (95PPU). During calibration, the p-factor (fraction of observed data within the 95PPU) was 0.73 and the r-factor (average width of 95PPU normalized by standard deviation of observations) was 0.84, both within the satisfactory ranges recommended by Abbaspour, (2014). During validation, p-factor = 0.68 and r-factor = 0.91, indicating well-constrained and consistent parameter uncertainty bounds. The findings confirm the calibrated model's ability to simulate streamflow dynamics in the Kunhar River Basin, supporting reliable projections under changing climate and LULC conditions. However, the mountainous terrain and reliance on a single gauging station introduce uncertainty in representing basin-wide hydrological variability accurately.

Impact of projected LULC changes on future streamflow and surface runoff

To evaluate the effect of projected LULCC on streamflow, three hypothetical future scenarios reflecting major land transitions were compared with a baseline scenario based on the 2022 LULC map. Consistent with prior observations, LULCC represents a critical driver capable of substantially altering watershed hydrological dynamics (Talib and Randhir, 2017). Key hydrologic components affected include surface runoff, lateral flow, and groundwater recharge. Fig. 10a illustrates the projected streamflow under varying LULCC scenarios for the reference years 2022, 2052, and 2082, delineating the temporal impacts of these transitions on basin hydrodynamics. Compared with observed streamflow, land use changes in 2052 and 2082 result in pronounced shifts. Specifically, streamflow is projected to peak earlier in May instead of June, followed by a gradual decline.

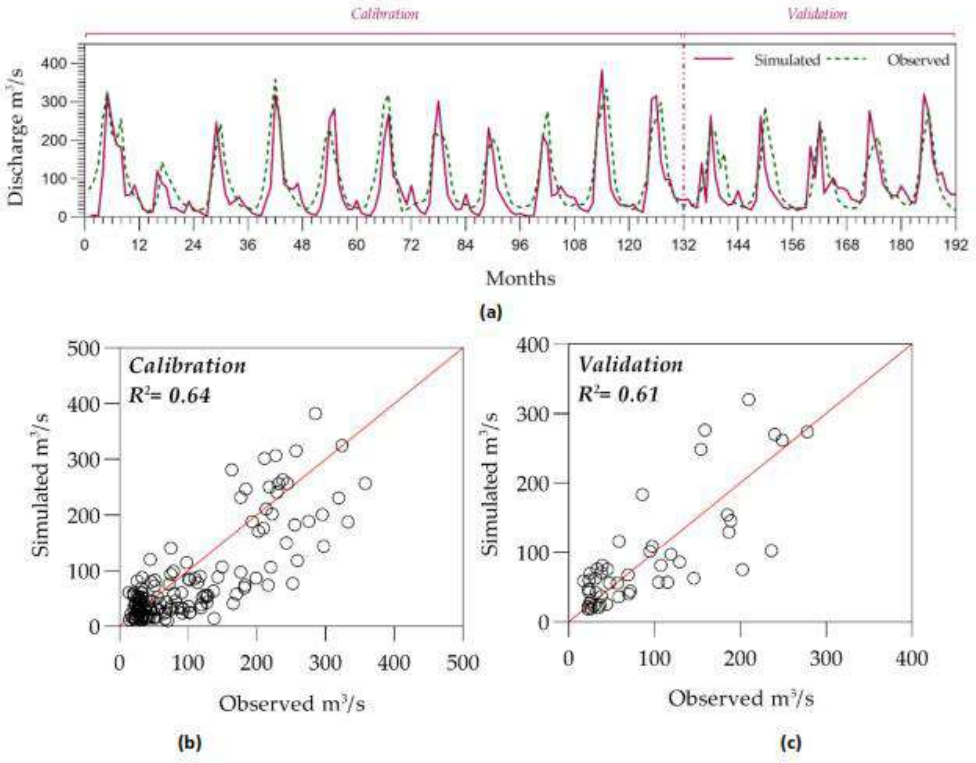

Fig. 9: (a) Observed and Calibrated hydrological model of Kunhar River; (b) Coefficient of determination R2 for calibration; (c) Coefficient of determination R2 for validation

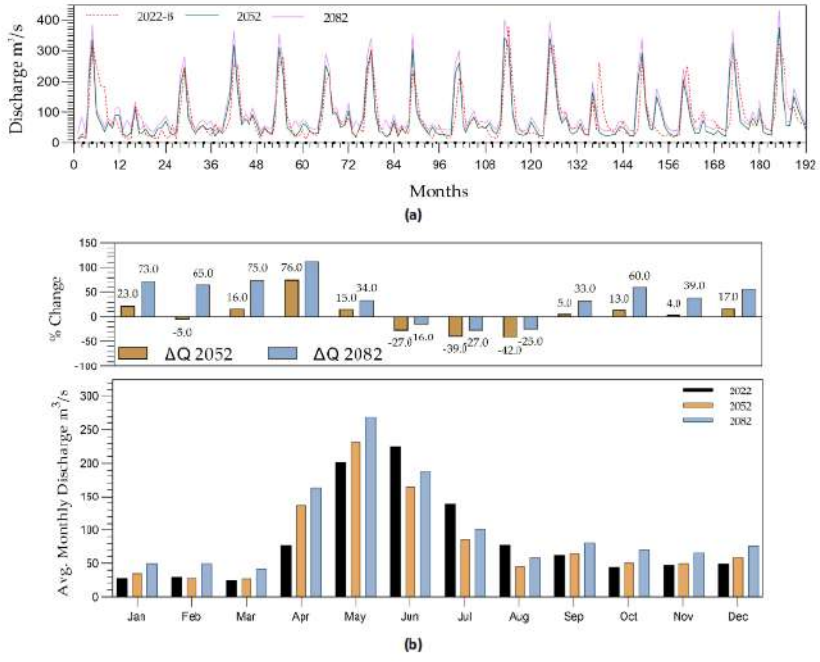

Fig. 10: (a) Impact of land use land changes on streamflow; (b) Average monthly change in the streamflow due to LULC changes

This shift is primarily attributed to forest-to-agriculture conversion, which accelerates surface runoff and intensifies early-season flows. Furthermore, the overall streamflow volume is projected to increase between 2052 and 2082, underscoring the strong hydrological influence of LULC change. These findings confirm that even modest land cover alterations can significantly affect catchment hydrology. Future LULC scenarios project increases in annual and early-season streamflow, punctuated by localized reductions during summer months (June–August). This pattern reflects the spatial heterogeneity of the Kunhar River Basin, where sub-basin characteristics, soil type, and topography can locally moderate runoff responses, even as the overall flow increases. Fig. 10b illustrates the percentage change in average monthly streamflow relative to the baseline period (2000-2016). Results show an overall increase in flows from January to May, while a decline is observed during the summer months (June-August). While downward trends dominate this interval, the hydrological response exhibits divergence, manifesting as oscillations relative to the baseline. Such variability reflects the complexity of the Kunhar River Basin, where hydrological responses to LULC are spatially heterogeneous across sub-basins. For instance, while urban expansion typically accelerates runoff via deforestation and the proliferation of impervious surfaces, certain sub-basins may exhibit reductions driven by localized topography, soil characteristics, or other mitigating mechanisms. These compensating effects align with observations from previous studies (Samie, 2020), indicating that basin-scale hydrological outcomes of LULCC often emerge from the interplay of multiple, sometimes opposing, processes.

Sensitivity analysis

Based on previously calibrated SWAT parameters and guidance from the SWAT manual, 18 parameters influencing surface runoff were identified as sensitive. Subsequently, a global sensitivity analysis was performed utilizing the SWAT-CUP software package to evaluate the relative importance of these parameters. In this approach, higher absolute values of the t-statistic and lower p-values indicate greater sensitivity (Andrade *et al.,* 2017). The calibrated parameter rankings for the Suki Kinari Dam watershed are presented in Table 2. During calibration, parameter ranges were systematically adjusted to minimize discrepancies between observed and simulated runoff until acceptable agreement was achieved. Global sensitivity analysis was performed within SWAT-CUP using the SUFI-2 algorithm with Latin Hypercube Sampling (LHS). Sensitivity analysis was conducted via t-statistics and p-values; greater absolute t-values indicated superior parameter sensitivity, while near-zero p-values confirmed statistical significance. The results revealed that the temperature lapse rate (v__TLAPS.sub, $t = -6.821$, $p < 0.001$) and snow melt base temperature (v__SMTMP.bsn, $t = -5.934$, $p < 0.001$) were the most sensitive parameters, confirming the dominant role of snowmelt processes in the Kunhar River Basin's hydrological regime. The SCS runoff curve number (v__CN2.mgt, $t = 5.412$, $p < 0.001$) and snowfall temperature (v__SFTMP.bsn, $t = 4.876$, $p < 0.001$) ranked third and fourth respectively, highlighting the combined influence of land surface runoff generation and snow accumulation dynamics. Groundwater-related parameters including v__GW_DELAY.gw ($t = -3.187$, $p = 0.005$) and v__GWQMN.gw ($t = 2.943$, $p = 0.008$) also showed significant sensitivity, reflecting the importance of subsurface flow contributions to streamflow in this mountain basin. Parameters such as v__GW_REVAP.gw, v_EVRCH.bsn, and v__CANMX.hru exhibited relatively lower sensitivity with p-values exceeding 0.05, indicating limited influence on streamflow simulation under the prevailing basin conditions. The relative sensitivity rankings for the entire set of 18 calibrated parameters are compiled in Table 2. The present study presents a quantitative comparison of five previous investigations that employed

Table 2: Best simulation parameters

Parameter	Optimized value	Min value	Max value	Description	t-test	p-value	Sensitivity
V_CN2.MGT	93.37	35.0	98.0	Curve number for runoff estimation, reflecting land use and soil properties.	5.412	0.000	Most Sensitive
v_ALPHA_BF.GW	1.0	0.0	1.0	Alpha factor controlling the baseflow recession rate (in days).	2.764	0.011	Moderately Sensitive
v_GW_DELAY.GW	428.20	0.0	500.0	Time delay in days between water recharge and appearance in the shallow aquifer.	−3.187	0.005	Moderately Sensitive
v_GWQMN.GW	4263.5	0.0	5000.0	Minimum aquifer water depth required for baseflow contribution to streamflow (mm).	2.943	0.008	Moderately Sensitive
v_GW_REVAP.GW	0.20	0.0	0.2	Groundwater evaporation coefficient controlling upward water movement from aquifer.	1.876	0.068	Less Sensitive
v_SOL_K().sol	942.0	0.0	2000.0	Saturated hydraulic conductivity of the soil (mm/hr), influencing percolation rate.	3.654	0.002	Highly Sensitive
v_SFTMP.bsn	4.232	0.0	20.0	Temperature above which snow begins to melt (°C).	4.876	0.000	Most Sensitive
v_SMTMP.bsn	-3.69	-20.0	20.0	Base temperature for snowmelt process (°C).	−5.934	0.000	Most Sensitive
v_SMFMX.bsn	0.706	0.0	20.0	Peak snowmelt rate during the warmest period of the year (mm/°C/day).	4.213	0.001	Highly Sensitive
v_SMFMN.bsn	0.23	0.0	20.0	Minimum snowmelt rate during the coldest period of the year (mm/°C/day).	2.318	0.026	Moderately Sensitive
v_TIMP.bsn	0.884	0.0	1.0	Lag factor influencing snowpack temperature dynamics.	−3.421	0.003	Highly Sensitive
v_TLAPS.sub	8.066	-10.0	10.0	Temperature lapse rate (°C/km) used for adjusting temperature with elevation.	−6.821	0.000	Most Sensitive
v_SNOCOVMX.bsn	69.15	0.0	500.0	Maximum snow water content indicating full snow cover (mm H_2O).	−3.987	0.001	Highly Sensitive
v_CH_N1.sub	28.35	0.0	30.0	Manning's roughness coefficient for small tributary channels.	−2.104	0.041	Moderately Sensitive
v_SURLAG.bsn	4.765	0.0	24.0	Lag time for surface runoff routing (days).	−2.531	0.018	Moderately Sensitive
v_EVRCH.bsn	0.849	0.5	1.0	Adjustment coefficient for evaporation from water channels.	1.643	0.107	Less Sensitive
v_CANMX.hru	100.0	0.0	100.0	Maximum canopy water holding capacity per HRU (mm).	1.412	0.164	Less Sensitive

SWAT-based hydrological modeling under LULC change scenarios across mountainous and sub-Himalayan basins. A consensus emerges across the literature regarding the hydrological trajectory induced by deforestation and urbanization: these land-use changes invariably elevate surface runoff and annual streamflow, conversely suppressing dry-season baseflow, groundwater recharge, and evapotranspiration decline. The magnitude of these responses, however, varies considerably with the extent of land cover change and basin characteristics. In the Andassa watershed, Ethiopia (1,644 km²), Gashaw *et al.* (2018) reported a surface runoff increase of 9.3% and an annual flow increase of 2.2% attributable exclusively to LULC change between 1985 and 2015, with projected further amplification under 2030 and 2045 CA-Markov scenarios (calibration NSE = 0.77, R^2 = 0.79). These magnitudes are comparable to those of the present study, where mean monthly streamflow is projected to increase by 2.64% by 2052 and 7.54% by 2082 because of a 38% forest loss and 154% urban expansion in the Kunhar River Basin (calibration NSE = 0.62, R^2 = 0.64). Compared to the substantial hydrological shifts reported for the Usri watershed (+62.6% runoff; +43% runoff-to-rainfall ratio (Kumar *et al.*, 2022)); and the Subarnarekha basin (+98.85 mm surface flow from 2013–2020 (Gaur *et al.*, 2021)), the annual flow increases in the Andassa and Kunhar basins remained relatively modest. This tempered response is primarily attributable to

scale effects—namely, the larger spatial extent of these basins—alongside the mitigating influence of remaining forest canopy. In the Usri watershed, the near-complete conversion of settlement area from 3% to 17% (+467%) and agriculture from 25% to 41% between 1976 and 2014 drove a substantially steeper runoff response, highlighting how the relative proportion of impervious and low-infiltration surfaces governs the sensitivity of a basin's water balance to land use change. Within the Kunhar Basin itself, Saifullah *et al.* (2021) identified that climate change accounts for approximately 60% of the observed streamflow trend, with anthropogenic LULC change contributing the remaining 40% (Mann-Kendall test, $p < 0.05$; NSE > 0.75), a finding that underscores the importance of isolating LULC-only effects — as deliberately pursued in the present study — before coupling with climate projections. The deforestation-driven runoff amplification and the shift in early-season peak flow (from June to May) observed in this study align closely with the dynamics reported by Jain *et al*. (2010). Examining the snow-dominated Suni–Kasol reach of the Satluj River in the Western Himalaya ($R^2 = 0.90$), the present study, similarly demonstrated that forest decline and cropland expansion act as the dominant catalysts for elevated runoff and sediment yields. Notably, across all five comparison studies, the SWAT model performed satisfactorily or better for monthly streamflow simulation (NSE ranging from 0.52 to 0.88), confirming the suitability of the SWAT framework for LULC-hydrology assessments in data-scarce mountainous catchments irrespective of geographic region. The seasonal asymmetry observed in the current study—characterized by elevated early-season flows alongside diminished summer baseflows—aligns with the dry-season flow reductions (−2.8%) reported by Gashaw *et al*. (2018). It further corroborates the groundwater declines identified by Kumar *et al.* (2022) and Gaur *et al.* (2021), confirming that deforestation systematically impairs subsurface storage and baseflow maintenance across heterogeneous hydroclimatic regions. Collectively, the cross-basin evidence confirms that the hydrological trajectory documented for the Kunhar River Basin, progressive surface runoff intensification, earlier peak discharge, and declining dry-season flows, represents a geographically robust response to deforestation and urban expansion, with direct implications for the long-term operational reliability of the Suki Kinari Hydropower Project.

CONCLUSION

This study employed the SWAT hydrological model to evaluate the effects of projected LULC changes on streamflow in the Kunhar River Basin under three future scenarios. The approach adopted in this study, combining SWAT modeling with CA–Markov projected LULC scenarios, represents a novel framework for assessing the hydrological implications of land cover change in mountainous river basins. These results indicate that intensifying demographic pressures and concurrent deforestation will substantially reshape the basin's land cover. Consequently, forested tracts are projected to undergo progressive conversion into agricultural land, urban settlements, and barren areas. For the runoff gauging station at Garhi Habibullah, the SWAT model was calibrated for 2000–2011 and validated for 2011–2016, achieving acceptable performance. The projected shift of peak runoff from June to May under future LULC scenarios has direct implications for hydropower operation. An accelerated peak flow regime implies an earlier annual window for maximum power generation. This shift induces a temporal decoupling between energy supply and regional demand, as peak electricity consumption in Pakistan is characteristically concentrated during the summer season. Operational management of the headrace intake, desilting chambers, and power generation units would need to account for this temporal redistribution of flows. Furthermore, the projected overall increase in streamflow (+7.54% by 2082) increases total annual energy generation potential, but the simultaneous decrease in summer base flows reduces generation reliability during low-flow months. This asymmetric seasonal

response—characterized by elevated early-season discharge contrasted with diminished late-season flows—necessitates the implementation of adaptive operational strategies. A critical resource management constraint identified herein is the complete absence of gauging stations within the upper reaches of the Kunhar watershed, particularly near the Suki Kinari Hydropower Project, compounded by a sparse monitoring network downstream. Establishing a well-distributed monitoring network across both upper and lower basin regions is therefore essential for effective watershed management, improved hydrological data collection, and informed decision-making. Transitions are also driven by unsustainable agricultural expansion, where communities rely on deforestation for fuel, construction, and income. Ultimately, evidence demonstrates that these practices definitively accelerate ecosystem degradation, leaving landscapes highly vulnerable to accelerated soil erosion and permanently altering hydrological runoff regimes. Sustainable land management strategies are urgently needed, balancing livelihood requirements with conservation objectives. To guarantee long-term operational sustainability alongside ecological integrity, future studies must systematically evaluate the specific ramifications of LULC alterations on the hydropower capacity of both projected and currently executing infrastructure developments. The observed rise in runoff and earlier peak flows, combined with soil erosion risks, may be compounded by climate change, with potentially severe consequences for local ecosystems and livelihoods, while this study provides important insights, several limitations should be noted. First, the analysis did not account for water withdrawals, consumption, or reservoir regulation, which can substantially affect hydrological regimes. To overcome current mapping limitations, the integration of high-resolution imagery (1–5 m) is recommended for future studies to enhance the delineation of fine-scale LULC transitions, thereby facilitating the precise differentiation between degraded forests and grasslands while capturing localized agricultural encroachments. Secondly, climate change impacts were not explicitly integrated, although these are likely to intensify the hydrological effects of LULC transitions. Additionally, the SWAT model does not incorporate slope alterations and soil property changes arising from grazing, tillage, compaction, and irrigation practices, all of which can significantly influence infiltration and runoff dynamics. Consequently, future modeling initiatives must transition toward holistic architectures that synthesize dynamic LULC variables, reservoir management constraints, water consumption patterns, and ensemble climate projections (e.g., CMIP6) to deliver highly resilient predictive insights. Such additions will strengthen the predictive capacity of SWAT and provide more comprehensive guidance for watershed and hydropower management under evolving environmental conditions. In conclusion, optimizing watershed management within the Kunhar Basin contingent upon a structured, multi-institutional architecture; this requires the Pakistan Meteorological Department (PMD) and WAPDA for hydro-meteorological monitoring and streamflow data collection, while SK Hydro executes for site-specific sediment and flow monitoring under its environmental management protocols, and the Khyber Pakhtunkhwa Forest Department implements targeted silvicultural protection and reforestation initiatives. In conclusion, achieving comprehensive disaster resilience requires a tri-sectoral approach wherein the National Disaster Management Authority (NDMA) oversees macro-level flood risk assessment and warning systems, academia delivers necessary predictive modeling and capacity enhancement, and localized governance—comprising district administrations and grassroots organizations—manages watershed protocols and land-use policies. The SWAT–CA-Markov integrated framework developed in this study is highly transferable to other run-of-river hydropower systems, both within Pakistan and elsewhere.

AUTHOR CONTRIBUTIONS

S. Sher conceived and designed the study, conducted the hydrological modeling and simulations, performed data collection and analysis, and prepared the original manuscript draft. G.H. Dars contributed to the study conceptualization, methodology development, software application, model validation, formal analysis, and manuscript review and editing. K. Ansari contributed to the conceptualization of research, software implementation, data curation, visualization, and manuscript review and editing. S. Hussain assisted in the formal analysis and interpretation of the results. F. Aziz and M. Waseem contributed to the formal analysis and technical evaluation of the study. M.A. Khan contributed to software application, visualization, and overall supervision of the research work. All authors have read and agreed to the submitted version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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
ALPHA_BF	Baseflow alpha factor (days)
ArcSWAT	ArcGIS extension for soil and water assessment tool
CA	Cellular Automata
CANMX	Maximum canopy storage (mm H_2O)
CH_N1	Manning n value for tributary channels
CN	Curve number
CN2	Initial SCS runoff curve number
DEM	Digital elevation model
EROS	Earth resources observation and science
EVRCH	Reach evaporation factor
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
FAO	Food and Agriculture Organization
GIS	Geographic information system

GWQMN	Threshold depth for shallow aquifer returns flow (mm H_2O)
GW_DELAY	Groundwater delay time (days)
GW_REVAP	Groundwater revap coefficient
HRU	Hydrological response unit
LULC	Land use and land cover
LULCC	Land use and land cover change
MW	Megawatt
NSE	Nash-Sutcliffe Efficiency
OLI	Operational land imager
PBIAS	Percent bias
PET	Potential Evapotranspiration
PMD	Pakistan Meteorological Department
R2	Coefficient of determination
SCS	Soil conservation service
SFTMP	Snowfall temperature (degrees C)
SKHPP	Suki Kinari Hydropower Project
SMFMN	Minimum snowmelt rate (mm/^{o}C/day)
SMFMX	Maximum snowmelt rate (mm/ ^{o}C /day)
SMTMP	Snowmelt base temperature (^{o}C)
SNOCOVMX	Minimum snow water content for 100% cover (mm H2O)
SOL_K	Saturated hydraulic conductivity (mm/h)
SRTM	Shuttle Radar Topography Mission
SURLAG	Surface runoff lag coefficient
SUFI-2	Sequential uncertainty fitting
SWAT	Soil and water assessment tool
TIMP	Snowpack temperature lag factor
TLAPS	Temperature rate (^{o}C/km)
USGS	United States Geological Survey
WXGEN	Weather generator

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ORIGINAL RESEARCH ARTICLE

Application of convolutional neural network architectures for coral reef health assessment

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ABSTRACT

BACKGROUND AND OBJECTIVES: Coral reefs provide vital ecological and economic benefits but are increasingly threatened by climate change, pollution, and anthropogenic stressors that drive bleaching and degradation. The critical need for effective monitoring is often bottlenecked by standard field assessment protocols, which are inherently labor-demanding, time-prohibitive, and limited by the availability of domain experts. The study objectives were to develop a convolutional neural network-based framework for automated classification of reef coral morphotypes and coral health status from underwater photographs; evaluate three transfer learning architectures, dense convolutional network with 169 layers, residual network with 152 layers, and visual geometry group network with 19 layers, under limited and imbalanced training data; and deploy the best-performing model for automated reef health monitoring across five sampling stations at Kelapa Dua Island, Indonesia.

METHODS: Reef coral morphotypes were stratified into distinct growth forms, specifically massive (boulder), branching, and tabular (table). Concurrently, physiological condition was evaluated using the standardized Coral Health Chart, with individuals assigned to discrete health categories: healthy, bleached, or partially bleached. Three convolutional neural networks architectures pre-trained on ImageNet were fine-tuned on datasets of 663 morphotype images and 624 health status images, with class-weighted loss applied to address pronounced imbalance in the health dataset.

FINDINGS: Dense convolutional network with 169 layers achieved the highest overall accuracy, reaching 93 percent for morphotype classification and 82 percent for health status assessment, substantially outperforming residual network with 152 layers 152 (66 percent and 64 percent) and Visual geometry group network with 19 layers (42 percent and 64 percent). Per-class evaluation indicated that the health classification performance was substantially confounded by class imbalance, driven by a disproportionate representation of the 'partially bleached' category, which accounted for 55 percent of the total health samples. Consequently, the model exhibited a pronounced systematic bias, yielding an F1-score of merely 0.44 for the 'healthy' class.

CONCLUSION: These findings demonstrate both the promise and the current limitations of deep learning for automated coral reef monitoring, and underscore the need for larger, class-balanced, and station-independent datasets for future model development. The dense convolutional network with 169 model was successfully deployed across five monitoring stations at Kelapa Dua Island. In situ observations revealed a predominance of partially bleached coral conditions, which correlated with elevated sea surface temperatures and suppressed salinity levels documented during the survey period.

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INTRODUCTION

Indonesia occupies the apex of the coral triangle and hosts an estimated 75 percent (%) of the world's known coral species, representing the highest marine biodiversity on Earth (Burke *et al.,* 2012; Burke and Selig, 2002). Beyond their ecological significance, coral reef ecosystems underpin local economies through fisheries and ecotourism, serving simultaneously as spawning, nursery, and feeding grounds for thousands of fish species (Utomo *et al.,* 2013; Widhiatmoko *et al.,* 2020; Elliff and Silva, 2017). Notwithstanding their profound ecological and socioeconomic significance, marine ecosystems within Indonesia are increasingly compromised by the intersecting impacts of climate change, ocean acidification, accelerated sedimentation, and diverse anthropogenic pressures (Burke and Selig, 2002; Hoegh-Guldberg *et al.,* 2007). The documentation of widespread and recurrent mass bleaching events globally (Hughes *et al.,* 2017) underscores the urgency of developing scalable and objective tools for continuous reef health monitoring. Although conventional reef assessment methodologies such as belt transects, point-intercept transects, and photo-quadrat surveys—yield high-fidelity ecological datasets, they are structurally constrained by high resource demands, localized spatial scales, and susceptibility to observer bias (Obura *et al.,* 2019). The Coral Health Chart (Siebeck *et al.,* 2006) offers a standardized visual reference for in-situ bleaching assessment based on coral coloration, yet the subjectivity of observer interpretation and the impracticality of applying the method to large photographic archives remain significant constraints. These limitations motivate the exploration of automated, image-based classification approaches capable of processing large volumes of underwater imagery with consistent, reproducible outcomes. Convolutional neural networks (CNNs) have demonstrated state-of-the-art performance across a broad spectrum of image recognition tasks (Fukushima, 1988), and transfer learning—the adaptation of models pre-trained on large benchmark datasets such as ImageNet—has proven effective in domains where annotated training data are scarce (Pan and Yang, 2009; Shin *et al.,* 2016). In the coral reef domain, CNN-based classifiers have been successfully deployed for substrate and taxonomic identification (Gomez-Rios *et al.*, 2019). However, deep learning applications specifically targeting morphotype discrimination and health status interpretation from in-situ photographs remain comparatively limited, particularly in the Indo-Pacific marine ecosystems. In contrast to prior CNN studies optimized for large-scale, balanced datasets, this research offers three unique contributions: 1) a controlled, identically trained comparison of dense, residual, and plain convolutional transfer learning backbones under conditions of data scarcity and class imbalance; 2) a dual-task classification approach that contrasts the tractability of shape-based versus color-based coral features; and 3) an empirical bridge between model development and field validation against expert observations at a novel Indo-Pacific monitoring site. This study addresses that gap by pursuing three specific objectives: 1) to develop CNN-based models for the automated classification of reef coral morphotypes (boulder, branching, and table) and health status (healthy, bleached, and partially bleached) from underwater photographs, building upon previous advances in automated coral image analysis and deep learning–based reef monitoring (Beijbom *et al.,* 2015; Gómez-Ríos *et al.,* 2019); 2) to evaluate and compare the performance of three well-established transfer learning architectures dense convolutional network with 169 layers (DenseNet169), residual network with 152 layers (ResNet152), and visual geometry group network with 19 layers (VGG19), under the constraints of a small and class-imbalanced dataset, an approach that has been shown to improve classification performance in coral reef applications with limited annotated data (Gómez-Ríos *et al.,* 2019;

Shao *et al.,* 2024); and 3) to deploy the best-performing model for automated health assessment at five monitoring stations in the waters of Kelapa Dua Island, Daerah Khusus Ibukota (DKI) Jakarta, Indonesia. By reporting per-class performance metrics in tandem with overall accuracy, and by explicitly characterizing dataset constraints, this study establishes a transparent and reproducible baseline for future deep learning frameworks applied to Indonesian coral reef monitoring. This study was conducted on the Kelapa Dua Island, Seribu Island Regency, DKI Jakarta Province, Indonesia in 2023.

MATERIALS AND METHODS

The study area and field data collection

Field data collection was conducted in the waters surrounding Kelapa Dua Island, Seribu Island Regency, DKI Jakarta Province with approximately 5°44' south (S), and 106°33' east (E) between 3 and 10 June 2023. Five monitoring stations were established a priori based on the presence of prominent coral reef structures, encompassing both natural and transplanted benthic assemblages at depths profile of 2 to 15 meters (m) (Fig. 1). Station positions were recorded with a global positioning system (GPS)-enabled dive computer to enable repeat visits in future monitoring campaigns. Underwater images were collected by trained observers using an Olympus underwater-capable digital camera model used for field photography (TG-6) camera housed in an appropriate underwater housing. Photographs were acquired while swimming along informal belt transects at each station, with observers maintaining a standardized distance of approximately 30-50 centimeters (cm) from the coral subject to maximize detail and color fidelity. In accordance with the methodology established by Siebeck *et al*. (2006), a Coral Health Chart reference card was deployed adjacent to individual coral colonies during photography wherever practicable to serve as an in situ radiometric baseline.

Dataset compilation and class distribution

Two independent datasets were compiled to support distinct classification tasks: one dedicated to reef coral morphotype categorization and the other to physiological health status evaluation. For each dataset, images were sourced from publicly available online repositories, specifically the Rosenstiel School of Marine and Atmospheric Science (RSMAS) and Structure RSMAS coral image collections—supplemented by Google Images and in-situ field photography (Table 1 and Table 2). Prior to model training, a manual curation process was conducted on the entire image repository to verify annotation fidelity. During this quality control phase, all duplicate frames and images failing to meet stringent clarity and resolution criteria were systematically excluded. The morphotype dataset comprised 663 images classified into three categories: boulder, branching, and table corals. The health status dataset comprised 624 images classified as bleached, healthy, or partially bleached, with category assignment guided by the color reference standards of the Coral Health Chart. Each dataset was partitioned into training, validation, and test subsets (Table 3). The health status dataset exhibits a pronounced class imbalance, driven by a skewed distribution where partially bleached samples constitute approximately 55% of the total repository. Conversely, the remaining categories—bleached and healthy—display a more equitable distribution, each accounting for roughly 22% of the dataset (Table 4). The dataset sizes used here (663 and 624 images) are modest relative to large-scale benchmark datasets used in general-purpose image recognition, but they are consistent with, and in several cases larger than, sample sizes reported in comparable coral image classification studies that relied on transfer learning specifically to compensate for limited annotated data (Gómez-Ríos *et al.,* 2019; Shao *et al.,* 2024). With respect to data provenance, imagery sourced from public repositories and web-based search engines

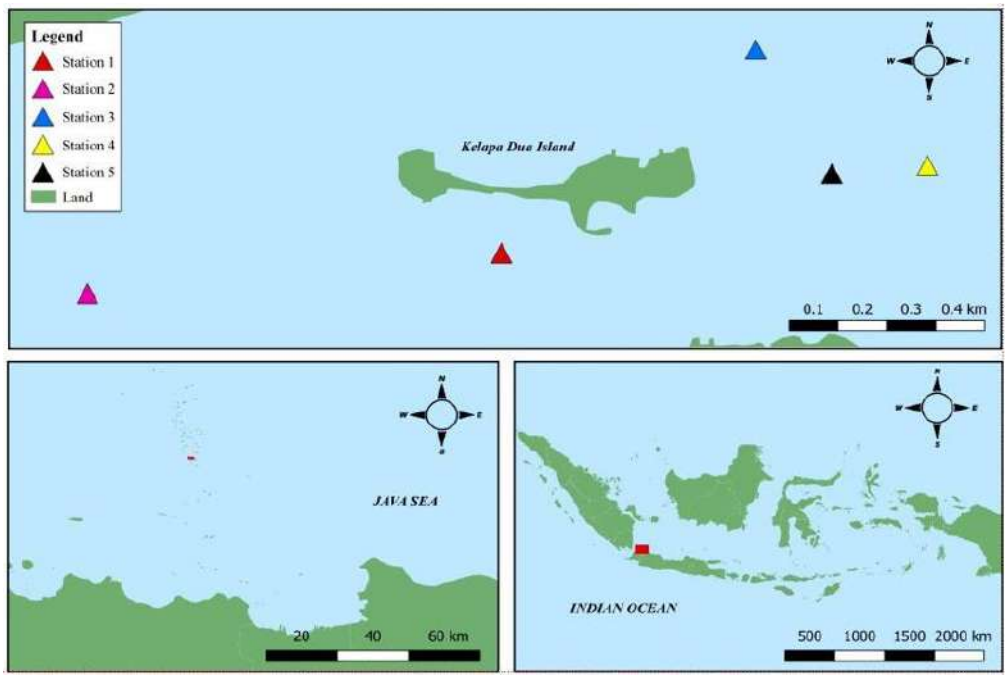

Fig. 1: Geographical location of the study area along with the five monitoring stations in Kelapa Dua Island, Seribu Island Regency, DKI Jakarta Province, Indonesia

Table 1: Source and image count for the reef coral morphotype dataset

Data source	Dataset	Number of images
Online repositories	Structure RSMAS	212
	RSMAS	157
	Google images	92
Field surveys	In-situ photography	202
Total		663

Table 2: Source and image count for the coral health status dataset

Data source	Dataset	Number of images
Online repositories	Structure RSMAS	193
	RSMAS	148
	Google Images	81
Field surveys	In-situ photography	202
Total		624

Table 3: Partition of training, validation, and test subsets for each dataset

Dataset	Training	Validation	Test	Total
Coral morphotypes	471 (71%)	118 (18%)	74 (11%)	663
Coral health status	416 (66%)	104 (17%)	104 (17%)	624

Table 4: Per-class image distribution across training, validation, and test splits

Dataset	B	Br	T	Bl	H	PB
Training	172	207	92	92	97	227
Validation	42	53	23	23	25	56
Test	30	32	12	9	9	86

Morphotype: Boulder (B), Branching (Br), Table (T); Health: Bleached (Bl), Healthy (H), Partially bleached (PB)

underwent a secondary screening process to ensure compliance with strict inclusion criteria. Specifically, candidate images were required to possess a spatial resolution sufficient to support a 224 × 224-pixel input framework without introducing upscaling artifacts, feature sharply focused target coral, and display an unambiguous, isolated morphotype or health state. Conversely, images were systematically excluded if they exhibited watermarks, textual overlays, confounding multi-colony assemblages, or excessive post-processing adjustments. Approximate-duplicate screening was performed by visual inspection for near-identical frames (e.g., consecutive burst-mode photographs or repeated use of the same source image across repositories), and any such duplicates were retained only once before dataset partitioning. Morphotype and health-status labels were assigned by two trained members of the research team with field experience in coral identification, working independently and using the Coral Health Chart as a standardized color reference for the health-status task; disagreements were resolved by joint review and consensus discussion rather than by a formal statistical inter-observer agreement measure. A recognized limitation of the current annotation phase is the absence of a quantitative inter-rater reliability statistic, such as Cohen's kappa. Incorporating such metrics is highly recommended for future expansions of the dataset, where a larger cohort of annotators will render these measures both statistically robust and operationally feasible.

Image preprocessing and data augmentation

All images were resized to 224 x 224 pixels prior to input to the CNN architectures, consistent with the input dimensions required by DenseNet169, ResNet152, and VGG19To facilitate network convergence, pixel intensities were rescaled to a normalized range of [0, 1] via division by a constant factor of 255. To mitigate overfitting in the context of the small training sets, online data augmentation was applied exclusively to training images. Augmentation operations included random horizontal flipping (p = 0.5), random rotation within ±15°, random zoom within a factor of 0.1, and random brightness adjustment within a factor of 0.1. Validation and test images received no augmentation; only normalization was applied. To mitigate the pronounced class imbalance within the health status dataset (Table 4), a class-weighted loss function was integrated into the training phase. Specifically, the categorical cross-entropy objective function was modified to penalize errors inversely proportional to the empirical frequency of each respective class. This approach penalizes misclassification of minority classes (bleached and healthy) more heavily than misclassification of the majority class (partially bleached), encouraging the model to learn discriminative features for all three health categories.

Model architecture and transfer learning

Three CNN architectures pre-trained on ImageNet were selected for comparison: DenseNet169, ResNet152, and VGG19. These network topologies embody fundamentally distinct architectural design paradigms and have been ubiquitously benchmarked within transfer learning frameworks for biological image classification (Dawson *et al.*, 2023; Shin *et al.*, 2016). For each architecture, the original classification head was replaced by a global average pooling layer followed by a fully connected layer with softmax activation outputting three classes. All base layer weights were frozen during an initial warm-up phase of five epochs, after which all layers were fine-tuned jointly. All models were implemented in Python (v3.9) using TensorFlow 2.x and Keras and trained on the Google Collaboratory platform using a single graphics processing unit used for model training (NVIDIA) T4 graphics processing unit (GPU). Training hyperparameters were held constant across architectures to enable fair comparison. Model training was executed for a maximum of 30 epochs utilizing a batch size of 32.

To mitigate overfitting, an early stopping protocol was implemented with a patience of 10 epochs, conditioned on the minimization of validation loss. The Adam optimizer was used with an initial learning rate of 1×10^{-4}, decayed by a factor of 0.5 whenever validation loss plateaued for three consecutive epochs. The loss function was categorical cross-entropy, modified with per-class weights for the health status task.

Model evaluation

Model performance was assessed on the held-out test set using overall accuracy and the per-class F1-score, which were computed from the confusion matrix for each architecture and task. In the presence of pronounced class imbalance, the F_1-score alone is insufficient to discern whether a classifier's errors are driven predominantly by false positives or false negatives for a specific category. Consequently, incorporating imbalance-robust summary statistics alongside overall accuracy is essential to expose hidden performance skews. In response to reviewer comments, per-class precision and recall, together with macro-averaged F1-score and balanced accuracy (the mean of per-class recall), will be computed directly from the retained test-set confusion matrices and added to Tables 6 and 8 in the next revision stage, after recomputation from the original model outputs; the headline accuracy and F1 figures already reported were not altered, as the reported values were directly verified against the confusion matrices in Fig. 2 and Fig. 4. To comprehensively characterize classifier behavior under conditions of class imbalance, per-class evaluation metrics are essential and are presented in tandem with confusion matrices in the results section. Overall accuracy was computed from the confusion matrix diagonal, using Eq. 1 (Farhadpour *et al.,* 2024; Jeong *et al.,* 2020; Adib *et al.,* 2022; Su *et al.,* 2025; Handayani *et al.,* 2025):

$$\text{Accuracy} = \Sigma(i = j)\, p_{ij} \,/\, \Sigma(\text{all})\, p_{ij} \quad (1)$$

Where: *pij* represents the *(i, j)* element of the confusion matrix. Model training dynamics were visualized using learning curves of accuracy and categorical cross-entropy loss as a function of epoch number, providing qualitative diagnostics of convergence behavior and the presence of overfitting.

RESULTS AND DISCUSSION

Reef coral morphotype classification

Table 5 summarizes the training and validation accuracy and loss for each architecture at epoch 30. DenseNet169 achieved the highest training accuracy (96.49%) and the lowest training loss (0.0418), with validation accuracy remaining high at 95.76%. The optimization trajectory for DenseNet169 demonstrated steady convergence, characterized by an absence of divergence between training and validation metrics. This alignment indicates strong generalization capacity within the localized training regime. ResNet152 reached a training accuracy of 76.89% but exhibited pronounced fluctuations in its learning curve, indicating that 30 epochs were insufficient for stable convergence on this dataset. VGG19 converged to a training accuracy of only 54.21%, consistent with its known requirement for large training corpora when fine-tuned from scratch (Dawson *et al.,* 2023). Motivated by these constraints, this study adopted a transfer learning approach wherein networks initialized with ImageNet-pretrained weights provided a generic visual baseline. This initialization significantly mitigated local data requirements, facilitating adequate fine-tuning despite a specialized domain dataset. Nonetheless, the dataset size remains a genuine constraint on model generalizability, and the substantially weaker performance of ResNet152 and VGG19 relative to DenseNet169 (Tables 5 to 8) indicates that not all architectures can be reliably fine-tuned on data of this scale; this limitation is discussed further below and is reflected in the cautious framing of the study's conclusions, which present the results as an initial

Table 5: Training and validation accuracy and categorical cross-entropy (CCE) loss for the three architectures on the reef coral morphotype task at epoch 30

Architecture	Train accuracy	Val. accuracy	Train loss (CCE)	Val. loss (CCE)
DenseNet169	96.49%	95.76%	0.0418	0.2919
ResNet152	76.89%	70.34%	0.6057	0.6787
VGG19	54.21%	55.93%	0.9530	0.9726

Table 6: Overall test accuracy and per-class F1-scores for the reef coral morphotype classification task

Architecture	Overall accuracy	Boulder (F1)	Branching (F1)	Table (F1)
DenseNet169	93%	0.97	0.94	0.83
ResNet152	66%	0.71	0.69	0.35
VGG19	42%	0.00	0.59	0.00

baseline rather than a generalizable operational model. When evaluated on the held-out test set, DenseNet169 significantly outperformed the alternative architectures, achieving an overall accuracy of 93%. In comparison, ResNet152 and VGG19 demonstrated markedly lower performance, yielding accuracies of 66% and 42%, respectively (Table 6). Per-class F1-scores reveal differential performance across morphotype categories. For DenseNet169, boulder and branching classes were classified with high F1-scores (0.97 and 0.94, respectively), while the table coral class showed somewhat lower performance (F1 = 0.83), likely reflecting the smaller number of table coral training samples (n = 92 images) and the morphological variability of this growth form. For VGG19, all test samples were predicted as branching coral, yielding F1-scores of 0.00 for boulder and table classes; this behavior is consistent with the model collapsing to the dominant class during training on a limited dataset. Inspection of the DenseNet169 confusion matrix (Fig. 2a) reveals that the primary misclassifications occur between table and branching coral morphotypes. This phenotypic overlap is likely a function of perspective distortion; at oblique camera angles, both growth forms exhibit analogous, elongated silhouette profiles with multi-branched geometric configurations under underwater conditions. Conversely, misclassification with the boulder morphotype was negligible, owing to its distinct hemispherical structural profile. Fig. 2a shows that DenseNet169 identifies all three coral types, although some samples are still misclassified, achieving an accuracy of 0.93 (93%). In Fig. 2b, ResNet152 identifies boulder and branching corals but has difficulty distinguishing table corals, resulting in an accuracy of 0.66 (66%). As illustrated in Fig. 2c, VGG19 collapsed into a majority-class classifier, assigning the branching coral label to all test samples. This catastrophic misclassification led to the lowest recorded overall accuracy of 0.42 (42%).

Coral health status classification

As shown in Fig. 3 and Table 7, the DenseNet169 model converges at approximately 0.80, achieving a final training accuracy of 79.33%, indicating relatively strong learning performance on the training dataset. Conversely, the VGG-19 architecture demonstrated an asymptotic convergence threshold at approximately 0.50, culminating in a final training accuracy of 48.80%. This failure to progress underscores the model's constrained capacity to capture the fine-grained, discriminative features necessary for this task. ResNet152 shows the lowest convergence level, stabilizing at approximately 0.46, which reflects comparatively weak training performance. These empirical observations are further substantiated by the training loss curves illustrated in Fig. 3, which reveal a consistent monotonic decline across all three network architectures throughout the optimization process. DenseNet169 achieves the lowest final training loss (0.4656), indicating

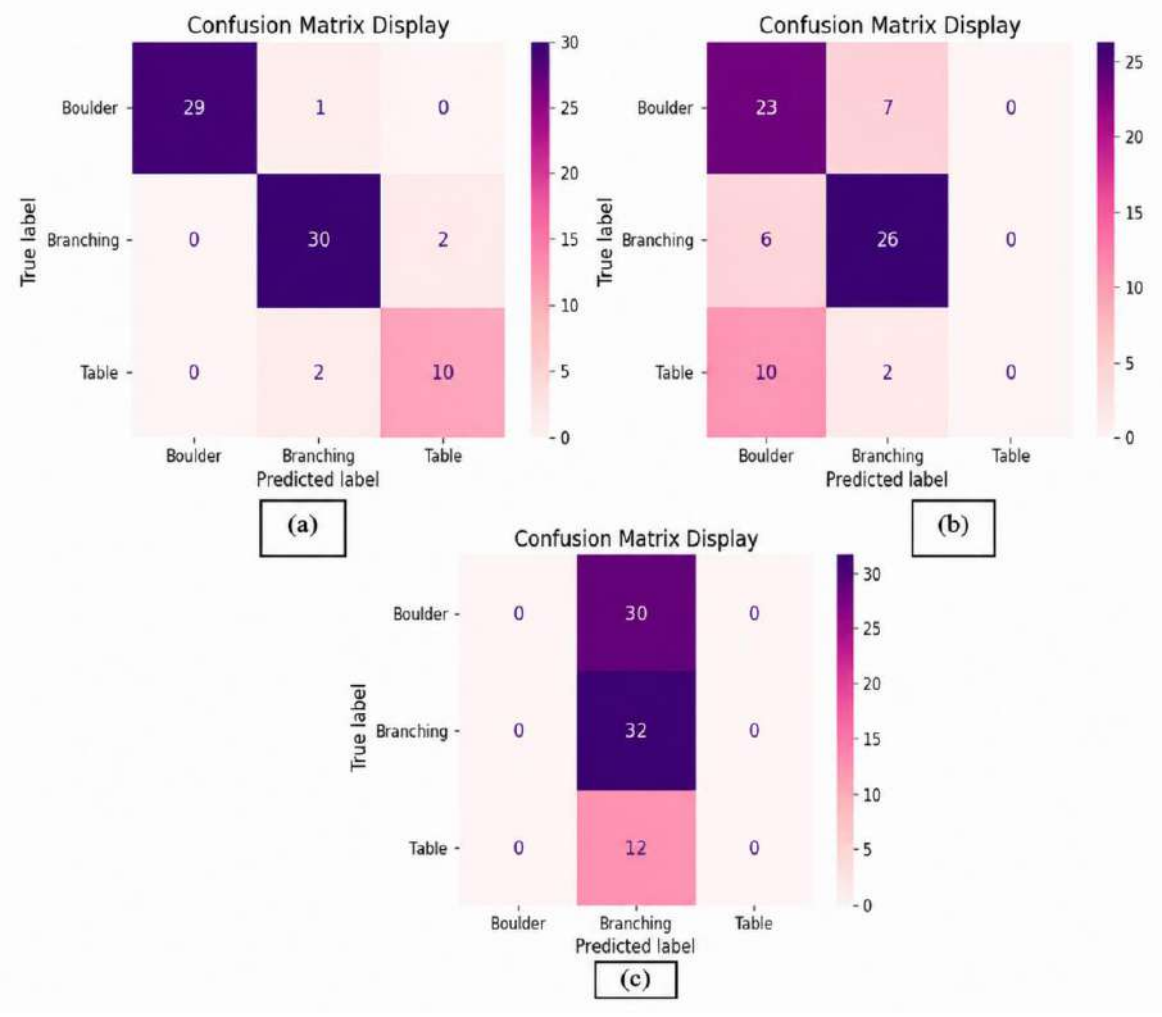

Fig. 2: Confusion matrices for reef coral morphotype classification: (a) DenseNet169, (b) ResNet152, (c) VGG19. Rows represent true classes; columns represent predicted classes

Table 7: Training and validation accuracy and CCE loss for the three architectures on the coral health status task at epoch 30

Architecture	Train accuracy	Val. accuracy	Train loss (CCE)	Val. loss (CCE)
DenseNet169	79.33%	77.88%	0.4656	0.5877
ResNet152	46.63%	50.96%	1.0548	1.0174
VGG19	48.80%	41.35%	1.0494	1.0947

more effective optimization and better fit to the training data than the other models. By comparison, ResNet152 and VGG19 yield substantially higher final loss values of 1.0548 and 1.0494, respectively, indicating failure to learn discriminative representations of the three health classes under the given training conditions. On the test set, DenseNet169 achieved 82% overall accuracy, compared with 64% for both ResNet152 and VGG19 (Table 8). Critically, per-class F1-scores reveal the impact of class imbalance on all three architectures. ResNet152 and VGG19 assigned all 104 test samples to the partially bleached category, yielding F1-scores of 0.00 for the bleached and healthy classes. This behavior demonstrates that aggregate accuracy is an

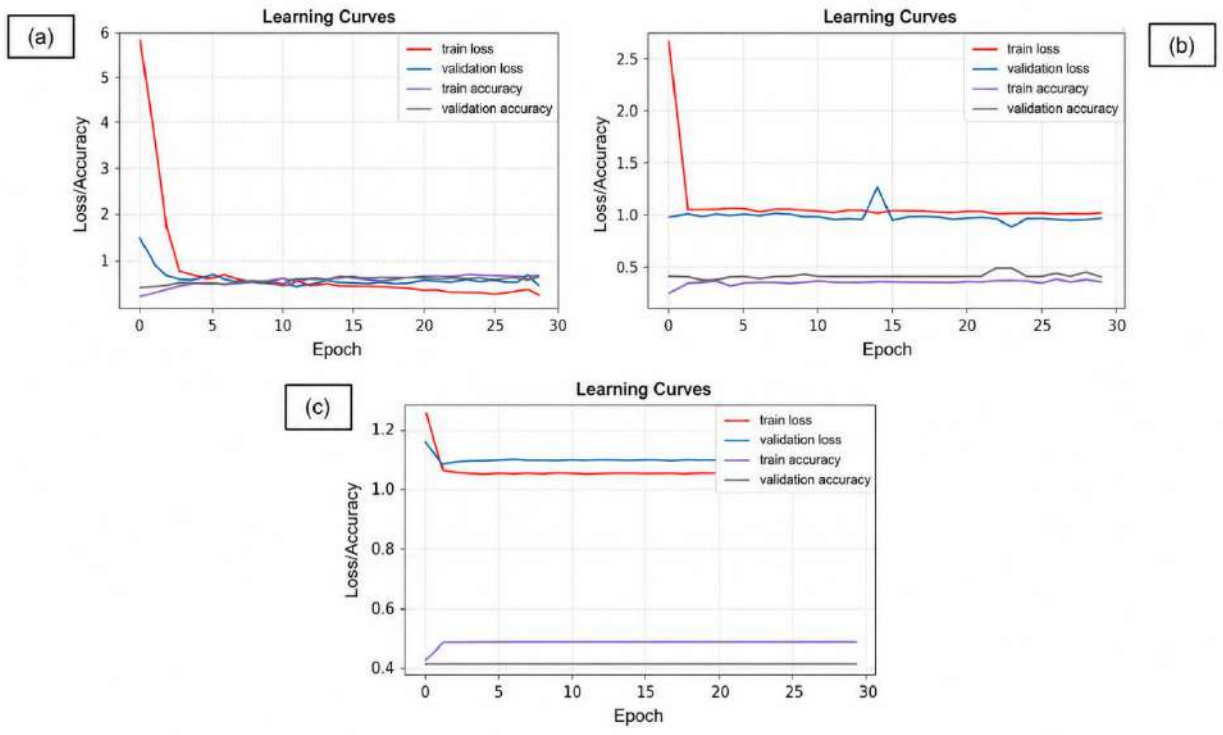

Fig. 3: Learning curves for the coral health status classification task: (a) DenseNet169, (b) ResNet152, (c) VGG19. Left panels: accuracy vs. epoch; right panels: categorical cross-entropy loss vs. epoch

Table 8: Overall test accuracy and per-class F1-scores for the coral health status classification task

Architecture	Overall accuracy	Bleached (F1)	Healthy (F1)	Part. Bleached (F1)
DenseNet169	82%	0.80	0.44	0.90
ResNet152	64%	0.00	0.00	0.78
VGG19	64%	0.00	0.00	0.78

inherently deceptive metric under severe class imbalance, masking systemic deficiencies in minority class recognition. DenseNet169 demonstrated substantially improved minority-class performance: the F1-score for the bleached class was 0.80, reflecting successful learning of bleaching-associated color features. However, the healthy class F1-score remained low at 0.44, indicating that a substantial proportion of healthy corals were misclassified, likely as partially bleached. This pattern reflects two compounding factors. First, with a baseline of only 97 training images, the healthy class was the most underrepresented category (Table 4), providing the model with minimal exposure to the visual and intra-class variance of unstressed coral coloration. Second, healthy and partially bleached corals occupy adjacent, overlapping positions on the pigmentation continuum captured by the Coral Health Chart, particularly under the variable underwater lighting and white-balance conditions of field and archival photography; partial bleaching is, by definition, an intermediate condition between fully healthy and fully bleached pigmentation, so misclassification toward this visually adjacent class is the expected failure mode under limited training data, rather than a failure to learn any coherent color signal at all. Crucially, class-weighted optimization only scales loss magnitude; it does not enrich the data diversity or structural variations presented to the network. As a result, it offered only a partial remedy for the

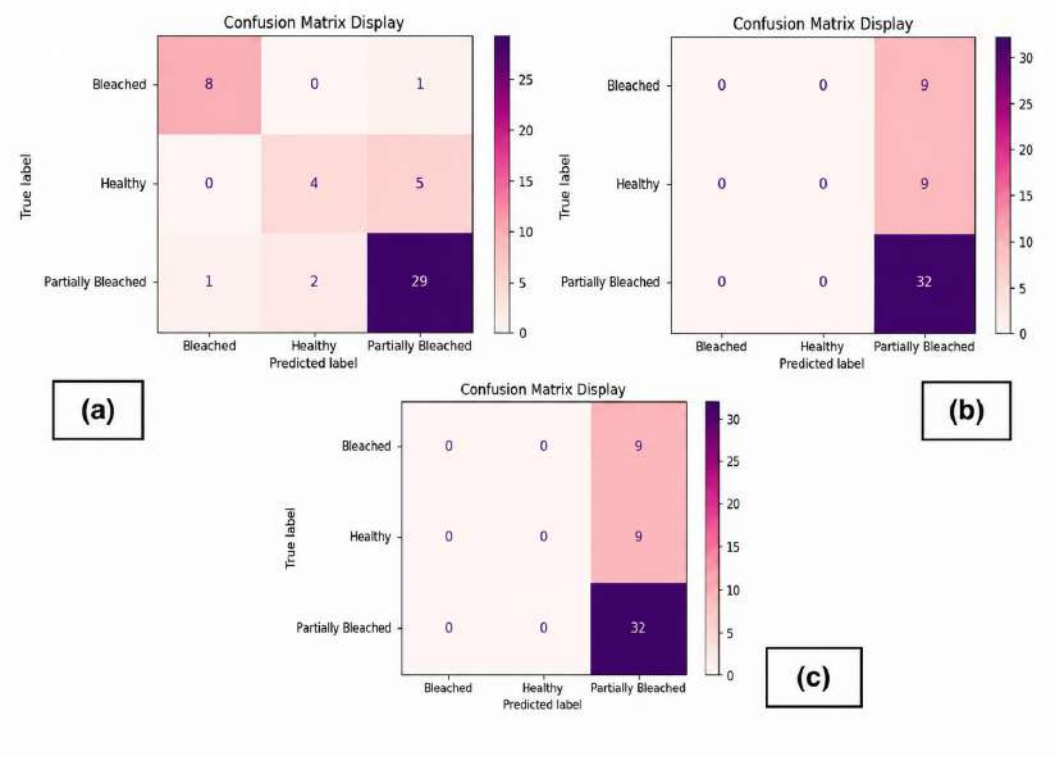

Fig. 4: Confusion matrices for coral health status classification: (a) DenseNet169, (b) ResNet152, (c) VGG19. Classes: Bleached (Bl), Healthy (H), Partially Bleached (PB)

concurrent challenges of a limited training cohort and shared visual feature spaces, aligning with the stagnant, low F_1-score reported for this category. Fig. 4a shows that DenseNet169 can identify the three coral reef health categories—Bleached, Healthy, and Partially Bleached—although some samples are still misclassified, achieving an accuracy of 0.82 (82%). In Fig. 4b, ResNet152 classifies all test samples as Partially Bleached, resulting in an accuracy of 0.64 (64%). Similarly, Fig. 4c shows that VGG19 also predicts all test samples as Partially Bleached, with the same accuracy of 0.64 (64%).

Deployment at Kelapa Dua Island monitoring stations

The DenseNet169 model was deployed to automate the interpretation of morphotype and health status from the 45 field images collected across five monitoring stations (Table 9). To ensure evaluative rigor, reference labels were derived from the manual interpretations of expert human annotators. At the station level, morphotype classification accuracy ranged from 88% (Station 3) to 100% (Stations 2, 4, and 5), with a single misclassification at Station 1 involving a table coral predicted as branching (Fig. 5). Health

Table 9: Station-level results of manual and automated coral health status identification using the DenseNet169 model. Manual observer labels are treated as ground truth

Station	n	Bleached (manual)	Bleached (model)	Healthy (manual)	Healthy (model)	Part. Bleached (manual/model)
1	15	4	4	1	1	10 / 10
2	13	1	1	4	2	8 / 8
3	8	1	1	1	1	6 / 6
4	5	1	0	1	0	3 / 3
5	4	2	2	1	0	1 / 0



Fig. 5: Representative outputs of the DenseNet169 model deployed at Kelapa Dua Island (A) morphotype classification examples showing boulder, branching, and table coral predictions with associated probability scores; (B) health status classification examples showing bleached, healthy, and partially bleached predictions

status accuracy ranged from 50% (Station 5) to 100% (Stations 1 and 3). The reduced accuracy at Stations 4 and 5 is attributable primarily to the tiny sample sizes at these stations (5 and 4 images, respectively), where a single misclassification produces a disproportionate reduction in reported accuracy. Across all five sampling stations, partially bleached phenotypes represented the predominant health status, accounting for 63% of the classified inventory. This high prevalence aligns with the elevated sea surface temperatures and anomalous salinity gradients documented during the survey window. This deployment evaluation, comprising 45 field images across five stations at a single site and survey period, should be interpreted as a proof-of-concept demonstration rather than a comprehensive validation of field performance. Confidence in the generalizability of the reported station-level accuracies to other reef environments, depths, or imaging conditions is limited by the small size of the deployment set and its origin from a single reef system. Owing to data availability constraints during this study, evaluating the classifier against an independent deployment dataset from a separate reef system was outside the current scope. It is therefore recommended that the trained model be tested in future work on independent field datasets collected at additional, geographically distinct reef sites, so that the extent to which performance is transferable beyond Kelapa Dua Island can be established. It is also noted that the high prevalence of partially bleached corals in both the training dataset (55%) and the field deployment (63%) is consistent with field conditions documented at the time of the underlying photographic surveys, as well as with the elevated sea-surface-temperature and reduced-salinity conditions reported in the Ecological context subsection below. However, because the training and deployment datasets share overlapping source archives and identical environmental stress contexts, the possibility of data selection bias cannot be entirely discounted. Consequently, the observed prevalence may partially reflect artifacts of the available imagery composition rather than true, statistically representative reef-wide conditions. This issue is therefore flagged as an interpretive caveat rather than a confirmed finding.

Differential architecture performance and the role of dense connectivity

The consistent superiority of DenseNet169 across both classification tasks is attributable to its dense connectivity pattern. Within this architecture, continuous feature reuse is enabled because every individual layer receives direct feed-forward inputs from all preceding feature maps, maximizing information flow (Huang *et al.,* 2016). This design promotes feature reuse and alleviates the vanishing gradient problem, which is particularly advantageous when fine-tuning on small datasets because earlier layers—which encode low-level features such as texture, edge, and color contribute directly to the final prediction without dilution through sequential bottleneck layers. By contrast, ResNet152 employs residual skip connections between non-adjacent layers with a deeper sequential architecture. Consequently, adapting its high-level feature representations demands a more extensive volume of domain-specific training data. VGG19, lacking skip connections entirely, exhibited the poorest adaptation performance, consistent with findings from Dawson *et al.* (2023) in carbonate rock classification. The observation that DenseNet169 performed markedly better on morphotype classification (93%) than on health status classification (82%) reflects the nature of the visual features being exploited. Reef coral morphotypes are defined primarily by three-dimensional skeletal architecture, which maps onto the two-dimensional image plane as

diagnostic shape, silhouette, and textural configurations. Health status, by contrast, is encoded primarily in coral coloration relative to the Coral Health Chart, a feature space that is highly susceptible to variation in underwater illumination, white balance, turbidity, and photographic depth (Borbon *et al.,* 2021; Siebeck *et al.,* 2006). In addition to these architectural considerations, the consistent data trends across Tables 5 to 8 provide independent empirical validation aligned with this hypothesis: DenseNet169 attained both the lowest training loss and the smallest train–validation gap of the three architectures on both tasks, indicating that its feature-reuse pathways converged to a stable, generalizable representation under identical hyperparameters and training budgets, whereas ResNet152 and VGG19 failed to converge within 30 epochs on data of this scale. This observation aligns with previous comparative evaluations of CNN backbones on constrained, domain-specific biological datasets. In such low-data regimes, the inductive biases of densely connected topologies consistently yield superior generalization efficacy compared to their deeper residual or plain counterparts (Dawson *et al.,* 2023). Relative to previously published coral reef deep-learning studies, the morphotype accuracy obtained here (93%) is comparable to or exceeds accuracies reported for CNN-based coral substrate and species classification on larger benchmark archives (Gómez-Ríos *et al.,* 2019; Beijbom *et al.,* 2015), while the health-status accuracy (82% overall, but only 0.44 F1 for the healthy class) falls within the range of reported difficulty for fine-grained, color-dependent coral condition assessment using multi-label or multi-class CNN approaches (Shao *et al.,* 2024), reinforcing that color-based health assessment remains a harder problem than shape-based morphotype recognition across the broader literature, not only in the present dataset. More recent architecture families, such as Efficient Net and Vision Transformers, were not evaluated in this study. These paradigms represent compelling candidates for subsequent comparative analyses—specifically, efficiency-optimized convolutional topologies and attention-based frameworks trained under highly robust, data-efficient regimes suitable for low-resource deployment. Further improvements in health-status classification performance may be achieved through these approaches. However, due to their lack of inherent inductive biases, Vision Transformers typically exhibit higher sample complexity during fine-tuning than their convolutional counterparts, necessitating substantially larger datasets unless data-efficient pretraining paradigms or robust data-augmentation strategies are implemented. Ensemble or hybrid approaches combining predictions from multiple backbones were also not explored. Different per-class error patterns were observed for DenseNet169, ResNet152, and VGG19, as shown in Tables 6 and 8. Consequently, leveraging an ensemble framework represents a plausible strategy for enhancing classification robustness, specifically by stabilizing the decision boundaries for the underrepresented healthy class. This approach is identified as a direction for future work. In terms of computational cost, DenseNet169, with approximately 14 million parameters, and ResNet152, with approximately 60 million parameters, were both trained to convergence within standard single-GPU Google Collaboratory sessions in this study. However, a full benchmark of training time, inference latency, and memory footprint across architectures was not performed. Such benchmarking would be relevant for real-time or embedded field deployment, such as onboard autonomous or remotely operated underwater vehicles, and is therefore noted as a direction for future work, particularly under diverse operational and environmental conditions encountered globally.

Class imbalance, data leakage, and overfitting risks

Accordingly, this study identifies three distinct methodological limitations that warrant consideration in subsequent research. First, the class imbalance in the health status dataset in which partially bleached samples constitute approximately 55% of total instances is a critical confound that inflates overall accuracy and suppresses minority-class performance (He and Garcia, 2009; Buda *et al.,* 2018). To mitigate these dataset imbalances in subsequent work, several multi-faceted strategies should be deployed: expanding the physical image repository with supplementary examples of healthy and bleached phenotypes, implementing synthetic manifold oversampling techniques such as SMOTE on extracted feature vectors (Chawla *et al*., 2002), and integrating cost-sensitive objective functions like weighted or focal loss during network training (Cui *et al.*, 2019; Lin *et al*., 2020). Future work should evaluate complementary strategies in combination with class weighting, including minority-class oversampling, focal loss (which down-weights well-classified majority-class examples during training and concentrates learning capacity on harder, often minority-class, examples), and balanced batch sampling, alongside the collection of additional healthy-class images, which would directly address the root cause of the imbalance rather than only its symptom. Second, the baseline dataset partitioning strategy—which randomly allocated images across the training, validation, and test splits irrespective of their station of origin—fails to strictly eliminate the risk of data leakage. Consequently, near-duplicate or highly correlated imagery from the same station may concurrently populate both the training and evaluation subsets. A station-based or transect-based holdout strategy, in which images from one or more entire stations are reserved for testing, would provide a more stringent and ecologically meaningful evaluation of model generalizability. This concern is further compounded using a single random train–validation–test split. Given the limited dataset size, the reported accuracies should be interpreted as point estimates that may be sensitive to the specific partition obtained. K-fold cross-validation was not performed in this study. Station-based and k-fold cross-validation, or repeated stratified k-fold cross-validation, are therefore identified as priority methodological additions for subsequent work. Such methodologies facilitate the direct quantification of variance across performance estimates. The degree of optimism introduced by random, non-station-aware splitting could also be measured directly, rather than inferred qualitatively as in the present analysis. Formal statistical comparisons among DenseNet169, ResNet152, and VGG19 were not performed in this study. Future investigations should incorporate statistical significance testing and confidence intervals to provide more robust, reliable, and generalizable comparative performance assessments. Examples include McNemar's test on paired test-set predictions and bootstrap confidence intervals for accuracy and F1-score. Given the magnitude of the observed performance gaps in Tables 6 and 8, statistical equivalence among the architectures is considered very unlikely. Nevertheless, integrating inferential statistical frameworks—such as confidence intervals or formal significance testing remains a critical prerequisite for future, large-scale extensions of this work to rigorously quantify performance uncertainty. Cross-validation folds would also provide a suitable basis for such tests. Third, mild overfitting in DenseNet169 on the health-status task is indicated by the gap between training and validation performance. This issue was partially mitigated through extensive data augmentation and early stopping strategies.

Ecological context of coral health at Kelapa Dua Island

Consistently observed across all five monitoring stations at Kelapa Dua Island, the predominance of partially bleached coral colonies aligns with the localized thermal stress and physicochemical conditions recorded during the sampling timeline. All stations recorded sea surface temperatures between 29.8 and 30.1°C, exceeding the upper thermal tolerance limit of 29 degrees Celsius (°C) commonly cited for Indo-Pacific reef corals, and salinities between 27.5 and 30.4 ppt, below the optimal range of 32-35 ppt. The persistence of partially bleached rather than fully bleached conditions across most stations suggests that these stressors represent chronic sub-lethal thermal and osmotic stress rather than acute bleaching episodes (Ainsworth and Brown, 2021; Spalding and Brown, 2015). It should be emphasized that the water quality measurements available for this study consist of single-point surface observations and do not constitute a dataset sufficient to establish causal relationships between specific physicochemical parameters and observed coral health status. Accordingly, the observed correlations between elevated temperature, suppressed salinity, and the prevalence of partially bleached corals are presented as a plausible, literature-substantiated interpretation rather than a definitively established causal mechanism. Readers should interpret these associations within the scope of this methodological boundary. Future monitoring efforts should incorporate standardized, replicated water quality sampling at multiple depths and time points, alongside photographic surveys, to enable rigorous analysis of environmental drivers of coral health. Integration of additional biological and ecological indicators would further strengthen inference, improve environmental interpretation, and enhance the robustness of future analyses.

Generalization, interpretability, and broader applications

Several broader questions raised in review merit explicit discussion as boundaries of the present study rather than as findings. First, the source imagery—comprising the RSMAS and structure RSMAS archives, Google Images, and field photography from a single Indonesian site—introduces inherent geographic and environmental constraints, failing to encapsulate the global diversity of reef ecosystems (Harahap *et al.,* 2025). Furthermore, the dataset lacks granular taxonomic resolution; the three morphotype and three health-status categories represent coarse, ecologically motivated groupings rather than species- or genus-level classifications. Consequently, species-level differences in skeletal form and pigmentation introduces confounding visual heterogeneity that the current model architecture was not designed to resolve. Accordingly, the reported accuracies reflect model performance exclusive to this dataset and may not transfer directly to external reef locations, alternative monitoring stations, or unrepresented imaging parameters (including lighting, turbidity, depth, camera angle, and resolution). While the preliminary field deployment addressed these confounding variables in part, full cross-domain validation remains an outstanding challenge. Second, this study did not evaluate whether the models can detect early-stage, visually subtle coral stress prior to overt bleaching, nor were explainable artificial intelligence (XAI) techniques such as class activation mapping applied to examine which image regions or features drove individual predictions; both directions would meaningfully improve the transparency, clinical-style interpretability, and trustworthiness of automated assessments and are recommended as priorities for follow-on work, alongside a systematic comparison of data augmentation strategies (beyond the geometric and brightness

operations used here) for their effect on generalization under limited training data. Third, the present framework was not designed to distinguish coral bleaching from other causes of coral discoloration, including disease, natural pigment variation, or recovery-stage re-pigmentation. Furthermore, the model has not been benchmarked directly against expert in situ visual assessments beyond the manual labels used as ground truth during deployment evaluation. Incorporating both comparative dimensions in future iterations would clarify how automated classifications align with and complement traditional reef-monitoring protocols. Crucially, it would also elucidate the ecological and managerial ramifications of false-positive and false-negative bleaching designations within a monitoring context. Fourth, environmental covariates (e.g., sea surface temperature, salinity, turbidity) were not incorporated as model inputs in this study; the single-point environmental measurements available were used only for post-hoc, qualitative interpretation, and their formal incorporation as auxiliary model inputs is identified as a promising direction that was outside the scope of the present analysis (Sakti *et al.,* 2026). Although feasibility at a single site was demonstrated through the deployment at Kelapa Dua Island, the transferability of the proposed framework to regional, national, or global reef-monitoring contexts has not yet been established. In addition, integration with autonomous or remotely operated underwater vehicles for low-cost continuous environmental surveillance remains unevaluated. Similarly, the synergistic benefits of deploying multi-architecture or ensemble learning approaches have yet to be explored. Because these aspects were beyond the scope of the present study, they are explicitly identified as important future research directions rather than implied capabilities of the current framework (Yuliana *et al.,* 2026).

CONCLUSION

This study demonstrated the applicability of convolutional neural networks combined with transfer learning for the automated classification of reef coral morphotypes and coral health status from underwater imagery. Among the three evaluated architectures, DenseNet169 consistently outperformed ResNet152 and VGG19 across both classification tasks, achieving an overall accuracy of 93% for reef coral morphotype identification and 82% for coral health status assessment, an advantage attributable to its densely connected architecture and consistent with its lower training loss and smaller train–validation gap on both tasks. Coral morphotype classification proved more tractable than the assessment of health status. This disparity reflects the relative stability of structural and textural features under varying conditions, whereas color-based features remain highly susceptible to environmental noise introduced by underwater illumination, water turbidity, and bathymetric depth. The pronounced class imbalance in the health status dataset, partially mitigated but not fully resolved by class-weighted loss, contributed to the persistently low F1-score for the healthy class (0.44) and to the collapse of ResNet152 and VGG19 toward the dominant partially bleached class—underscoring that overall accuracy alone is an insufficient and potentially misleading metric under class imbalance, and that per-class metrics should be reported as standard practice in similar ecological classification studies. Deployment of the DenseNet169 model at five monitoring stations around Kelapa Dua Island confirmed its practical feasibility. The model's classifications highly agreed with expert visual assessments, identifying partial bleaching as the dominant coral health status throughout the study area. This finding is consistent with local records of elevated sea surface temperature and suppressed salinity; however, given the constraints of the

environmental sampling design, this linkage should be treated as a literature-supported interpretation rather than a statistically verified causal relationship. These findings should be regarded as an initial, site-specific baseline: the relatively small and randomly partitioned dataset, the absence of station-based or k-fold cross-validation, and the modest scale of the field deployment together mean that broader regional or global transferability of the proposed framework, including potential integration with autonomous or remotely operated underwater vehicles for continuous low-cost monitoring, remains to be established rather than demonstrated by the present results. Future, iterations of this framework should prioritize expanding the scale and geographic diversity of the baseline imagery alongside implementing station-stratified k-fold validation protocols. Methodological enhancements should also integrate robust class-balancing strategies for underrepresented health cohorts, rigorous statistical comparison of model performance, explainable-AI diagnostics. Ultimately, incorporating environmental covariates will facilitate the transition toward automated, scalable, and reproducible reef health assessment systems, empowering scientists, conservation practitioners, and resource managers track marine ecosystem dynamics across broader spatio-temporal scales.

AUTHOR CONTRIBUTIONS

S. Nurdjaman, as the corresponding author, was responsible for the study conceptualization, supervision of data acquisition and analysis, interpretation of the CNN outputs, and manuscript writing. B. Fahimna carried out the field surveys, while D.W. Purnaningtyas collected the in-situ data, developed the image datasets, and conducted model training and performance evaluation. L.I. Bernawis contributed to data interpretation, whereas R. Rachmayani supported the study design, data interpretation, and ecological contextualization of the findings. K. Kasim assisted with manuscript revision and editing, A.A.P. Yanhas provided logistical support during field activities, and F. Saputra contributed to image preprocessing.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests 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) declare that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
°C	Degrees Celsius
Adam	Adaptive Moment Estimation optimizer
B	Boulder
Bl	Bleached
Br	Branching
CCE	Categorical cross-entropy
CNN	Convolutional neural network
CNN-based	Based on Convolutional Neural Network methods
cm	Centimeter
Coral Health Chart	Standardized visual reference chart for assessing coral bleaching based on color
CoralWatch	Coral reef monitoring and education program using the Coral Health Chart
DenseNet169	Dense convolutional network with 169 layers
DKI Jakarta	Daerah Khusus Ibukota Jakarta
e.g.	Exempli gratia; for example
Eq.	Equation
et al.	Et alia; and others
F1-score	Harmonic mean of precision and recall
Fig.	Figure
Fine-tuned	Further trained on a specific target dataset
GPU	Graphics processing unit
GPS	Global positioning system
H	Healthy
i.e.	Id est; that is
ImageNet	Large-scale visual recognition benchmark dataset
In-situ	Observed or collected directly at the original field location
Keras	High-level deep learning application programming interface
m	Meter
Macro-averaged F1-score	Average F1-score calculated equally across all classes
n	Number of samples
NVIDIA T4	Graphics processing unit used for model training
Olympus TG-6	Underwater-capable digital camera model used for field photography
p	Probability
PB	Partially Bleached
ppt	Parts per thousand
Pre-trained	Previously trained on a large benchmark dataset
ResNet152	Residual network with 152 layers
RSMAS	Rosenstiel School of Marine and Atmospheric Science
SMOTE	Synthetic Minority Oversampling Technique
Softmax	Activation function used for multi-class classification
Station-based holdout	Validation strategy using entire monitoring stations as independent test data

T	Table
TensorFlow	Open-source machine learning framework
Transect-based holdout	Validation strategy using entire transects as independent test data
VGG19	Visual geometry group network with 19 layers

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ORIGINAL RESEARCH ARTICLE

Biomonitoring of lead and cadmium pollution using *Oreochromis niloticus* physiological stress responses

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ABSTRACT

BACKGROUND AND OBJECTIVES: Heavy metal pollution is a major environmental problem because these contaminants are toxic, persistent, and able to accumulate in aquatic ecosystems. Lead and cadmium are among the most hazardous heavy metals due to their toxicity and potential bioaccumulation. The study objectives were to evaluate lead and cadmium contamination in water, sediment, and *Oreochromis niloticus*. As well as assess hematological and histopathological responses as biomarkers of heavy metal pollution from the downstream Brantas River, Indonesia.

METHODS: Water, sediment, gill, and liver samples of *Oreochromis niloticus* were collected from five sampling stations along the Jagir River. The concentration of lead and cadmium was determined using Atomic Absorption Spectrophotometry. Hematological and histopathological responses were assessed as biomarkers of heavy metal exposure. Statistical differences between stations were evaluated using analysis of variance followed by the least significant difference test. Meanwhile, principal component analysis was used to was applied to examine multivariate relationships among variables.

FINDINGS: Heavy metal accumulation increased toward downstream stations, with the highest lead concentration recorded at Station 5. Increased metal accumulation was associated with decreases in erythrocytes count (24.3 percent), hematocrit value (31.7 percent), hemoglobin concentration (26.5 percent), and lymphocyte percentage (25.4 percent). In contrast, leukocyte increased by 14.8 percent, neutrophil by 53.4 percent, and micronuclei by 40.0 percent, indicating physiological stress and genotoxic effects. Histopathological alterations became progressively more severe with increasing contamination levels and included hyperplasia, lamellar fusion, edema, necrosis, hepatocyte degeneration, and hemorrhage. These findings demonstrate a strong relationship between heavy metal accumulation and biological responses in *Oreochromis niloticus*.

CONCLUSION: Histopathological changes became more severe with increasing contamination levels and included hyperplasia, lamellar fusion, edema, necrosis, hepatocyte degeneration, and hemorrhage. These findings indicate that hematological and histopathological changes in *Oreochromis niloticus* are sensitive biomarkers and can function as biomonitoring tools capable of detecting heavy metal pollution in aquatic ecosystems.

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INTRODUCTION

Heavy metal pollution is an environmental problem of global concern due to its toxic, persistent, and non-biodegradable nature. Heavy metals can accumulate in sediments and aquatic organisms, disrupting ecosystem balance (Kowalik *et al*., 2021; Zeng *et al*., 2024). Heavy metals can accumulate in the water column and sediments, then enter aquatic organisms through direct absorption and the food chain. Heavy metals such as lead (Pb) and cadmium (Cd) can undergo both bioaccumulation and biomagnification in aquatic food webs. Bioaccumulation refers to the uptake and retention of contaminants within individual organisms, while biomagnification describes the progressive increase in contaminant concentrations across successive trophic levels. Due to their non-biodegradable and persistent nature, these metals can become increasingly concentrated in higher trophic organisms, posing greater ecological and health risk (Sonone *et al*., 2020). This dynamic process allows bioaccumulation in fish tissues, particularly in organs involved in metabolism and detoxification, such as the gills and liver (Zeng *et al*., 2024). Accumulated heavy metals can disrupt the physiological balance of organisms by inducing oxidative stress, cellular damage, and impaired hematological and reproductive function in fish (Chowdhury and Saikia, 2020). Among the various heavy metals, lead and cadmium are of particular concern due to their high toxicity and persistence, as well as their tendency to bioaccumulate in aquatic environments. These metals can originate from various anthropogenic activities such as industry, transportation, agriculture, domestic waste, and urban activities (Raj and Maiti, 2020). Accumulation of Pb and Cd in aquatic environments has the potential to cause physiological, hematological, reproductive disorders and even death in aquatic organisms (Yu *et al*., 2024). One of the main river systems in East Java is the Brantas River, which flows from the upstream area around Batu City and Malang Regency, through Mojokerto, Jombang, Sidoarjo, and Surabaya. The Surabaya River is one of the main branches of the Brantas River, which in the Wonokromo area branches into the Mas River and Jagir River, each of which empties into the Madura Strait. The Surabaya River has a flow length of approximately 42 kilometres (km) from the Mojokerto area to Surabaya. This river system receives a significant pollution load, with waste contributions dominated by industrial waste with 64 percent (%) and domestic waste (36%) (Rahardja *et al*., 2012). As part of the Brantas River Basin, which stretches from the upstream area in East Java through urban and industrial areas in the densely populated city of Surabaya, the Jagir River receives a cumulative pollutant load transported from the upstream watershed as well as local anthropogenic inputs (Abdillah *et al*., 2025). However, rapid urbanisation, domestic wastewater discharge, road runoff, small industries, fish farming activities, and commercial development along the riverbanks have increased the risk of contaminant accumulation, including potentially toxic heavy metals (Deb *et al*., 2021). The presence of heavy metals in the Jagir River system has been reported in several previous studies, which showed Pb and Cd contamination in the water column (Kriswandana *et al*., 2024), as well as increasing Pb concentrations in estuarine water and sediments towards the coast (Prasita *et al*., 2025). Additionally, other heavy metals such as mercury and copper have also been detected in the water, sediment, and biota in the area (Kusmana *et al.,* 2018). *Oreochromis niloticus* is widely used as a bioindicator species in ecotoxicological studies due to wide distribution, ecological relevance, sensitivity to environmental quality changes, and increasing water temperature in the Jagir River (Osman, 2012). Its benthic feeding behaviour and continuous exposure to both water and sediment increase its susceptibility to heavy metal accumulation, particularly lead and cadmium. Furthermore, this species is known to bioaccumulate heavy metals

in key organs such as gills and liver, which are directly involved in respiration and detoxification processes, making it a reliable model for assessing sub-lethal toxic effects in contaminated river systems (Choudhary *et al*., 2023). Research on the toxic impacts of metals on fish is conducted through analysis of changes in various hematological and biochemical blood parameters (Senthamilselvan *et al*., 2012). Heavy metals such as Pb and Cd are of particular concern due to their persistence, bioaccumulation, and toxicity, and among the most toxic non-essential heavy metals, are commonly detected in the Brantas River, exhibit high bioaccumulation potential, which can disrupt physiological and hematological functions in fish (Raj and Maiti, 2020). Hematological parameters are widely used as sensitive biomarkers to evaluate physiological stress, immune responses, and health status in fish exposed to environmental contaminants (Pandey and Mishra, 2025). Histopathological examination of fish organs, particularly gills and liver, has been widely applied as early warning biomarkers for environmental contamination because tissue changes can occur before external clinical symptoms are visible. Gill and liver tissues are considered sensitive target organs for evaluating the toxic effects of heavy metals on aquatic organisms (Mahboob *et al*., 2020). Although Pb and Cd contamination in the Jagir River has been widely documented, existing studies have largely focused on environmental measurements or individual biological indicators (Tuska *et al*., 2025). Integrated assessments combining heavy metal accumulation in water, sediment, and fish tissues with both hematological and histopathological biomarkers in *Oreochromis niloticus* remain limited. Therefore, the present study aimed to evaluate Pb and Cd contamination in water, sediment, gill, and liver tissues of *Oreochromis niloticus* and to assess hematological and histopathological responses as biomarkers of heavy metal exposure. It was hypothesised that increased Pb and Cd concentrations would result in higher bioaccumulation in fish tissues and significant alterations in hematological and histopathological parameters of *Oreochromis niloticus*. This study was conducted in the Jagir River, Surabaya, Indonesia, at five different locations, with three replicates at each station in 2025.

MATERIALS AND METHODS

Study area and sample collection

Based on the research map in Fig. 1, sampling was conducted at five stations representing different conditions along the river during the rainy season (October–December 2025) and was repeated three times. This period was chosen because increased rainfall can increase surface runoff, erosion of water catchment areas, and resuspension of river sediments which play a role in the transport and redistribution of heavy metals in aquatic environments (Nguyen *et* al., 2020). Five sampling stations were selected using a purposive sampling approach to represent the main anthropogenic influences and spatial variability along the lower Brantas River. The stations were distributed to capture the upstream-downstream gradient and dominant pollution sources, including residential, industrial, and aquaculture activities. The characteristics of each sampling point are presented in Table 1. Water samples were collected from each sampling station using two 100 milliliter (mL) glass bottles from each point. Surface sediment samples at a depth of 0-5 centimeters (cm) were obtained using an Ekman grab sampler (Wildco®, United States of America) and transferred into pre-cleaned polyethylene containers. All collected samples were stored in a cooler filled with ice and transported to the laboratory for further analysis. Three sampling replicates were conducted at each station. During each sampling event, a total of ten individuals of *Oreochromis niloticus* were collected from each sampling station using a fishing net. Individuals within a similar size class were selected to reduce biological variability among simples. After the fish was caught, blood samples were taken using a

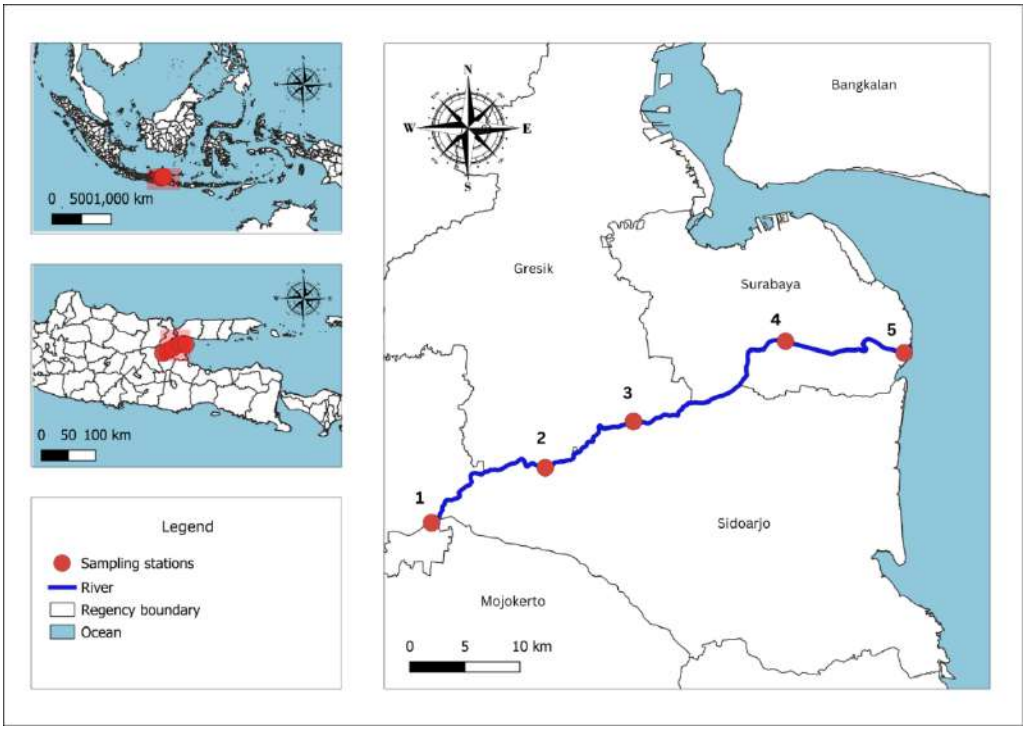

Fig. 1: Geographical location of the study area along with the sampling stations on the Jagir River, Surabaya, Indonesia

Table 1: Characteristics of the five sampling stations

Station	Geographic coordinates		Dominant activities	Sediment characteristics
	Latitude	Longitude		
1	7°26'59.41"S	112°27'03.29"E	Residential and agricultural area near the Rolak Songo floodgate	Sand-silt
2	7°24'16.57"S	112°32'40.18"E	Urban-agricultural area	Silt
3	7°21'59.48"S	112°37'01.67"E	Mixed residential and agricultural area	Clay
4	7°18'02.39"S	112°44'32.52"E	Industrial and urban area	Silt-Clay
5	7°18'36.86"S	112°50'24.07"E	Mangrove estuarine area	Clay-sand

1 mL sterile syringe (Terumo®, Japan) containing ethylenediaminetetraacetic acid (EDTA) anticoagulant from the caudal vein, then transferred to a K3-EDTA tube (Vacutainer®, USA) for hematological examination (Seibel *et al.*, 2021).

Fish sampling and biological examination

Based on Table 2, a total of 150 *Oreochromis niloticus* individuals were collected from five sampling stations during three sampling periods. The sampled population consisted of both males and females, with relatively balanced sex composition across stations and sampling periods. Fish total length ranged from 17.0 to 25.5 cm, while body weight ranged from 164 to 193 grams (g). The observed size range indicated that individuals included in the study belonged to comparable size classes, thereby minimizing potential size-related variation in biomarker responses.

Heavy metal analysis

Water samples were collected from each sampling station using pre-cleaned 100 mL glass bottles that had been acid-washed and immediately acidified with concentrated nitric acid (65% HNO_3; Merck®, Germany) to achieve a

Table 2: Number of biotic samples, length and weight

Station	Sampling	N	Male	Female	Length (cm)	Weight (g)
1	1	10	4	6	19-25	164-179
	2	10	5	5	20-23.5	165-182
	3	10	4	6	17.5-24	170-187
2	1	10	3	7	18-25.5	169-175
	2	10	2	8	22-25	184-190
	3	10	6	4	18.5-24	173-185
3	1	10	5	5	17-22	165-172
	2	10	4	6	21-25	168-174
	3	10	3	7	19-24	184-192
4	1	10	4	6	18.7-23	169-174
	2	10	7	3	19.4-24	169-179
	3	10	8	2	18.5-25	179-190
5	1	10	4	6	20-25	166-189
	2	10	5	5	21-24	171-193
	3	10	4	6	18-23	165-176

potential of hydrogen (pH) below 2 prior to laboratory analysis. Surface sediment samples with 0-5 cm depth were obtained using an Ekman grab sampler (Wildco®, USA) and transferred into clean polyethylene containers. All samples were preserved in an ice cooler and transported to the laboratory for subsequent analysis. Fish specimens were dissected to separate gill and liver tissues, which were then homogenized. Approximately 1.0 g of each tissue sample was placed in a 150 mL beaker, followed by the addition of 10 mL of concentrated HNO_3. The mixture was heated until dense white fumes were observed, indicating completion of the initial digestion process. After cooling, 10 mL of 25% hydrochloric acid (HCl) was added, and the digest was transferred into a 250 mL volumetric flask and diluted to volume using deionized water. For water samples, aliquots were evaporated to dryness in screw-cap tubes. Subsequently, 10 mL of concentrated HNO_3 was added, and the samples were reheated to near dryness. The residues were then diluted to 20 mL with deionized water, filtered, transferred into 250 mL volumetric flasks, labeled, and stored at low temperature until instrumental analysis. Sediment samples of 1–2 g wet weight were digested using a mixture of HNO_3 and hydrogen peroxide (H_2O_2), which was added gradually under heating until the volume was reduced. The resulting digest was then diluted with deionized water to a final volume of 250 mL. Heavy metal concentrations in water samples were expressed as milligrams per liter (mg/L), while concentrations in sediment and fish tissues (gill and liver) were expressed as milligrams per kilogram (mg/kg) wet weight. This standardization follows established laboratory protocols to ensure comparability across different environmental matrices and biological tissues. The concentrations of Pb and Cd in all samples were determined using an atomic absorption spectrophotometer (AAS) AA-7000, Shimadzu®, Japan, in accordance with standard procedures of the American Public Health Association (APHA, 2022). The method detection limits (MDL) of the instrument were 0.01 part per million (ppm) for Pb and 0.001 ppm for Cd, as defined by the analytical laboratory based on instrument calibration and signal-to-noise evaluation.

Quality assurance and quality control (QA/QC)

Quality assurance and quality control procedures were implemented to ensure the reliability of analytical results. Instrument calibration was performed using certified standard solutions of Pb and Cd to construct calibration

curves prior to sample analysis. Reagent blanks (using deionized water and acidified matrix) were analyzed to correct for potential background contamination and instrument drift. All samples were analyzed in triplicate to ensure analytical precision, and the mean values were used for further statistical analysis. Periodic calibration verification was conducted throughout the analytical sequence to maintain instrument stability and accuracy. Instrument performance was continuously monitored to ensure data quality, reproducibility, and compliance with standard analytical procedures.

Hematological of Oreochromis niloticus

Hematological profile analysis of *Oreochromis niloticus* was performed by measuring the number of erythrocytes, leukocytes, hemoglobin, hematocrit values, and calculating the difference in leukocytes based on standard protocols (Witeska *et al*., 2022). Erythrocytes and leukocytes were counted manually using a Neubauer hemocytometer (with Hayem's and Turk's solution) in units of $\times 10^6$ cells per cubic millimeter (cells/mm³) and $\times 10^3$ cells/mm³, while hemoglobin levels were measured using the Sahli method grams per deciliter (g/dL). Hematocrit values were determined using the microhematocrit method through centrifugation at 12,000 revolutions per minute (rpm) for 5 minutes. Finally, blood smears stained with giemsa solution were examined under a microscope to determine the difference in leukocytes (lymphocytes, neutrophils, monocytes, eosinophils, and basophils) with a count of at least 100 cells per smear, which was then expressed as a percentage (Aktar *et al*., 2025).

Histopathological analysis

Fish samples were transported to the laboratory, where their total length and body weight were recorded. The specimens were then euthanized by cervical dislocation or by severing the spinal cord anterior to the dorsal fin in accordance with established ethical protocols (van Dyk *et al*., 2009). Subsequently, fish were dissected, and macroscopic lesions in the target organs were recorded. Gill and liver tissues were excised, fixed in 10% buffered formalin, placed in labeled containers, and prepared for histological analysis (Getnet *et al*., 2024). Tissue samples were processed following standard histological procedures and stained with hematoxylin and eosin (H and E). Histopathological sections were then observed under a bright-field microscope at magnifications of 1000×. Structural alterations in gill and liver tissues were identified and recorded based on visible morphological abnormalities. Tissue damage was assessed using a semi-quantitative scoring approach based on the proportion of affected tissue. Percentage of damaged cells was calculated based on the cell counting approach as described in morphological quantification methods using Eq. 1 (von Bohlen und Halbach, 2013):

$$\text{Percentage of damage} = \frac{\text{Number of damage cells}}{\text{Total observed cells}} \text{x } 100\% \quad (1)$$

Histopathological lesions were classified into four categories: score 0 (no damage), score 1 (mild damage, less than 15%), score 2 (moderate damage, 15–30%), and score 3 (severe damage, greater than 30%) (Cavicchioli *et al*., 2015).

Data analysis

Data were analyzed using Statistical Package for the Social Sciences (SPSS) version 27. Microsoft Excel was used for data organization and preliminary processing. Principal component analysis (PCA) was performed using Paleontological Statistics (PAST) version 4.16. Prior to analysis, data normality was tested using the Shapiro–Wilk test, and homogeneity of variance was assessed using Levene's test. Data are presented as mean ± standard deviation (SD). Fish samples were collected from five sampling stations. At each station, sampling was conducted three times (three independent sampling replicates). Each replicate consisted of at least ten

individual fish. Individual fish measurements within each replicate were averaged to obtain a single replicate value. Thus, the statistical unit of analysis was the replicate (n = 3 per station). Differences among sampling stations were analyzed using one-way analysis of variance (ANOVA) at a significance level of $p < 0.05$. When significant differences were detected, post hoc comparisons were performed using Tukey's honestly significant difference (HSD) test to identify pairwise differences among stations.

RESULTS AND DISCUSSION

Lead concentration in water, sediment, gills, and liver

Pb concentrations in water, sediment, gill and liver samples showed an increasing trend from Station 1 to Station 5 (Table 3). Pb accumulation was detected in all environmental and biological matrices, indicating the presence of heavy metal contamination along the Jagir River. Based on Table 3, Pb concentrations in water ranged from 0.025 to 0.041 mg/L, with the highest value observed at Station 5 and the lowest at Station 1. Concentrations at Stations 1 to 3 remained below the water quality guideline value established by the Swedish Environmental Protection Agency (0.025 mg/L), whereas Stations 4 and 5 exceeded this threshold (PSEA, 2000), indicating increased contamination in downstream areas. In addition, Pb concentrations increased significantly along the river continuum from Station 1 to Station 5, showing a clear spatial gradient. Tukey HSD analysis confirmed significant differences among all sampling stations (a, b, c, d, e), indicating a consistent increasing pattern. This suggests continuous Pb input and accumulation along the river flow, likely influenced by anthropogenic activities in downstream regions. This pattern aligns with research showing that heavy metals in the water column increase with intensifying anthropogenic activities downstream (Raj and Maiti, 2020). In sediments, Pb concentrations ranged from 0.206 ± 0.009 mg/kg to 0.400 ± 0.017 mg/kg, with Tukey HSD results showing three distinct clusters (a, b, c), indicating that sediments serve as a major sink for heavy metals due to the adsorption of fine particles and long-term deposition. In fish tissues, Pb showed progressive bioaccumulation in the liver and gills. Concentrations in the liver increased from 0.064 ± 0.001 mg/kg to 0.121 ± 0.009 mg/kg with overlapping Tukey HSD patterns (a, ab, abc, b, c), reflecting gradual accumulation due to environmental exposure. Meanwhile, the gills showed the most obvious and significant increase pattern (a, ab, bc, cd, d), indicating that this organ is highly sensitive to direct exposure to heavy metals in water. This is in line with the findings (Shaalan *et al*., 2024) which state that gills are an early biomarker of heavy metal pollution due to direct contact with the aquatic environment. Statistically, the results of one-way ANOVA showed highly significant differences between stations in all compartments ($p < 0.001$), with high F values (water = 400.238; sediment = 120.897; liver = 39.746; gill = 117.824), indicating strong spatial variation in Pb distribution. Overall, this pattern indicates the transfer of Pb from water to sediment, then continuing to bioaccumulate in fish tissues, which is influenced by anthropogenic activities such as domestic waste, industry, and agricultural runoff (Almashhadany *et al*., 2024).

Cadmium concentration in water, sediment, gill, and liver

Cd concentrations in water, sediment, gill, and liver samples generally increased from Station 1 to Station 5 (Table 4). Cd contamination was detected in all environmental and biological matrices, indicating the distribution and accumulation of Cd along the Jagir River. The results showed a consistent increase in Cd concentrations from Station 1 to Station 5 in all environmental compartments (water and sediment) and fish tissue (liver and gills), indicating a spatial gradient of heavy metal contamination along the Jagir River.

Table 3: Heavy metal test results for Pb in water, sediment, gill and liver organ samples

Parameters	Unit	S1	S2	S3	S4	S5	F	p-Value
Water	mg/L	0.025 ± 0.0005^{a}	0.027 ± 0.0005^{b}	0.034 ± 0.0006^{c}	0.038 ± 0.0007^{d}	0.041 ± 0.0005^{e}	400.238	<.001
Sediment	mg/kg	0.206 ± 0.009^{a}	0.229 ± 0.013^{a}	0.273 ± 0.012^{b}	0.390 ± 0.016^{c}	0.400 ± 0.017^{c}	120.897	<.001
Liver	mg/kg	0.064 ± 0.001^{a}	0.066 ± 0.003^{a}	0.067 ± 0.005^{ab}	0.089 ± 0.009^{bc}	0.121 ± 0.009^{c}	39.746	<.001
Gill	mg/kg	0.241 ± 0.020^{a}	0.302 ± 0.011^{ab}	0.350 ± 0.030^{bc}	0.501 ± 0.020^{cd}	0.582 ± 0.026^{d}	117.824	<.001

Note: Concentrations are expressed as mg/L for water samples and mg/kg wet weight for sediment, gill, and liver tissues. Values are presented as mean ± SD. Different superscript letters within the same row indicate significant differences among sampling stations based on Tukey's HSD post hoc test ($p < 0.05$). Means sharing the same letter are not significantly different, while different letters indicate significant differences. Statistical assumptions of normality and homogeneity of variance were tested using Shapiro–Wilk and Levene's tests, respectively.

Table 4: Heavy metal test results for Cd in water, sediment, gill and liver organ samples

Parameters	Unit	S1	S2	S3	S4	S5	F (4,10)	p-Value
Water	mg/L	0.0085 ± 0.0004^{a}	0.0094 ± 0.0003^{ab}	0.0099 ± 0.0002^{b}	0.0114 ± 0.0003^{c}	0.0123 ± 0.0004^{d}	64.059	<.001
Sediment	mg/kg	0.0039 ± 0.0005^{a}	0.0041 ± 0.0004^{a}	0.0058 ± 0.0005^{b}	0.0059 ± 0.0005^{b}	0.0065 ± 0.0005^{b}	15.719	<.001
Liver	mg/kg	0.0021 ± 0.0002^{a}	0.0023 ± 0.0002^{ab}	0.0027 ± 0.0001^{abc}	0.0034 ± 0.0002^{bc}	0.0035 ± 0.0008^{c}	6.203	0.009
Gill	mg/kg	0.0010 ± 0.0001^{a}	0.0021 ± 0.0001^{a}	0.0025 ± 0.0001^{b}	0.0033 ± 0.0001^{c}	0.0048 ± 0.0001^{d}	417.600	<.001

Note: Concentrations are expressed as mg/L for water samples and mg/kg wet weight for sediment, gill, and liver tissues. Values are presented as mean ± SD. Different superscript letters within the same row indicate significant differences among sampling stations based on Tukey's HSD post hoc test ($p < 0.05$). Means sharing the same letter are not significantly different, while different letters indicate significant differences. Statistical assumptions of normality and homogeneity of variance were tested using Shapiro–Wilk and Levene's tests, respectively.

In water, Cd concentrations increased from 0.0085 ± 0.0004 mg/L at Station 1 to 0.0123 ± 0.0004 mg/L at Station 5, with Tukey HSD results showing significant differences between most stations (a, ab, b, c, d), indicating gradual and continuous spatial variation. This pattern indicates the accumulation of anthropogenic inputs along the river. In sediment, Cd concentrations increased from 0.0039 ± 0.0005 mg/kg to 0.0065 ± 0.0005 mg/kg. However, sediment Cd concentrations at all stations remained below the recommended sediment quality guideline value of 0.07 mg/kg (CCME, 1999). Tukey HSD results formed two main clusters (Station 1-Station 2 and Station 3-Station 5), indicating that sediment acts as the primary medium for heavy metal accumulation, particularly in downstream areas. This phenomenon aligns with the characteristics of fine sediment, which has a high adsorption capacity for heavy metals (Que *et al*., 2024). In fish tissue, Cd concentrations in the liver (0.0021-0.0035 mg/kg) showed a gradual bioaccumulation pattern with overlap between stations (a, ab, abc, bc, c), reflecting a progressive accumulation process with environmental exposure. Meanwhile, the gills showed the clearest pattern, with significant differences across all stations (a, a, b, c, d), indicating that the gills are the most sensitive organ to direct exposure to heavy metals in the water (Choudhary *et al*., 2023). Statistically, one way ANOVA results showed highly significant differences between stations across the entire matrix ($p < 0.05$ to $p < 0.001$), which was reinforced by Tukey HSD results, which confirmed the existence of intergroup differences or spatial gradients. Overall, this pattern indicates the transfer of Cd from the water column to the sediment, then continued bioaccumulation in fish tissue. Increased Cd concentrations at downstream stations were likely associated with anthropogenic activities surrounding the river, including domestic discharge, industrial effluents, agricultural runoff, and urban activities (Raj and Maiti, 2020).

Hematological responses of Oreochromis niloticus

The hematological profile of *Oreochromis niloticus* showed noticeable variations among sampling stations, indicating physiological responses associated with increasing heavy metal exposure along the Jagir River. Erythrocyte counts, hemoglobin levels, and hematocrit values gradually decreased from Station 1 to Station 5, whereas leukocyte counts, micronuclei frequency, monocyte percentage, eosinophil percentage, and neutrophil percentage generally increased toward downstream stations. Conversely, lymphocytes percentages showed a declining trend across stations. Based on Table 5, the hematology of *Oreochromis niloticus* exposed to heavy metal contamination in the Jagir River shows that all blood parameters show varying physiological and immunological responses between stations. Erythrocytes, hematocrit, and hemoglobin show a decreasing pattern from upstream to downstream stations, with significant differences in some compartments. The decrease in erythrocyte count, hemoglobin, and hematocrit values indicates the hematotoxic effects of Pb and Cd, which can disrupt erythropoiesis, induce hemolysis, and inhibit hemoglobin synthesis, ultimately reducing oxygen transport capacity in fish (Kadiene *et al*., 2020). Erythrocytes show a distinct clustering between Station 1 (the highest) and the lower stations, while hematocrit values show a significant difference at Station 1 compared to Stations 2 through 5, which are relatively homogeneous. Essentially, a low hematocrit level below 22% can indicate anemic fish, while a hematocrit value above 60% indicates stress. Anemia and stress conditions impact metabolic processes and fish growth, as decreased red blood cell levels can indicate insufficient nutrient supply to fish tissues and organs (Xu *et al*., 2021). Hemoglobin showed a stronger overlapping pattern, with most stations showing no significant differences, except for the most pronounced decrease at Station 5. The decrease in hemoglobin was accompanied by a decrease in red blood cell count. This decrease in red blood cells was associated with decreased oxygen demand (Yanuhar *et al*., 2018). Several of these parameters showed statistical significance ($p < 0.05$ to $p < 0.001$), indicating a spatial influence on fish physiological conditions. Similarly, the percentages of neutrophils, monocyte and leukocytes increased progressively downstream, reflecting an active immune response to environmental stress, where heavy metal exposure triggers an inflammatory reaction and stimulates innate immune defenses. Conversely, the percentage of lymphocytes decreased from 63% at Station 1 to 47% at Station 5, likely reflecting the immunosuppressive effects of prolonged heavy metal exposure (Wang et al., 2021). Genotoxically, micronuclei showed a gradual increase from upstream to downstream, forming two main clusters, with Station 5 having the highest values and distinct from the other stations. This pattern indicates increasing red blood cell deoxyribonucleic acid (DNA) damage with increasing environmental exposure. Micronuclei values remained within the normal range for tilapia, namely 8-23 cells/1,000 (Hertika *et al*., 2024). The higher the concentration of heavy metal pollutants, the higher the frequency of micronuclei formation. Micronuclei formation can be caused by exposure to heavy metals present in the water (Chaves *et al*., 2016). Overall, the Tukey HSD results indicate that physiological (erythrocytes, hematocrit, hemoglobin), immunological (lymphocytes, neutrophils, monocytes), and genotoxic (micronuclei) parameters form a graded biological response pattern from relatively stable conditions upstream to higher biological stress downstream. This indicates that the pollution gradient in the Jagir River has affected the overall hematological system of fish through the mechanisms of physiological stress, immune dysfunction, and increased cell damage.

Table 5: Hematological responses of *Oreochromis niloticus* exposed to heavy metal contamination in the Jagir River

Parameters	Unit	Quality standard	S1	S2	S3	S4	S5	F	P-value
Erythrocytes	x10^6 cells/mm^3	3.0–4.2 (Witeska *et al*., 2022)	2.06 ± 0.09^a	1.91* ± 0.05^{ab}	1.81 ± 0.06^{bc}	1.61 ± 0.05^c	1.56 ± 0.05^c	36.111	<0.001
Leukocytes	x10^3 cells/mm^3	15–150 (Martínez-Yáñez, 2026)	138.3 ± 2.1^a	147.1 ± 2.7^b	148 ± 0.4^b	156.3* ± 2.1^c	158.8* ± 2.9^c	40.471	<0.001
Hematocrit	%	20–45 (Martínez-Yáñez, 2026)	30.3 ± 1.52^a	24.7 ± 1.52^b	24 ± 2.64^b	22 ± 2^b	20.7* ± 1.52^b	11.481	<0.001
Hemoglobin	g/dL	7–12 (Martínez-Yáñez, 2026)	8.3 ± 0.61^a	7.93 ± 0.83^{ab}	7.17 ± 1.12^{ab}	6.83* ± 0.91^{ab}	6.1* ± 0.36^b	3.511	0.049
Micronuclei	cells/1000	8–23 (Hertika *et al*., 2024)	9.0 ± 0.55^a	9.3 ± 0.78^a	9.9 ± 1.36^a	10.4 ± 0.21^{ab}	12.6 ± 0.87^b	8.562	0.003
Monocytes	%	<5 (Purbomartono *et al*., 2024)	10.3* ± 1.53^a	11* ± 1^a	11.3* ± 0.58^a	12.6* ± 1.53^a	13.3* ± 0.58^a	3.605	0.46
Lymphocytes	%	60–85 (Martínez-Yáñez, 2026)	63* ± 1^a	59* ± 1^{ab}	53* ± 1^{bc}	49.6* ± 2.08^{cd}	47* ± 1^d	78.400	<0.001
Basophil	%	0–5 (Witeska *et al*., 2022)	2 ± 1^a	2.33 ± 0.58^a	2.33 ± 0.58^a	2.67 ± 0.58^a	3 ± 1.15^a	1.150	0.388
Eosinophil	%	0–5 (Martínez-Yáñez, 2026)	4 ± 1^a	4.3 ± 0.58^a	4.7 ± 1.15^a	5.3* ± 0.58^a	6* ± 1^a	2.417	0.118
Neutrophil	%	6–8 (Saomadia *et al*., 2024)	20.6* ± 1.53^a	23.3* ± 0.58^a	29* ± 1^b	31* ± 1^b	31.6* ± 1.53^b	51.024	<0.001

Note: * indicates values outside the optimal physiological range. Values are presented as mean ± standard deviation (SD) based on three sampling replicates per station (n = 3). Superscript letters indicate the results of Tukey's Honestly Significant Difference (HSD) post hoc test following one-way analysis of variance (ANOVA). Means with different superscript letters differ significantly among stations ($p < 0.05$), whereas means sharing the same letter are not significantly different. Prior to ANOVA, the assumptions of normality and homogeneity of variances were assessed.

Histopathological changes in the liver

Histopathological examination of liver tissues in *Oreochromis niloticus* revealed the occurrence of hepatocyte degeneration, necrosis, and hemorrhage at all sampling stations. The percentage of tissue damage generally increased toward downstream stations, suggesting progressive liver impairment associated with environmental contamination in the Jagir River, differences were found between stations ($p > 0.05$). The hemorrhage (Fig. 2A), ranged from 19.67 to 25.67%, with the highest value at Station 5, but ANOVA results showed no significant difference ($F = 1.564$; $p = 0.258$). Hemorrhagic spots appeared on the mucosal or serosal layers of the organ. If the hemorrhage was extensive, purpura would occur, and red blood cells would be visible outside the blood vessels (Shahid *et al*., 2022). A similar pattern was also found for necrosis (Fig. 2B), which ranged from 17–22.33% with slight fluctuations between stations and showed no statistically significant differences ($F = 1.161$; $p = 0.384$). Necrosis is usually caused by excessive fat accumulation in the liver, which results in liver cell death (Xie *et al*., 2026). Meanwhile, hepatocyte degeneration (Fig. 2C), which is a change in cell morphology due to intracellular metabolic disturbances that cause changes in cell structure (Jerald *et al*., 2024), showed an increasing trend from Station 1 to Station 5 (21.67–27%), but remained statistically insignificant ($F = 2.730$; $p = 0.090$), although approaching the significance level. In general, although all histopathological parameters were categorized as "moderate," there was a tendency for increasing levels of tissue damage towards downstream stations, particularly at Station 5. Based on Table 6, histopathological analysis of the liver of *Oreochromis niloticus* showed varying levels of tissue damage across all observation stations, although no statistically significant. This suggests higher environmental stress in the downstream region, potentially related to the accumulation of contaminants in the water. However, Tukey HSD results indicated that all stations were in the same homogeneous group, so

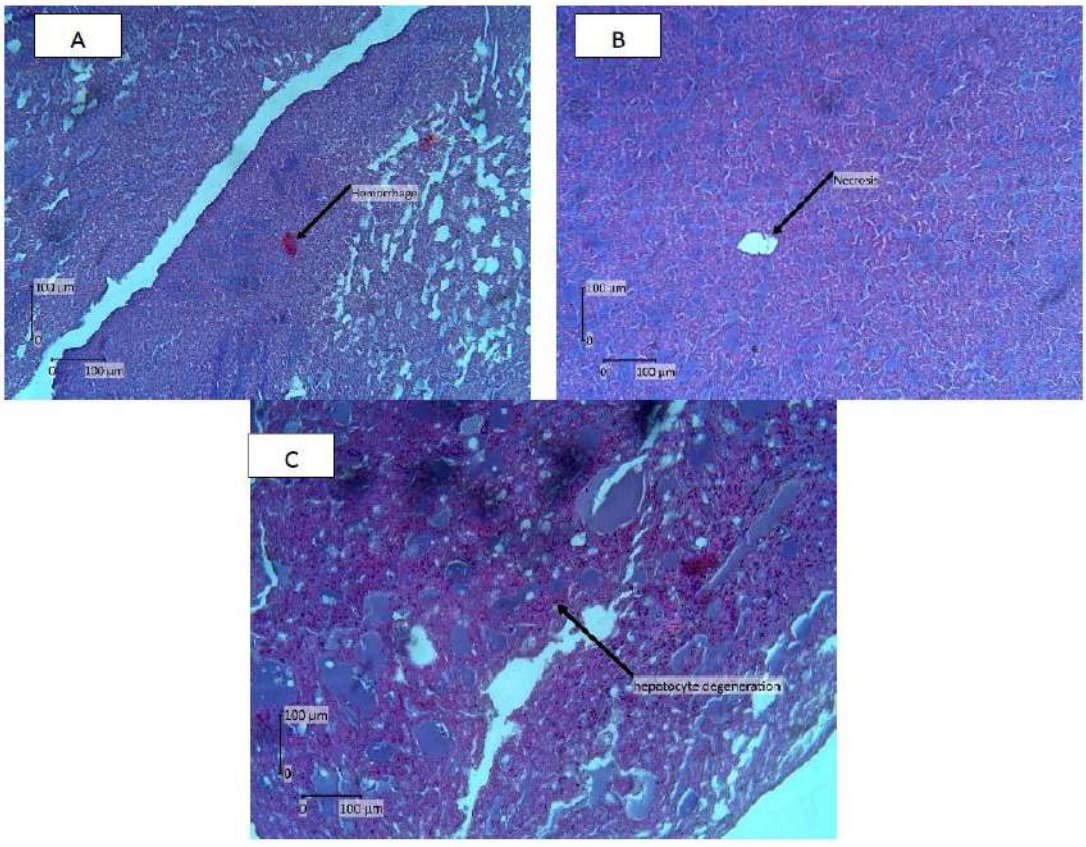

Fig. 2: Histopathological changes in the liver tissues of *Oreochromis niloticus* exposed to heavy metal contamination at different sampling stations in the Jagir River. (A) hemorrhage, (B) necrosis, and (C) hepatocyte degeneration observed in the gill tissues of *Oreochromis niloticus* (H and E staining; 1000× magnification)

Table 6: Histopathological alterations in liver tissues of *Oreochromis niloticus*

Type of damage	Unit	S1	S2	S3	S4	S5	Score	F	P-value	Category
Hemorrhage	%	21.33 ± 4.51 [a]	21.67 ± 3.51 [a]	19.67 ± 2.52 [a]	22.33 ± 2.31 [a]	25.67 ±1.53 [a]	2	1.564	0.258	Moderate
Necrosis	%	17 ± 4[a]	18.67 ± 2.52 [a]	17.67 ± 4.04 [a]	18 ± 3 [a]	22.33 ± 3.06 [a]	2	1.161	0.384	Moderate
Hepatocyte degeneration	%	21.67 ± 5.86 [a]	18.33 ± 2.52 [a]	22.67 ± 2.08 [a]	23 ± 2 [a]	27 ± 2 [a]	2	2.730	0.090	Moderate

Note: Data are presented as mean ± SD (n = 3 per station). Superscript letters indicate Tukey's HSD post hoc test following one-way ANOVA. Different letters indicate significant differences among stations ($p < 0.05$), whereas shared letters indicate no significant difference. Normality and homogeneity of variances were verified before ANOVA.

variations remained within a relatively uniform biological range. Therefore, the observed liver damage is more representative of a mild to moderate chronic stress response that has not reached statistically significant spatial differences among the sampling stations.

Histopathological changes in the gill

Histopathological analysis of gill tissue showed hyperplasia, lamella fusion, and edema in *Oreochromis niloticus* at all sampling stations. The percentage of tissue damage generally increased toward downstream stations, indicating

progressive gill damage associated with increasing environmental stress along the Jagir River. Based on Table 7, histopathological analysis of *Oreochromis niloticus* gills revealed varying structural tissue changes across observation stations. Lamellar hyperplasia (Fig. 3A) increased gradually from Station 1 to Station 5 (20.67-27.67%), with ANOVA results showing significant differences between stations ($F = 6.500$; $p = 0.008$). Tukey's HSD test further indicated that Station 1 was distinct from the other stations, while Stations 2 to 5 tended to overlap, indicating an increased adaptive response to downstream environmental stress. Lamellar fusion (Fig. 3B) also showed a more pronounced increase from Station 1 to Station 5 (18.33-28%), with a statistically significant difference ($F = 5.376$; $p = 0.014$). The observed lamellar hyperplasia and fusion represent protective and adaptive responses aimed at reducing direct contact between toxic substances and gill tissue. Hyperplasia is generally associated with lamellar fusion. This process, driven by lamellar cell proliferation, progressively fills the spaces between secondary lamellae with newly formed cells, leading to adhesion between adjacent secondary lamellae (El-Geneady *et al*., 2026). Gills are generally more sensitive due to their direct contact with the aquatic environment and their role in gas exchange and ion regulation, making them a primary site of direct contaminant exposure (Macirella and Brunelli, 2017). Tukey's HSD results showed that Station 1 had lower values than the other stations, indicating increasing structural damage to the gills downstream. In contrast, edema (Fig. 3C) showed a slight increase from Station 1 to Station 5 (23-26.33%), but this difference was not statistically significant ($F = 2.450$; $p = 0.114$), thus remaining within the relatively homogeneous biological variation between stations. Overall, although all parameters were categorized as "moderate" damage, the pattern of increasing lamellar hyperplasia and lamellar fusion suggests an adaptive and degenerative response in gill tissue to increasing environmental stress along the river gradient. However, these structural changes may impair respiratory efficiency by reducing the surface area available for gas exchange. Gill edema is characterized by tissue swelling due to the accumulation of intracellular fluid in the gill lamellae, which generally occurs due to epithelial damage and increased blood vessel permeability due to exposure to environmental stress or toxic substances (Abduljabbar *et al*., 2025). Histopathological changes in the form of edema indicate increased gill tissue permeability due to exposure to toxic substances, resulting in fluid infiltration in the gill lamellae (Carvalho *et al*., 2020). This suggests that exposure to downstream contaminants contributes to progressive histological changes in fish gills, although some parameters, such as edema, did not show statistically significant differences.

The integration of hematological and histopathological responses

The integration of hematological and histopathological responses provides a comprehensive understanding of the multi-level biological effects of heavy metal exposure in *Oreochromis niloticus*. Hematological changes, including decreased erythrocyte count, hemoglobin, and hematocrit levels along with increased frequencies of leukocytes, neutrophils, and micronuclei, reflect early systemic physiological disturbances induced by Pb and Cd exposure (Naz *et al*., 2021). These changes indicate decreased oxygen transport capacity, immune system activation, and genotoxic stress at the celullar level (Ahmed *et al*., 2022). In parallel, histopathological modifications observed in gill and liver tissues, such as lamellar hyperplasia, lamellar fusion, hemorrhage, and hepatocyte degeneration, represent structural manifestations of prolonged contaminant exposure at the organ level (Abdel-Moneim *et al*., 2012). Gills, as the primary interface with the aquatic environment, respond rapidly to waterborne pollutants (Patra *et al*., 2026), while the liver accumulates contaminants over time as a central detoxification

Table 7: Histopathological alterations in gill tissues of *Oreochromis niloticus*

Type of damage	Unit	S1	S2	S3	S4	S5	Score	F	P-value	Category
Hyperplasia lamella	%	20.67 ± 2.51^{a}	24.67 ± 1.15^{ab}	25.33 ± 2.51^{ab}	26.67 ± 1.52^{b}	27.67 ± 0.57^{b}	2	6.500	0.008	Moderate
Lamella fusion	%	18.33 ± 5.03^{a}	24 ± 2.65^{b}	25.67 ± 0.58^{b}	27.67 ± 3.06^{b}	28 ± 1^{b}	2	5.376	0.014	Moderate
Edema	%	23 ± 2^{a}	24 ± 2^{a}	24.33 ± 1.53^{a}	25.33 ± 1.53^{a}	26.33 ± 0.58^{a}	2	2.450	0.114	Moderate

Note: Data are presented as mean ± SD (n = 3 per station). Superscript letters indicate Tukey's HSD post hoc test following one-way ANOVA. Different letters indicate significant differences among stations ($p < 0.05$), whereas shared letters indicate no significant difference. Normality and homogeneity of variances were verified before ANOVA.

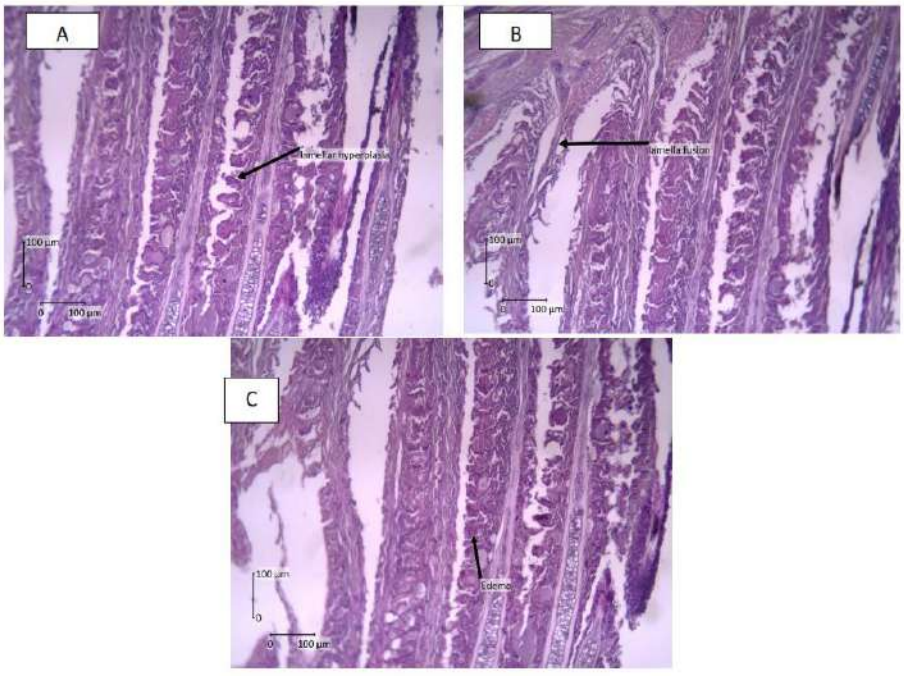

Fig. 3: Histopathological changes in the gill tissues of Oreochromis niloticus exposed to heavy metal contamination at different sampling stations in the Jagir River. (A) lamellar hyperplasia, (B) fusion of lamellae, and (C) edema observed in the gill tissues of Oreochromis niloticus (H and E staining; 1000× magnification).

organ, leading to cumulative tissue damage (Bawuro *et al.*, 2018). Together, these complementary biomarker responses demonstrate a consistent, dependent relationship between environmental contamination and biological effects, linking molecular and cellular perturbations with functional physiological disturbances and structural changes in tissues (Gusso-Choueri *et al.*, 2026). This integrated response framework strengthens the interpretation of ecological risk by linking systemic blood-based indicators with organ-level pathological evidence in fish exposed to contaminated river conditions (Javed *et al.*, 2017).

Water quality assessment

Based on Government Regulation of the Republic of Indonesia Number 22 of 2021, most water quality parameters measured in the Jagir River were still within the permissible limits for Class II waters intended for freshwater fisheries and aquatic biota. The water temperature at all stations ranged from 28.8-30.3 degrees Celsius (°C), slightly exceeding the standard range of

22-28°C (Government of Indonesia, 2021), indicating potential alterations in thermal conditions influenced by anthropogenic activities and local hydrological characteristics. Furthermore, heavy metals may remain toxic even at relatively low concentrations due to their persistence and bioavailability in aquatic systems (Zhang *et al*., 2023). Based on Table 8, TDS values ranged from 305.67 to 515.33 mg/L and remained below the maximum permissible limit of 1000 mg/L (Government of Indonesia, 2021), while TSS ranged from 26.33 to 41.67 mg/L and was also below the quality standard threshold. However, the relatively higher TDS and TSS values observed at several stations may indicate increased anthropogenic inputs and pollutant loads into the river system. Elevated TSS levels reflect a higher load of suspended particles in the water column, which can serve as carriers for heavy metals and various other pollutants. Consequently, elevated TSS levels are often associated with increased transport and distribution of heavy metals in aquatic environments (Jeong *et al*., 2020). DO concentrations ranged from 6.17 to 7.16 mg/L, which was still above the minimum quality standard of 4 mg/L (Government of Indonesia, 2021). DO is essential to the respiratory metabolism of most aquatic organisms and the ecological functioning of freshwater ecosystems. However, DO levels tend to decrease as the amount of organic waste in the waters increases. pH values range from 7.11 to 7.34, indicating neutral to slightly alkaline conditions that are still suitable for aquatic organisms (Qu *et al*., 2026). Changes in pH can disrupt biota life in waters due to an imbalance in carbon dioxide (CO_2) levels (Thomas *et al*., 2022). Overall, although the measured water quality parameters were within acceptable standards, spatial variations among stations indicate differing environmental pressures along the Jagir River. Regulatory compliance does not necessarily ensure ecological safety, as fish biological responses reflect cumulative exposure to multiple stressors and bioaccumulation, revealing ecological impacts not captured by conventional water quality assessments.

Principal component analysis

PCA is a linear combination of the initial variables, which geometrically represents a new coordinate system obtained from the rotation of the original system. The PCA method is very useful when the existing data has a large number of variables and there is correlation between the variables (Nasution, 2020). Based on Fig. 4, PCA based on a correlation matrix was applied to evaluate the relationship between heavy metal exposure and biological response biomarkers in fish. The analysis extracted four principal components, with the first two components explaining 67.54% of the total variance (PC1 = 39.46%; PC2 = 28.08%). PC1 represented the dominant ecological gradient in the dataset, characterized by a strong association between heavy metal concentrations (Pb and Cd in water, sediment, and liver) and histopathological alterations such as necrosis, edema, and lamellae hyperplasia. In contrast, hematological parameters including hemoglobin, hematocrit, and lymphocyte counts were positioned oppositely, indicating an inverse relationship with contamination and tissue damage. PC2 accounted for 28.08% of the variance and reflected secondary variability associated with physiological and immunological responses, particularly leukocyte-related parameters. This axis reflects biological variation beyond contaminant exposure. Overall, the PCA revealed a contamination-response gradient, with increasing heavy metal exposure associated with greater biological and histopathological impairment, while hematological changes indicate compensatory responses to environmental stress.

Multi-stressor effects on fish biological responses

The results of this study indicate that the biological responses of Oreochromis niloticus fish in the Jagir River, such as hematological,

Table 8: Summary of water quality parameters at the five sampling stations

Stations	Parameters	Unit	Mean	SD	Min.	Max.	Water Quality Standards	
							Government of Indonesia No.22/2021	USEPA (2022)
1	Total dissolved solids (TDS)	mg/L	382.67	61.19	312	418	1000	NA
2			305.67	177.20	116	467		
3			515.33	125.22	371	595		
4			511.67	263.97	334	815		
5			391.33	46.92	358	445		
1	Total suspended solids (TSS)	mg/L	34.67	17.61	24	55	70	NA
2			26.33	11.01	19	39		
3			41.67	7.50	34	49		
4			28.67	8.38	19	34		
5			34.33	13.31	23	49		
1	pH	-	7.22	0.29	7	7.56	6-9	6.5-9
2			7.15	0.27	7	7.47		
3			7.34	0.36	6.93	7.6		
4			7.11	0.11	7	7.23		
5			7.28	0.19	7.08	7.46		
1	Dissolved oxygen (DO)	mg/L	7.07	0.49	6.50	7.36	≤4	≤5
2			6.17	0.48	5.61	6.50		
3			6.55	0.60	5.85	6.90		
4			6.52	0.50	6	7		
5			7.16	0.30	6.82	7.40		
1	Temperature	°C	29.1	2.48	26.3	30.7	22-28	NA
2			28.8	2.23	26.3	30.5		
3			30.1	1.61	28.3	31.2		
4			29.5	0.3	29.2	29.8		
5			30.3	29.8	29.6	31.5		

Note: The Table Included mean, SD, minimum, maximum values, and their comparison with applicable water quality standards according to national (Government of Indonesia, 2021) No. 22 and international (USEPA, 2022). Not Available (NA) indicates that the parameter is not regulated in the respective standard

Immunological and histopathological changes, are related to exposure to heavy metals, particularly Pb and Cd, detected in the water, sediment, and fish tissue. Increased heavy metal concentrations at downstream stations were consistent with increases in several stress biomarkers, including micronuclei, changes in blood parameters, and gill and liver tissue damage. This indicates the influence of environmental stress on the physiological condition of fish along the river gradient. However, because this research was a field-based study, the observed biological responses cannot be attributed entirely to Pb and Cd exposure. Aquatic ecosystems are influenced by multiple environmental factors, including physicochemical conditions (temperature, pH, and dissolved oxygen), organic inputs, and domestic, agricultural, and industrial wastes. These factors can act as additional stressors affecting fish physiology and histology. Therefore, the findings are best interpreted as the combined effects of multiple environmental stressors, with heavy metals playing a significant, but not exclusive, role in shaping river ecosystem health. Nevertheless, the observed spatial trends provide valuable ecological evidence supporting integrated biomarker assessments as effective tools for monitoring cumulative environmental impacts and informing adaptive river management strategies.

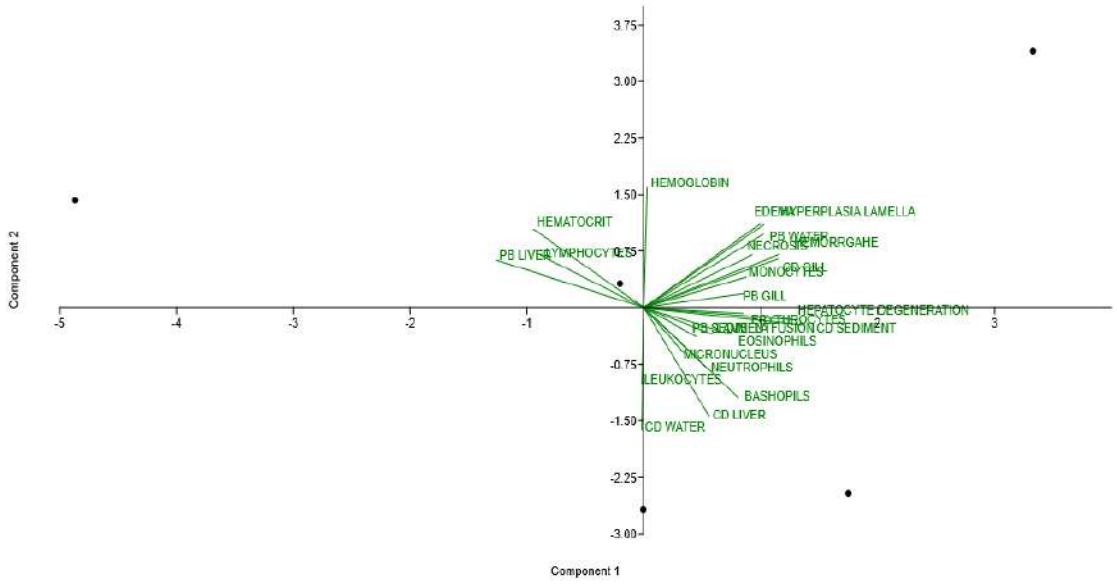

Fig. 4: PCA for heavy metals, hematologicals, and histopathologicals

CONCLUSION

The present study demonstrates that *Oreochromis niloticus* is a reliable bioindicator for assessing heavy metal contamination in freshwater ecosystems. The findings indicate that exposure to Pb and Cd is associated with progressive ecological stress along the Jagir River continuum, particularly in downstream areas, leading to integrated biological responses at physiological, immunological, and tissue levels. This study highlights that heavy metal contamination in riverine systems should be interpreted within a multi-stressor environmental framework, where biological effects are influenced not only by metal exposure but also by other environmental pressures typical of urbanized river systems. Therefore, reliance solely on water quality parameters may underestimate actual ecological risk. This study is limited by its field-based design, which does not allow full control over environmental variability and restricts causal attribution to a single pollutant source. In addition, fish age and gonadal maturity stage were not assessed, thereby limiting evaluation of their potential influence on biomarker responses and suggesting that these factors should be considered in future research. Despite these limitations, the results provide important ecological evidence of contaminant effects under natural conditions. Future monitoring programs should integrate biomarker-based approaches with routine physicochemical assessments to improve early detection of ecological risks, alongside strengthened pollution control strategies targeting anthropogenic discharges into the Jagir River. Long-term accumulation of Pb and Cd in aquatic food webs may pose ecological risks to fish populations and potential health risks to humans through trophic transfer. Overall, the conceptual framework linking heavy metal contamination, bioaccumulation, physiological stress, and histopathological alterations provides a comprehensive understanding of pollutant impacts on freshwater fish health.

AUTHOR CONTRIBUTIONS

L.A. Fitri, as the first author, designed the study, conducted field sampling, performed data analysis, and prepared the manuscript. U.

Yanuhar, as the corresponding author, supervised the research, contributed to the study design, coordinated the research activities, and critically revised the manuscript. M. Musa contributed to data interpretation and manuscript review. H. Suryanto supervised the laboratory work and statistical analyses and critically reviewed the manuscript. R. Ranjithkumar contributed to data interpretation, scientific discussion, and manuscript revision.

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CONFLICT OF INTEREST

The authors declare that no conflicts of interest exist in relation to the publication of this manuscript. Furthermore, all ethical standards relevant to scientific research and publication have been strictly adhered to, including those concerning plagiarism, informed consent, research misconduct, data fabrication or falsification, duplicate publication or submission, and redundancy.

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ABBREVIATIONS

%	Per cent
<	Less than
>	Greater than
±	3-component
°	Degree
°C	Degree Celcius
AAS	Atomic absorption spectrophotometer
AI	Artificial intelligence
ANOVA	Analysis of variance
APHA	American Public Health Association
Cd	Cadmium
Cm	Centimeters
Cells/mm^3	Cells per cubic milimeter
CO_2	Carbon dioxide
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
EDTA	Ethylenediaminetetraacetic acid
Fig.	Figure
g	Gram
g/Dl	Gram per deciliter

H and E	Hematoxylin and Eosin
H_2O_2	Hydrogen peroxide
HCl	Hydrochloric acid
HNO_3	Nitric acid
Km	kilometres
MDL	Method detection limits
mL	Milliliter
mg/kg	Milligrams per Kilogram
mg/L	Milligrams per liter
NA	Not Available
PAST	Paleontological statistics
Pb	Lead
PCA	Principal component analysis
pH	Potential of hydrogen
ppm	Part per million
rpm	Revolutions per minute
SPSS	Statistical package for the social sciences
TDS	Total dissolved solids
TSS	Total suspended solids
USA	Uniter States of America
USEPA	United States Environmental Protection Agency

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ORIGINAL RESEARCH ARTICLE

Effectiveness of *Pennisetum purpureum* and *Panicum maximum* planted drying beds for fecal sludge treatment at variable loading rates

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable fecal sludge treatment poses challenges in low-resource tropical regions due to urbanization and inadequate sanitation. Planted drying beds represent a viable technology; however, their treatment performance is governed by an interplay between specific vegetation typologies and hydraulic loading dynamics. The study objectives were to assess the treatment effectiveness of two grasses, *Pennisetum purpureum* and *Panicum maximum*, at varying hydraulic loading rates of 42.9, 64.3, and 85.7 liters per day, benchmarked against unplanted beds as controls.

METHODS: The experimental setup involved fifteen pilot-scale rectangular cement-brick drying beds organized into three treatment units. Each unit contained two beds with *Pennisetum purpureum*, two with *Panicum maximum*, and one control bed. Each bed measured 1.75 × 1.25 × 1.0 meters with a 1 percent slope for drainage. To evaluate system performance over a four-month monitoring period, treatment efficacy was systematically quantified by monitoring the removal efficiencies of key water quality parameters, including Total Kjeldahl Nitrogen, ammonium, nitrite, nitrate, total phosphorus, phosphate, total suspended solids, biochemical oxygen demand, and chemical oxygen demand. Microbiological analyses monitored total coliforms, *Escherichia coli*, *Shigella*, and *Salmonella*, with assessments of eutrophication potential to evaluate the environmental impact of the effluents.

FINDINGS: Planted drying beds consistently achieved higher removal efficiencies than unplanted controls across all studied parameters. Among the vegetated systems, *Pennisetum purpureum* achieved the highest treatment efficiencies, particularly at the lowest hydraulic loading rate (42.9 liters per day). Maximum removal efficiencies reached 89.3 percent for Total Kjeldahl Nitrogen, 87.1 percent for ammonium, 90.0 percent for total suspended solids, 95.0 percent for biochemical oxygen demand, 92.0 percent for chemical oxygen demand, 89.1 percent for total phosphorus, and 89.9 percent for phosphate. Pathogen reductions ranged from 92 percent to 94 percent, while eutrophication potential decreased by 87.3 percent. An inverse relationship was observed between hydraulic loading rates and treatment efficacy; furthermore, the unplanted control beds exhibited the highest vulnerability to these increased loads, demonstrating a substantial drop in operational performance.

CONCLUSION: *Pennisetum purpureum*-vegetated planted drying beds are a viable and cost-effective method for treating fecal sludge in tropical settings, operating at a hydraulic loading rate of 42.9 liters per day. To fully validate operational stability, scalability, and field applicability under fluctuating environmental conditions, executing extended, larger-scale investigations remains imperative.

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NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
58	9	6

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INTRODUCTION

Fecal sludge (FS) management poses a significant challenge to sanitation systems in developing countries, especially in sub-Saharan Africa. The lack of robust infrastructure dedicated to the management, treatment, and final disposal of FS continues to compound sanitation vulnerabilities across these areas. The growing reliance on on-site sanitation systems, such as septic tanks and pit latrines, has resulted in the accumulation of substantial amounts of FS, which is characterized by high organic matter content, nutrients, and pathogenic microorganisms. In the absence of adequate treatment and management strategies, untreated FS is frequently released directly into the ecosystem, causing severe soil and aquatic pollution (Muoghalu *et al.,* 2023 ; Lamore *et al.,* 2026). Consequently, such practices pose significant risks to public health by increasing the likelihood of waterborne disease transmission, highlighting the urgent need for improved FS management strategies to mitigate these health concerns (Gitonga *et al.,* 2021; Taweesan *et al.,* 2026). Several technologies have been developed for FS treatment, including sedimentation-thickening ponds, unplanted drying beds (NPBs) and composting systems. However, the widespread deployment of these technologies is frequently impeded by elevated operational expenditures, high energy consumption, or significant footprint requirements, ultimately restricting their viability in resource-constrained environments. Among nature-based treatment technologies, planted drying beds (PDBs) have emerged as a promising and sustainable alternative because of their low operating costs, operational simplicity, and adaptability to tropical climatic conditions (Singh *et al.,* 2017; Lamore *et al.,* 2026). The treatment performance of PDBs is governed by a combination of physical, biological, and hydraulic processes, including drainage, filtration, organic matter mineralization, evapotranspiration, and rhizospheric activity associated with macrophytes. These mechanisms facilitate pollutant removal via distinct physical and biochemical pathways: solids retention and filtration, microbial degradation of organic matter, and plant-mediated nutrient uptake. Additionally, nutrients are adsorbed and transformed within the substrate, while pathogens are systematically reduced through sedimentation, predation, natural die-off, and exposure to adverse environmental conditions. The interaction of these processes enables PDBs to effectively reduce nutrient loads, organic pollutants, and pathogen concentrations in FS treatment systems (Stefanakis *et al.,* 2014). Previous studies have demonstrated that PDBs can achieve substantial removal efficiencies for suspended solids, organic matter, nutrients, and pathogenic microorganisms from FS. Beyond pollutant removal, PDBs play a critical role in FS management by enhancing sludge dewatering, solids accumulation, stabilization, and mineralization. Prior Studies indicate that evapotranspiration serves as the primary driver of water loss in PDBs, dictating roughly 58 to 84 percent (%) of total water removal. In contrast, drainage accounts for 13% to 41%, leaving merely a minor fraction retained within the sludge layer (Stefanakis and Tsihrintzis, 2011). As dewatering progresses, the accumulated sludge undergoes stabilization and pathogen reduction within the biologically active rhizosphere, ultimately producing biosolids suitable for soil improvement and nutrient recycling (Osei *et al.,* 2019). The performance of PDBs is strongly influenced by operational conditions, particularly hydraulic loading rate (HLR), filter media characteristics, and plant species selection (Goussanou *et al.,* 2023). Globally, the common reed (*Phragmites* sp.) represents the most prevalent macrophyte utilized for sewage sludge treatment in PDBs, particularly across Europe, Asia, and the Americas. Nevertheless, its application is complicated by its classification as an invasive species in many regions (Farouk *et al.,* 2023). Despite the increasing use of PDBs for FS treatment, limited

information exists on how tropical grass species and HLR jointly influence filtrate quality, nutrient and pathogen removal, and eutrophication mitigation. This knowledge gap is particularly important because the sustainability of PDBs depends not only on effective sludge dewatering and stabilization but also on the environmental quality of the treated effluent. Consequently, a deeper insight into plant species efficacy and the optimization of loading rates is essential to facilitate the evidence-based design and operation of FS treatment systems under tropical climates. In the African context, Goussanou *et al.* (2023) identified *Echinochloa pyramidalis* as the most widely used plant species in PDB processes, alongside notably *Typha domingensis*, *Cyperus alopecuroides*, and *Bambusa vulgaris*. However, studies investigating various Poaceae species for wastewater treatment in wetlands, including PDBs, have shown that *Echinochloa pyramidalis, Pennisetum purpureum* as reported by Zahui *et al.* (2021), and *Panicum maximum* as reported by Ouattara *et al.* (2011) exhibit comparable treatment performance. Consequently, the proven efficacy of these macrophytes in constructed wetlands indicates they could yield comparable—or potentially superior—treatment efficiencies when deployed in FS planted drying beds. *P. maximum* and *P. purpureum* are indeed widespread across all tropical geographic regions, characterized by high biomass productivity, extensive root systems, and strong tolerance to wetlands environmental conditions. These species exhibit vigorous growth and dense root development (APG IV, 2016) which can enhance substrate aeration, improve hydraulic conductivity, and stimulate microbial activity within the rhizosphere. Thus, their integration holds significant potential to optimize FS dewatering rates and elevate overall pollutant removal efficiencies within PDBs. Nonetheless, the treatment potential of these widely available, tropical grasses remains largely unexplored in FS PDBs systems. Although both species have demonstrated viable treatment efficiencies in constructed wetlands, translating their performance metrics to FS PDBs is constrained by significant system variations. Specifically, the configurations differ substantially across sludge matrix properties, hydraulic behavior, dewatering pathways, and localized plant–substrate interactions. Furthermore, previous studies have rarely investigated the combined effects of plant species selection and HLR on the simultaneous removal of organic matter, nutrients, pathogens, and eutrophication-causing pollutants in FS treatment systems. Consequently, there remains insufficient evidence to guide the selection of appropriate vegetation and loading regimes for optimizing planted drying bed performance under tropical conditions. The lack of comprehensive knowledge in this area impedes the establishment of definitive design criteria and operational protocols required for sustainable FS management across sub-Saharan Africa. To address these gaps, the present study provides a comparative evaluation of *P. purpureum and P. maximum* in pilot-scale PDBs operated under varying HLRs and benchmarked against NPBs controls for the treatment of FS under tropical climatic conditions. In addition to evaluating standard physicochemical and microbiological treatment efficiencies, this study incorporates the mitigation of eutrophication as a primary metric of environmental performance. By simultaneously examining the influence of plant species selection, HLRs, and environmental impacts, the study advances current knowledge and provides a basis for optimizing PDBs for sustainable FS treatment under tropical conditions and long-term operational efficiency improvement. This study evaluated the treatment performance of planted drying beds vegetated with *P. purpureum* and *P. maximum* for the treatment of FS under tropical climatic conditions. It emphasized the influence of hydraulic loading rate on the hydraulic behavior of the system and its efficiency in pollutant removal. This study was conducted at the Research Station of the University of Man, located in western Côte d'Ivoire in 2025.

MATERIALS AND METHODS

Study area

The experimental trial was conducted at the research station of the University of Man in western Côte d'Ivoire located at 7.35052° north (N) and 7.62594° west (W), at an altitude of 353 meters (m) above sea level (Fig. 1). The study area is characterized by a humid tropical climate, with mean annual rainfall ranging between 1300 and 1500 millimeters (mm) and average annual temperatures varying from 25 to 30 degrees Celsius (°C). Characterized by a bimodal precipitation pattern, the region undergoes two distinct wet periods (March–June and September–November) interspersed with two dry seasons. This seasonal variability exerts a profound influence on local ambient temperature and evapotranspiration dynamics, while the mean relative humidity consistently surpasses 75% annually (Coulibaly *et al.,* 2025).

Experimental design

Configuration of treatment beds

The experimental setup consisted of fifteen rectangular cement-brick beds, the FS feeding system comprising intermediate bulk containers (IBC) and polyvinyl chloride (PVC) pipes, and a filtrate collection system. The experimental configuration comprised three distinct treatment units, each configured with five independently fed beds (Fig. 2). Every individual unit was composed of:

- Two PDBs with *P. purpureum* (including one replicate);
- Two PDBs with *P. maximum* (including one replicate);
- One NPBs serves as the control.

The internal dimensions of each bed were 1.75 m (length) × 1.25 m (width) × 1.00 m (height). The bottom had a 1% slope toward a PVC outlet pipe (Ø 40 mm), allowing gravity drainage of the treated effluent.

Filter bed

The filter bed consisted of three superimposed layers of washed gravel (Fig. 3), separated from bottom to top by geotextiles:

- 0.10 m of coarse gravel (20/25 mm),
- 0.20 m of intermediate gravel (5/15 mm),
- 0.50 m of fine gravel (4/6 mm).

Perforated vertical PVC pipes (Ø40 mm) were installed at the corners of the beds to promote passive ventilation. A supplemental horizontal aeration system was integrated into the drainage layer to enhance oxygen mass transfer and mitigate the development of strictly anaerobic conditions.

Vegetation establishment

Two perennial tropical grasses, *P. purpureum* and *P. maximum*, were used for revegetating the drying beds due to their high biomass production, dense root systems, and adaptation to tropical conditions (APG IV, 2016). Within the rhizosphere, filter bed stability, percolation capacity, and nutrient assimilation are significantly augmented by these species (Ouattara *et al.,* 2011; Zahui *et al.,* 2021). The beds were planted at a density of 4 plants/m², with a spacing of 40 × 40 cm.

HLR and operating conditions

Applied hydraulic load and operating conditions

The drying beds were fed with raw FS at three hydraulic loading regimes: 100, 150, and 200 L, corresponding to flow rates of 42.9, 64.3, and 85.7 L/d and HLRs of 13.7, 20.6, and 27.4 mm/d, respectively. To guarantee an uninterrupted supply throughout the experimental period, the fecal sludge (FS) utilized in this study was procured from the municipal sewage collection service in Man via a formal contractual agreement. At the research site, cubitainers were filled with the collected FS and subsequently used to feed the drying beds, with loading operations conducted three times per week.

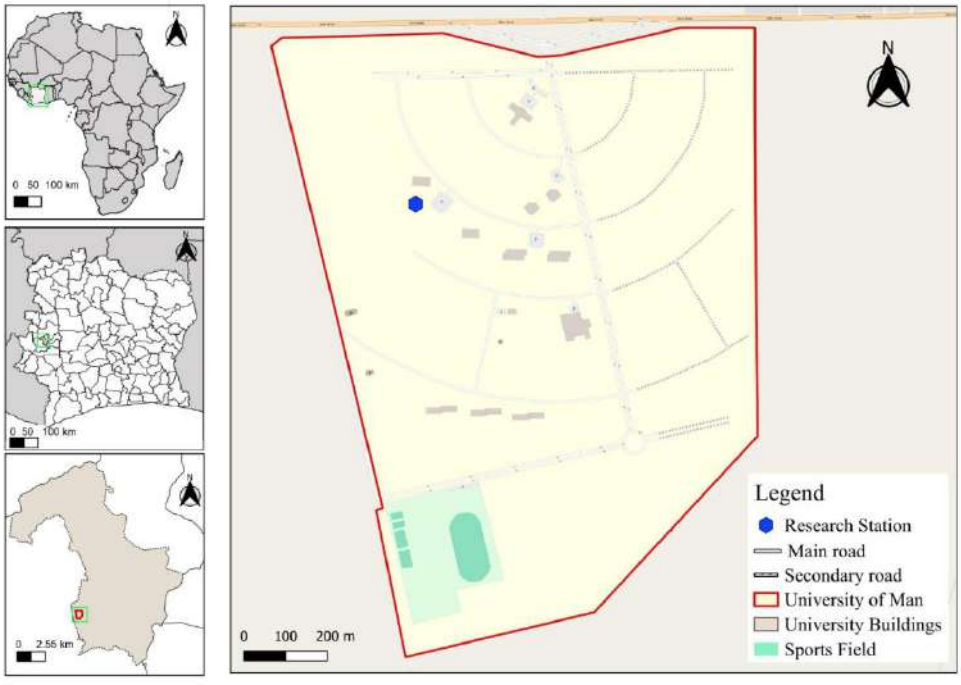

Fig. 1: Geographical location of the study area in the research station of the University of Man in western Côte d'Ivoire



Fig. 2: Schematic layout of FS experimental setup



Fig. 3: Materials used in the beds: A = gravel with a diameter of 20/25 mm, B = gravel with a diameter of 5/15 mm and C= gravel with a diameter of 4/6 mm

This approach reflects the sanitation context of the city of Man, which, like many cities in developing countries, relies predominantly on on-site sanitation systems that require frequent desludging and FS collection. Consequently, the collected FS exhibits high heterogeneity in both its physicochemical characteristics and retention age, which spans from several weeks to upwards of ten years (Mwamlima *et al.,* 2025). The FS loading volumes applied in this study were based on the methodology proposed by Zahui *et al.* (2021). However, the initial FS volume of 100 L, corresponding to the pore saturation volume of the filter bed, was increased by 50% and 100% to establish higher loading conditions. Consequently, the drying beds were loaded with fecal FS volumes of 100, 150, and 200 L to evaluate the treatment variations. Based on the bed surface area and a feeding frequency of three times per week, these loading volumes corresponded to HLRs of 13.7, 20.6, and 27.4 millimeters per day (mm/d), respectively. The compositions of experimental treatments are presented in Table 1. Sludge application onto the drying beds was conducted intermittently at a frequency of three times per week, utilizing a gravity-fed distribution network supplied by elevated storage tanks. Prior to FS feeding, a one-month acclimatization phase was carried out using tap water irrigation to allow for root system establishment. The experiment was conducted over two consecutive vegetative growth cycles, each lasting two months, from January to April 2025, corresponding to the dry season in the Man region (Coulibaly *et al.,* 2025). This specific timeframe was chosen to mitigate potential precipitation-induced dilution of the (FS during household collection and onsite treatment, thereby maintaining uniform FS characteristics across the study duration.

Sampling and analysis of physicochemical and microbiological parameters

Raw FS and filtrate samples were collected every two weeks at the inlet (influent) and outlet (effluent) of each drying bed and stored in polyethylene bottles at 4 °C prior to analysis. Over the course of the study, a total of eight discrete sampling campaigns were executed. During each sampling campaign, influent and effluent samples were systematically collected from both the inlet and outlet zones of all 15 drying beds. Consequently, 120 filtrate samples (15 beds × 8 outlet samples) and 8 influent FS samples were collected and analyzed, resulting in a total of 128 samples. Physicochemical parameters, including potential of hydrogen (pH), dissolved oxygen (DO), and turbidity, were measured in situ using a multi-parameter HI 9829 probe. Total suspended solids (TSS), chemical oxygen demand (COD), and five-day biochemical oxygen demand (BOD_5) were

Table 1: Treatment composition of the experimental unites

Treatment category	Treatment code	HLR/ Description
	PBPP 42.9	Feed 42.9 liters per day (L/d)
Planted beds of *P. purpureum*: PBPP	PBPP 64.3	Feed 64.3 L/d
	PBPP 85.7	Feed 85.7 L/d
	PBPM 42.9	Feed 42.9 L/d
Planted beds of *P. maximum*: PBPM	PBPM 64.3	Feed 64.3 L/d
	PBPM 85.7	Feed 85.7 L/d
	NPB 42.9	Feed 42.9 L/d
No planted bed: NPB	NPB 64.3	Feed 64.3 L/d
	NPB 85.7	Feed 85.7 L/d

analyzed according to ISO 11923 (1997), ISO 6060-2 (1989), and ISO 5815-1 (2019)**,** respectively. Nitrogenous compounds, namely total Kjeldahl nitrogen (TKN), ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-), were determined following ISO 5663 (1984), ISO 7150-1 (1984), ISO 6777 (1984), and ISO 7890-3 (1988), respectively. Total phosphorus (TP) and orthophosphate (PO_4^{3-}) concentrations were quantified in accordance with ISO 6878-2 (2004). Microbiological analyses, including total coliforms, Escherichia coli, Shigella, and Salmonella, were performed according to ISO 9308-1 (2014), ISO 21567 (2004), and ISO 6579-1 (2017), respectively. Pollutant removal efficiencies were determined quantitatively based on the concentration differentials between the influent and effluent of each system, using Eq 1 (Abissy and Mandi, 1999):

$$\text{Removal Efficiency } (\%) = \frac{\text{Influent Load } (\text{mg}) - \text{Effluent Load } (\text{mg})}{\text{Influent Load } (\text{mg})} \text{ x } 100 \quad (1)$$

Where:
Influent load = Concentration (mg/L) × Volume of raw wastewater (L)
Effluent load = Concentration in milligram per liter (mg/L) × Volume of treated water (L)

Plant growth response assessment

Plant growth responses were assessed by quantifying aboveground biomass production over a two-month growth period and measuring stump diameter, following the methodology of (Zahui *et al.,* 2021). Over the course of the experimental trial, two discrete harvesting events were executed, following which stump diameters were quantified to the nearest mm. Fresh aboveground biomass was determined using a precision balance (SARTORIUS EB 150 FEG-I) with an accuracy of 5×10^{-3} kilograms (kg). To achieve spatial representativeness and experimental consistency, plant stump diameters were systematically measured at the peripheral corners and the central axis of each reactor. Aboveground biomass yield was expressed in kilograms per square meter (kg/m²) and calculated using Eq. 2 (Zahui *et al.,* 2021):

$$\text{Aboveground biomass } (\text{Kg/m}^2) = \frac{\text{AB}}{\text{S}} \quad (2)$$

Where:
AB = Aboveground mass (m)
S = Area of the dry bed (m^2)

Determination of the eutrophication impact (EI) of drying beds

The eutrophication index was calculated for both influent and effluent streams to assess the environmental impacts of raw FS and filtrates. This assessment adhered to the protocol developed by Heijungs *et al.* (1992) and subsequently adapted by Marín-Muñiz *et al.* (2024) and Traoré *et al.* (2025). The eutrophication index was calculated

based on the eutrophication potentials (EPs) of various substances including PO_4^{3-}, TP, TKN, NH_4^+, NO_3^-, NO_2^-, and COD. These potentials are expressed in terms of PO_4^{3-} equivalents, using Eq. 3 (Heijungs *et al.,* 1992; Traoré *et al.,* 2025) The corresponding conversion coefficients expressed in PO_4^{3-} equivalents are presented in Table 2.

$$Eutrophication = \sum PE_i \times m_i \quad (3)$$

Where:
Eutrophication: expressed in kg PO_4^{3-} equivalents
PE_i: Eutrophication potential of substance i (kg PO_4^{3-} eq.)
m_i: Mass of substance i emitted into the water (kg).

The rate of reduction in eutrophication of the drying beds was determined, using Eq. 4 (Heijungs *et al.,* 1992; Traoré *et al.,* 2025):

$$\text{Reduction Efficiency (\%)} = \frac{\text{Eutrophi E (kg éq } PO_4^{3-}) - \text{Eutrophi S (kg éq } PO_4^{3-})}{\text{Eutrophi E (kg éq } PO_4^{3-})} \text{ x } 100 \quad (4)$$

Where:
Eutrophi E = Eutrophication at the reactor inlet (in kg equivalent PO_4^{3-});
Eutrophi S = Eutrophication at the outlet of the reactors (in kg equivalent PO_4^{3-}).

Data analysis

Univariate analyses

Statistical analyses were conducted after verifying data normality using the Shapiro–Wilk test. Eight measurements were obtained from the influent FS and eight from the outlet of each treatment under the different HLRs. Prior to statistical analysis, data derived from the duplicate treatment beds for both *P. maximum* and *P. purpureum* were pooled and averaged. Statistical evaluations were executed using either parametric or non-parametric methods based on data distribution characteristics; specifically one-way analysis of variance (ANOVA), Student's t-test, Kruskal–Walli's test, and Mann–Whitney U test, were applied as appropriate. All statistical analyses were performed using R software version 4.3.0, with statistical significance established at $p < 0.05$.

Hierarchical classification of drying bed performance

The treatment performance of the drying beds was assessed using physicochemical and microbiological parameters grouped into four categories of pollutants: organic matter, nitrogen compounds, phosphorus compounds, and pathogenic microorganisms. To discern operational similarities and performance trends across the treatment units, an agglomerative hierarchical cluster analysis was executed. This evaluation utilized Euclidean distance metrics and Ward's linkage method in accordance with the approach described by Randriamihamison *et al.* (2021), Yu *et al.* (2020), and Cabezas *et al.* (2023) (Fig. 4), thereby enabling robust classification of treatment units based on performance.

Principal component analysis (PCA)

PCA was conducted to discriminate among the reactors based on the removal efficiencies of physicochemical and microbiological parameters, as well as eutrophication reduction rates. Utilizing this multivariate framework enabled the elucidation of complex correlations among the evaluated parameters and underscored distinct variations in efficiency across the treatment systems. Interpretation of the PCA results was based on eigenvalues, the correlation circle, and the factor map of the reactors, facilitating assessment of parameter interactions and treatment performance differentiation. All statistical analyses and graphical representations were performed using RStudio (R version 4.3.0).

Table 2: PO_4^{3-} equivalence coefficients of substances in terms of EP (Heijungs *et al.,* 1992)

Parameter	EP (kg/PO_4^{3-} Eq./kg)
PO_4^{3-}	1.00
TP	3.00
TKN	0.42
NH_4^+	0.35
NO_3^-	0.10
NO_2^-	0.10
COD	0.02

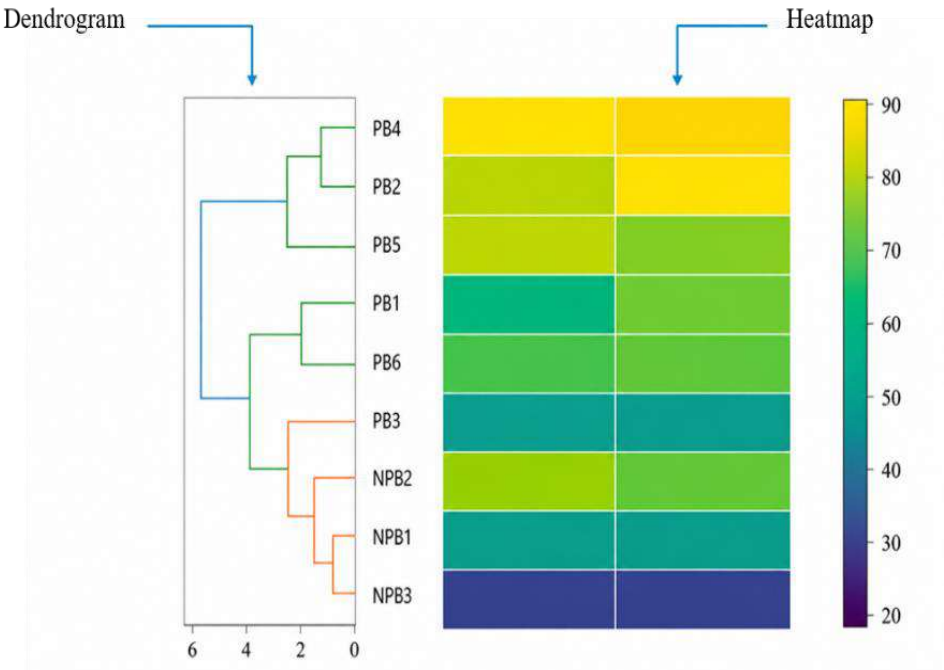

Fig. 4: Graph of the integrated approach, combining the classification structure from the dendrogram and the yield distribution observed on the heatmap

RESULTS AND DISCUSSION

Plant growth response

The aboveground biomass and stump diameters of plants in the drying beds at the end of the growth cycles are presented in Fig. 5 and Fig. 6. *P. purpureum* consistently outperformed *P. maximum* in biomass production across all HLRs. Biomass yields for *P. purpureum* ranged from 13.3 ± 0.6 to 19.1 ± 1.5 kg/m², compared with 8.8 ± 0.7 to 16.7 ± 1.0 kg/m² for *P. maximum* (Fig. 5). The pronounced tillering capacity and robust nutrient assimilation of this species presumably driven its accelerated growth within sludge-amended substrates. Despite differences in productivity, both species showed good regeneration after each harvest, indicating strong adaptability to FS PDB conditions. Collectively, the biomass outcomes validate the robustness and elevated yield potential of these grass species within FS treatment facilities, aligning with the observations documented by Ouattara *et al.* (2011) and Zahui *al.* (2021). This growth pattern was also reflected in an increase in clump diameter between the two cutting periods (Fig. 6). Mean diameters of *P. purpureum* (15.1 ± 2.2 to 23.3 ± 6.9 cm) remained higher than those of *P. maximum* (11.7 ± 2.5 to 20.3 ± 6.6 cm), indicating greater vegetative development in the former species (APG IV, 2016). The correlation noted between biomass production and clump diameter implies that these

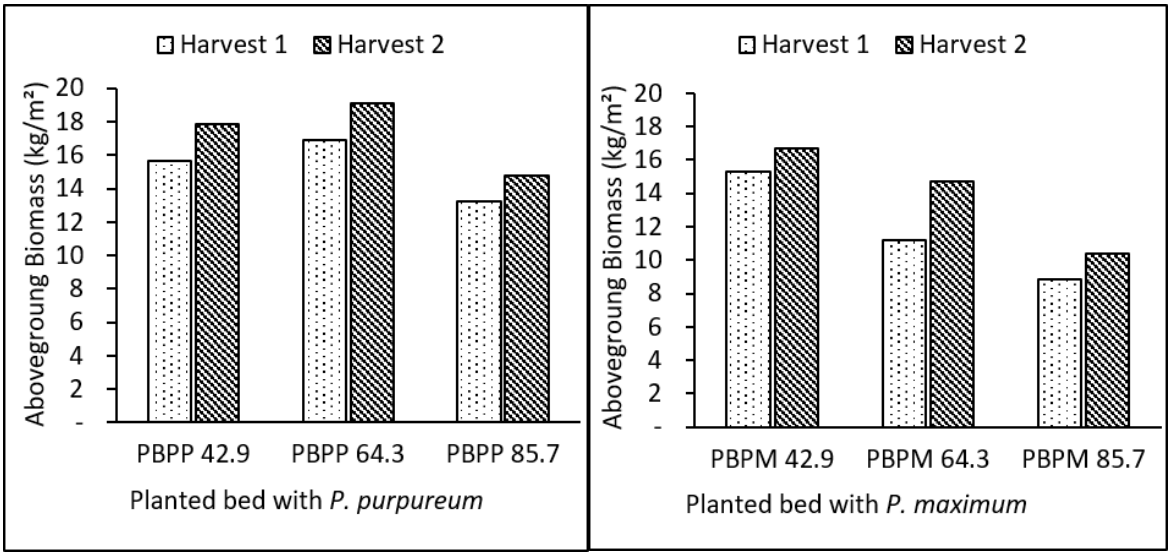

Fig. 5: aboveground biomass yields of two plant species, *P. purpureum* and *P. maximum*, across two harvesting periods; PBPP42.9, PBPP64.3 and PBPP85.7: beds planted with *P. purpureum*, fed with 42.9, 64.3 and 85.7 L/d respectively; PBPM42.9, PBPM64.3 and PBPM85.7: beds planted with *P. maximum*, fed with 42.9, 64.3 and 85.7 L/d respectively

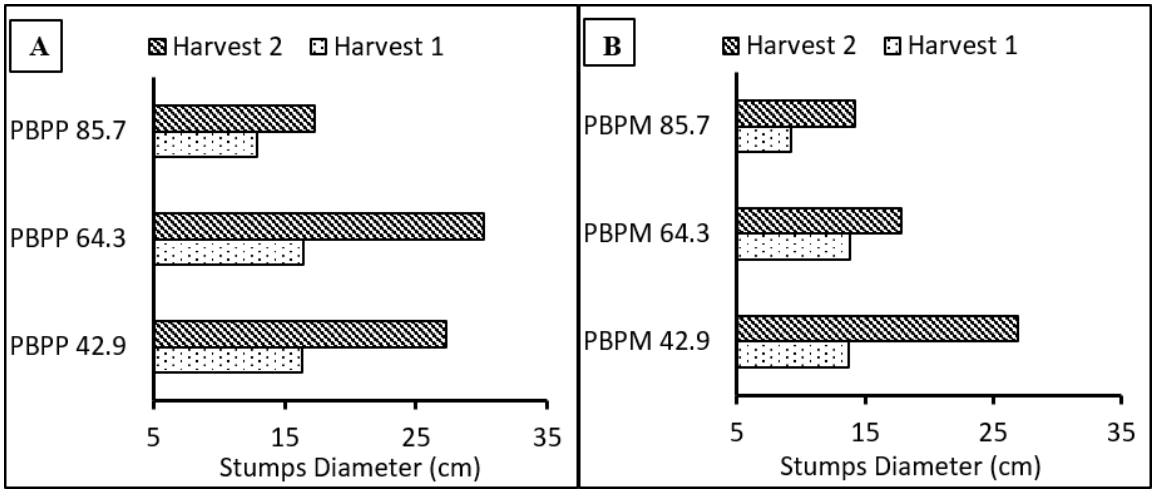

Fig 6: Diameters of stumps from plants measured during two harvesting periods across various drying beds; PBPP42.9, PBPP64.3 and PBPP85.7: beds planted with *P. purpureum*, fed with 42.9, 64.3 and 85.7 L/d respectively; PBPM42.9, PBPM64.3 and PBPM85.7: beds planted with *P. maximum*, fed with 42.9, 64.3 and 85.7 L/d respectively

two metrics functions as mutually reinforcing indicators of plant vigor in PDBs. However, the two species responded differently to HLRs. *P. purpureum* achieved optimal performance at the intermediate HLR (64.3 L/d), in terms of both biomass production and clump diameter. In contrast, *P. maximum* performed best under the lowest HLR (42.9 L/d), with growth progressively declining as the HLR. These outcomes indicate that the ecophysiological responses to substrate moisture conditions are highly species-specific. While *P. purpureum* benefits from increased water and nutrient inputs up to an intermediate threshold, *P. maximum* appears more sensitive to

elevated moisture conditions, where higher applied volumes may induce hydraulic stress and reduce growth performance. Generally, the results indicate that excessive hydraulic loading can suppress or negatively impact vegetative growth and development. The lowest biomass production and clump diameter values were recorded at the highest HLR (85.7 L/d) for both species. This decline is likely associated with reduced substrate aeration and limited oxygen transfer within the rhizosphere under highly saturated conditions. Consistent with these findings, prior studies on vegetated treatment systems indicate that excessive moisture can restrict root aeration and activity, ultimately hindering macrophyte growth performance (Kengne *et al.,* 2014). Higher biomass production is generally associated with greater root surface area, which enhances nutrient uptake and stimulates microbial activity in the rhizosphere (Wankhade *et al.,* 2025). In addition to its primary function in sludge treatment, the harvested biomass also represents a valuable secondary raw material with viable pathways for animal feed formulation, composting, and bioenergy generation. Taken together, these findings underscore the multifaceted advantages of introducing select macrophyte species into PDBs to concurrently optimize pollutant removal efficiency, bolster system stability, and promote the valorizations of generated by-products (Zahui *et al.,* 2021; Traoré *et al.,* 2025).

Removal of particulate and organic compounds in drying beds

Table 3 presents the concentrations and removal efficiencies of the different physicochemical quality parameters in the raw FS and filtrates of the drying beds under varying operational treatment conditions. The raw FS had average concentration of 1864.42±134.06 mg/L for TSS, 2374.53±118.36 NTU for turbidity, 1800.78±89.49 milligrams oxygen per liter (mg O_2/L) for COD, and 1001.5±104.51 mg O_2/L for BOD_5. The minimal variation observed in organic compound concentrations within the treated FS can likely be attributed to dry-season sampling, which effectively precluded any precipitation-driven dilution effects (Worku *et al.,* 2026). This highlights the importance of sampling timing in accurately representing pollutant concentrations. Consequently, additional studies are required to evaluate how seasonal sampling variations and distinct operational conditions influence overall treatment efficiency. Filtrate concentrations decreased significantly after treatment in all systems (Kruskal–Wallis, $p < 0.05$). Removal efficiencies ranged from 89.5–96.1% for TSS, 84.7–94.0% for turbidity, 73.2–91.5% for COD, and 69.6–95.0% for BOD_5. While residual COD and BOD_5 concentrations increased with HLR, TSS and turbidity generally declined, particularly in PDBs (Mann–Whitney, $p < 0.05$). The highest COD and BOD_5 removals were achieved in PBPP 42.9 L/d, whereas maximum TSS and turbidity removals were observed in the NPB85.7 system. As illustrated in Fig. 7A, the summary of particulate and organic compound removal performance reveals total efficiencies spanning 52.1% to 96.1%, categorized according to the criteria defined by (Zahui *et al.,* 2021):

PBPP42.9 ≈ PBPP64.3 > PBPM42.9 > PBPM64.3 ≈ NPB42.9 > PBPP85.7 > PBPM85.7 > NPB64.3 > NPB85.7 (5)

These findings confirm that particulate matter removal in drying beds is primarily driven by physical processes such as sedimentation, filtration, and particle retention within the filter media (Bohórquez *et al.* 2017; Goussanou *et al.* (2023). The elevated removal efficiencies recorded in NPBs indicate that substrate attributes, specifically porosity and particle-size distribution, acted as primary drivers of particle

Table 3: Purification efficiency of organic pollutants in drying beds. The mean values of the same column that have identical letters as superscripts (such as a, b, c, etc.) indicate no significant differences at a p-value of less than 0.05

Parameters		DO	Turbidity		TSS		BOD_5		COD	
		Value (mg/L)	Value (NTU)	R (%)	Value (mg/L)	R (%)	Value (mg O_2/L)	R (%)	Value (mg O_2/L)	R (%)
Raw FS	Avg	0.681±0.21^{a}	2374.53±118.36^{a}	-	1864.42±134.06^{a}	-	1001.5±104.51^{a}	-	1800.78±89.49^{a}	-
	Max	1.1	2 695.0	-	2176	-	1161.66	-	1959.1	-
	Min	0.3	2 187.5	-	1628	-	870.181	-	1575.62	-
PBPP 42.9	Avg	6.194±0.161^{d}	473.39±15.1^{b}	86±1.37^{a}	265.9±16.25^{b}	90±1.64^{a}	71.15±5.48^{b}	95.1±0.58^{a}	198.06±50.81^{b}	92.3±1.76^{a}
	Max	6.63	500.48	-	288.35	-	78	-	304	-
	Min	5.94	434.87	-	233.86	-	53.2	-	73.5	-
PBPP 64.3	Avg	3.949±0.185b^{c}	268.8±21.57^{c}	91.5±1.02^{b}	151.91±21.54^{c}	93.9±1.17^{b}	116.49±15.99^{b}	91.3±1.67^{a}	208.03±53.88^{b}	91.4±2.2^{a}
	Max	4.35	298.95	-	181.49	-	145.39	-	334.30	-
	Min	3.65	230.36	-	111.5	-	93.16	-	82.9	-
PBPP 85.7	Avg	1.907±0.085^{a}	177.78±18.64^{d}	93.9±0.68^{c}	112.14±13.69^{e}	95.1±1.3^{cd}	280.54±104.72^{d}	77.1±12.88^{d}	453.85±119.03^{d}	79.4±5.27^{b}
	Max	2.13	212.29	-	133.3	-	420.58	-	728	-
	Min	1.65	144.98	-	87.77	-	118.97	-	291.34	-
PBPM 42.9	Avg	4.634±0.303^{c}	575.52±16.09^{b}	84.8±1.44^{a}	310.29±16.28^{b}	89.6±1.61^{a}	104.58±2.19^{b}	93.5±0.71^{a}	334.35±14.11^{c}	88.4±1.29^{ab}
	Max	5.36	604.80	-	333	-	107.3	-	353.67	-
	Min	3.94	547.04	-	276.03	-	98.63	-	309.32	-
PBPM 64.3	Avg	2.999±0.231^{ab}	332.15±20.72^{c}	90.4±1.11^{b}	203.95±12.95^{d}	92.5±1.06^{b}	182.15±12.55^{c}	87.5±1.55^{bc}	441.96±72.55^{d}	83.2±2.62^{b}
	Max	3.38	380.49	-	235.22	-	206	-	684.34	-
	Min	2.53	300.48	-	184.48	-	158.74	-	364.71	-
PBPM 85.7	Avg	1.662±0.15^{a}	183.34±11.76^{d}	93.8±0.7^{c}	127.68±12.42^{e}	94.5±0.88^{c}	376.85±115.95^{de}	69.7±11.44^{de}	596.82±108.65^{e}	73.3±4.41^{c}
	Max	1.87	201.06	-	138.80	-	613.15	-	770.37	-
	Min	1.33	147.85	-	99	-	209.80	-	418.45	-
NPB 42.9	Avg	2.179±0.121^{a}	548.06±30.71^{b}	88.2±1.11^{a}	286.71±13.16^{b}	92.2±1.04^{b}	311.79±36.09^{d}	84.1±1.95^{c}	736.69±107.48^{f}	79±3.46^{b}
	Max	2.38	590.50	-	308.50	-	378.66	-	940.25	-
	Min	1.91	507.35	-	263.78	-	223.76	-	539.08	-
NPB 64.3	Avg	1.605±0.137^{a}	281.39±23.81^{c}	92.9±0.57^{b}	179.39±14.09^{c}	94.2±0.65^{c}	431.84±44.35^{e}	73.9±3.33^{d}	811.1±184.87^{g}	72.7±7.77^{c}
	Max	1.83	335.98	-	217.2	-	492.98	-	1125	-
	Min	1.37	234.10	-	146.34	-	355.63	-	408.36	-
NPB 85.7	Avg	1.25±0.196^{a}	167.09±23.81^{d}	94±0.6^{c}	84.94±14.06^{e}	96.2±0.49^{d}	561.11±70.56^{f}	52.1±11.81^{e}	947.45±202.55^{g}	55.1±12.39^{d}
	Max	1.71	221.68	-	112.74	-	691.46		1337.77	-
	Min	0.84	119.80	-	42.52	-	401.17		597.85	-

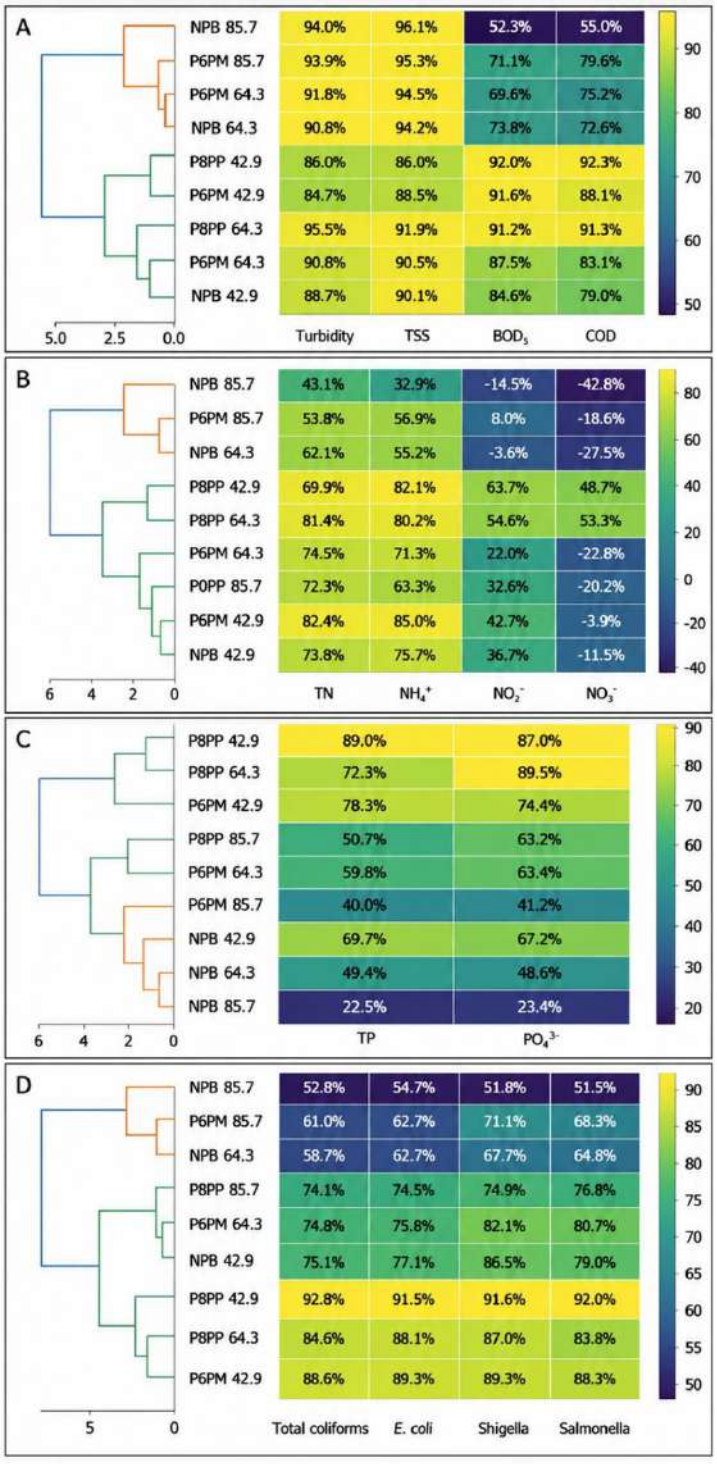

Fig. 7: Synthesis of the purification yields of organic compounds (A), nitrogen compounds (B), phosphorus compounds (C) and pathogenic germs (D) in drying beds; PBPP42.9, PBPP64.3 and PBPP85.7: beds planted with *P. purpureum* fed with 42.9, 64.3 and 85.7 L/d respectively; PBPM42.9, LSPM64.3 and PBPM85.7: beds planted with *P. maximum* fed with 42.9, 64.3 and 85.7 L/d respectively; NPB42.9, NPB64.3 and NPB85.7: NPBs fed with 42.9 L/d, 64.3 L/d and 85.7 L/d, respectively

retention. However, residual TSS concentrations exceeded the Ivorian discharge limit of 50 mg/L (MEWF, 2008). This shortfall points to an inadequate retention of fine particulate matter, which was likely driven by short-circuiting or preferential flow pathways that compromised overall filtration performance. Organic matter was also significantly reduced after treatment (Kruskal–Wallis, $p < 0.05$), with COD and BOD_5 removal efficiencies ranging from 55–92% and 52.1–95%, respectively. Unlike particulate pollutants, the elimination of organic matter was heavily dictated by the biological activity within the systems. PDBs, particularly those vegetated with *P. purpureum*, exhibited the lowest residual organic matter concentrations and the highest DO levels, reaching 6.16 mg/L in PBPP42.9 compared with less than 2 mg/L in heavily NPBs. This elevated oxygenation is presumably driven by root proliferation, which enhances gas exchange and accelerates rhizosphere microbial activity, thereby stimulating the degradation of organic matter (Nielsen and Stefanakis, 2020; Al-Rashdi *et al.,* 2025). Overall, the results suggest that PDBs performance depends on a balance between hydraulic loading, oxygen transfer, and biological activity (Brix, 2017; Tan *et al.,* 2024). An increase in hydraulic loading corresponded with elevated residual concentrations of organic matter, nutrients, and microorganisms, thereby signaling a reduction in overall treatment efficiency. This trend suggests that beyond a critical loading threshold, hydraulic residence time and oxygen transfer become insufficient to sustain effective biological processes. Under these specific conditions, the performance variations between PDB and NPB systems became less pronounced, signaling media saturation and suppressed microbial activity that ultimately jeopardized system stability, treatment reliability, and long-term operational sustainability under elevated loading conditions.

Removal of nitrogen compounds

Raw FS exhibited average concentrations of 307.56 ± 43.52 mg/L TKN and 142.18 ± 8.30 mg/L NH_4^+. The minimal variation observed across the collected samples demonstrates the stability of influent characteristics throughout the experimental period. The concentrations and removal efficiencies of TKN, NH_4^+, NO_2^-, and NO_3^- measured in the filtrates from the different treatment systems are presented in Table 4. Parallel to the trends observed for organic compounds, nitrogen concentrations displayed minimal fluctuation. This consistency underscores the critical need to prevent dilution, which otherwise risks shifting the core characteristics of the FS being treated. After treatment, TKN and NH_4^+ concentrations decreased significantly across all systems (Kruskal–Wallis, $p < 0.05$), with removal efficiencies ranging from 41.1–89.3% and 32.9–87.1%, respectively. In contrast, NO_2^- concentrations in the filtrates increased with HLR and were consistently higher in NPBs than in PDBs ($p < 0.05$). At comparable HLRs, PBPP treatments exhibited significantly lower NO_2^- concentrations than PBPM. In a similar manner, effluent NO_3^- concentrations from the PBPP configurations remained below the baseline levels of the raw FS, whereas a noticeable increase in nitrate levels was recorded within both the PBPM and NPB systems. NO_3^- concentrations generally increased with HLR, with significant differences between raw FS and filtrates (ANOVA, $p < 0.05$). Consequently, removal efficiencies ranged from −14.5% to 63.3% for NO_2^- and from −44.6% to 53.1% for NO_3^-. The highest NO_3^- removal efficiencies were achieved in PBPP64.3 (53.1 ± 6.1%) and PBPP42.9 (48.8 ± 5.3%), whereas the lowest values were recorded in RNP85.7 (−44.6 ± 15.7%) and PBPM85.7 (−39.6 ± 15.7%). The comparative ranking of the treatment configurations regarding their capacity for nitrogen compound removal was established utilizing Eq. 6 (Zahui *et al.,* 2021):

Table 4: Purification efficiency of nitrogen pollutants in drying beds. The mean values of the same column that have identical letters as superscripts (such as a, b, c, etc.) indicate no significant differences at a p-value of less than 0.05

Parameters		TKN		NH_4^+		NO_2^-		NO_3^-	
		Value (mg/L)	R (%)	Value (mg/L)	R (%)	Value (mg/L)	R (%)	Value (mg/L)	R (%)
Raw FS	Avg	307.56±43.52^{a}	-	142.18±8.3^{a}	-	0.14±0.01^{a}	-	25.42±1.52^{a}	-
	Max	395.76	-	155.62	-	0.157	-	27.6	-
	Min	245.33	-	123.44	-	0.112	-	23.32	-
PBPP 42.9	Avg	47.1±8.04^{b}	89.3±1.4^{a}	26.02±2.62^{b}	87.2±2.47^{a}	0.05±0.02^{b}	63.3±9.52^{a}	13.01±1.41^{b}	48.9±5.27^{a}
	Max	56.33	-	31.74	-	0.076	-	15.3	-
	Min	31.27	-	18.56	-	0.012	-	9.04	-
PBPP 64.3	Avg	76.2±21.64^{c}	81.4±3.72^{b}	37.31±2.39^{c}	80.3±4.01^{b}	0.07±0.02^{c}	54.5±7.94^{b}	11.93±1.11^{b}	53.1±6.09^{b}
	Max	105.87	-	41.66	-	0.086	-	15.5	-
	Min	40.35	-	33.00	-	0.037	-	8.6	-
PBPP 85.7	Avg	104.15±25.79^{d}	72.3±4.37^{c}	63.8±9.16^{d}	63.3±5.14^{c}	0.09±0.02^{d}	32.7±10.9^{c}	20.25±5.05^{c}	20.4±19.9^{c}
	Max	150.03	-	81.37	-	0.125	-	29.33	-
	Min	60.48	-	47.72	-	0.053	-	12.15	-
PBPM 42.9	Avg	85.85±19.73^{c}	82.5±2.76^{b}	42.85±7^{c}	81.1±3.84^{b}	0.08±0.01^{d}	42.8±4.33^{c}	26.92±2.51^{a}	-5.9±10.63^{d}
	Max	142.06	-	60.44	-	0.096	-	32.47	-
	Min	60.41	-	34.39	-	0.046	-	22.28	-
PBPM 64.3	Avg	114.19±21.02^{d}	74.5±4.11^{c}	59.33±7.14^{d}	71.4±4.43^{d}	0.11±0.02^{a}	22±6.9^{d}	31.21±3.17^{d}	-22.8±11.52^{e}
	Max	167.31	-	74.75	-	0.134	-	38.96	-
	Min	77.79	-	50.96	-	0.065	-	26.3	-
PBPM 85.7	Avg	139.2±21.98^{e}	63.5±4.37^{d}	75.87±5.56^{e}	56.9±6.13^{c}	0.13±0.02^{a}	8.1±9.74^{e}	35.5±4.29^{f}	-39.7±15.69^{f}
	Max	187.7	-	84	-	0.153	-	43.8	-
	Min	92	-	66.32	-	0.077	-	30.44	-
NPB 42.9	Avg	158.09±26.23^{f}	73.7±5.2^{c}	67.36±8.23^{e}	75.7±3.05^{d}	0.11±0.01^{a}	18.7±4.77^{d}	28.34±3.87^{de}	-11.5±12.93^{g}
	Max	194.68	-	80.95	-	0.125	-	35.24	-
	Min	104.97	-	54.91	-	0.08	-	21.32	-
NPB 64.3	Avg	192.09±25.09^{g}	62.1±5.92^{d}	104.99±11.98^{f}	55.2±5.85^{c}	0.14±0.02^{a}	-3.7±7.34^{f}	32.52±3.27^{ef}	-28±8.29^{h}
	Max	241.69	-	129.71	-	0.168	-	38.45	-
	Min	146.37	-	77.29	-	0.106	-	28.4	-
NPB 85.7	Avg	211.79±27.85^{g}	41.2±6.64^{e}	111.55±11.78^{g}	33±7.75^{e}	0.16±0.02^{e}	-14.5±6.9^{g}	36.76±4.17^{f}	-44.6±15.72^{i}
	Max	255.12	-	134.3	-	0.184	-	44.32	-
	Min	170.05	-	97.06	-	0.104	-	30.69	-

PBPP42.9 PBPP64.3 > PBPM42.9 > PBPM64.3 ≈ PBPP85.7 > NPB 42.9 > PBPM85.7 > NPB64.3 > NPB85.7 (6)

These findings demonstrate that PDBs, especially those with *P. purpureum* under lower HLR conditions, exhibited superior nitrogen removal performance compared to PBPM and NPB treatments (Fig. 7B). Higher treatment efficiencies observed in the presence of *P. purpureum* can be ascribed to increased root-zone oxygenation and greater plant biomass, both of which support dense microbial biofilm proliferation and enhanced phytoremediation of nitrogen (Abbasi *et al.,* 2017; Tho *et al.,* 2017). These results align with previous studies, showing comparable removal efficiencies for TKN and NH_4^+ largely like those found in earlier research such as those for Zahui *et al*. (2021) and Traoré *et al.* (2025). Conversely, higher concentrations of NO_2^- and NO_3^- at increased HLRs in NPB systems indicate a dominance of nitrification processes over denitrification. The negative removal efficiencies for NO_3^- reflect the accumulation of oxidized nitrogen species resulting from ammonium oxidation (Ouattara *et al.,* 2011; Goussanou *et al.,* 2023). Much like in constructed wetlands, the simultaneous presence of aerobic and anaerobic microenvironments within PDBs is essential for driving nitrogen transformation pathways. The vertical flow configuration promotes greater substrate aeration than horizontal-flow systems, creating favorable conditions for nitrification. Under these conditions, aerobic microorganisms oxidize NH_4^+ to NO_2^- and subsequently to NO_3^-, which explains the presence of these oxidized nitrogen forms in the filtrates (Nivala *et al.,* 2020). The exceptional nitrogen removal efficiency demonstrated in *P. purpureum* beds can likely be ascribed to the species' robust capacity for nitrate uptake and metabolic assimilation, which subsequently minimizes NO_3^- accumulation in the effluent (Zahui *et al*., 2021).

Removal of phosphorus compounds

The concentrations and removal efficiencies of TP and PO_4^{3-} in the raw FS and filtrates from the different drying beds are presented in Table 5. Concentration of TP in the raw FS ranged from 8.4 to 14.2 mg/L, with an average value of 11.12 ± 2.12 mg/L, while PO_4^{3-} concentrations ranged from 7.84 to 11.38 mg/L, with an average value of 9.81 ± 1.00 mg/L. The minimal standard deviations associated with the mean phosphorus concentrations demonstrate low temporal fluctuation, confirming that the characteristics of the influent FS remained uniform across the experimental timeframe. TP and PO_4^{3-} concentrations decreased significantly across all systems after treatment (Kruskal–Wallis, $p < 0.05$). However, residual phosphorus concentrations generally increased with HLR (Mann–Whitney, $p < 0.05$). Removal efficiencies ranged from 22.5–89.1% for TP and 23.2–89.9% for PO_4^{3-}. The highest phosphorus removal efficiencies were achieved in PBPP treatments, with maximum TP removal recorded in PBPP42.9 (89.0 ± 2.4%) and maximum PO_4^{3-} removal in PBPP64.3 (87.0 ± 7.0%). In contrast, the lowest removal efficiencies were observed in the NPB85.7 system. As illustrated in Fig. 7C, the overall performance summary for phosphorus compound removal reveals efficiencies spanning 22.5% to 89.9%, categorized according to the criteria defined by Eq. 7 (Zahui *et al.,* 2021):

PBPP42.9 > PBPP64.3 > PBPM42.9 > NPB42.9 > PBPM64.3 > PBPP85.7 > NPB64.3 > PBPM85.7 > NPB85.7 (7)

These findings indicate that PBPP systems exhibit superior phosphorus removal efficiency

Table 5: Purification efficiency of phosphorus pollutants in drying beds. The mean values of the same column that have identical letters as superscripts (such as a, b, c, etc.) indicate no significant differences at a p-value of less than 0.05

Parameters		TP		PO_4^{3-}	
		Value (mg/L)	R (%)	Value (mg O_2/L)	R (%)
Raw FS	Avg	11.12±2.12[a]	-	9.81±1[a]	-
	Max	14.16	-	11.38	-
	Min	8.36	-	7.83	-
PBPP 42.9	Avg	1.74±0.38[b]	89.1±2.42[a]	1.28±0.64[b]	87±7.07[a]
	Max	2.32	-	2.1	-
	Min	1.06	-	0.34	-
PBPP 64.3	Avg	4.07±0.49[c]	72.5±4.87[b]	1±0.49[b]	89.9±4.34[a]
	Max	5.03	-	2.78	-
	Min	3.03	-	0.21	-
PBPP 85.7	Avg	6.7±0.6[d]	50.8±10.44[c]	3.61±1.05[c]	63.3±7.97[b]
	Max	8.225	-	5.82	-
	Min	5.87	-	2.012	-
PBPM 42.9	Avg	3.84±0.52[c]	78.3±4.4[d]	2.32±0.48[d]	76.5±3.03[c]
	Max	4.65	-	3.06	-
	Min	3.16	-	1.38	-
PBPM 64.3	Avg	6.51±0.64[d]	59.8±2.45[e]	3.59±0.48[c]	63.5±3.23[b]
	Max	7.81	-	4.4	-
	Min	5.63	-	2.83	-
PBPM 85.7	Avg	8.18±1.03[e]	40.6±7.71[f]	5.77±1.02[e]	41.3±10.75[d]
	Max	9.93	-	7.561	-
	Min	6.775	-	4.12	-
NPB 42.9	Avg	6.64±0.68[d]	69.7±3.78[g]	3.22±0.51[c]	67.3±5.84[b]
	Max	8.37	-	4.63	-
	Min	5.47	-	2.39	-
NPB 64.3	Avg	9.35±1.63[ea]	49.5±6.09[h]	5.05±0.74[e]	48.7±6.75d
	Max	12.3	-	6.43	-
	Min	7.36	-	3.39	-
NPB 85.7	Avg	10.18±1.94[a]	22.6±4.6[i]	7.54±1[f]	23.3±6.14[e]
	Max	13.2	-	9.18	-
	Min	7.72	-	5.71	-

compared to both PBPM and NPB configurations, a trend that is especially pronounced under low-to-moderate HLRs. The high removal efficiency achieved in PBPP treatments are likely attributable to the combined effects of plant uptake, adsorption onto substrate surfaces, and co-precipitation with metal oxides (Abdoli *et al.,* 2024). Nevertheless, the reduction in phosphorus mitigation recorded at elevated HLRs points to the incremental saturation of substrate binding sites, which subsequently diminished the overall phosphorus retention capacity (Webb *et al.,* 2025). Prolonged saturation may also contribute to clogging and reduced substrate porosity, ultimately impairing system performance. The slightly better treatment performance of *P. purpureum* relative to *P. maximum* may be associated with its greater biomass production and more extensive root system, which enhances substrate aeration, improve hydraulic conductivity, stimulate rhizospheric microbial activity, and increase nutrient uptake, thereby promoting more effective pollutant and pathogen (Abbasi *et al.,* 2017).

EI of filtrates from drying beds

The evolution of the EI in raw FS and filtrates from the PDBs and NPBs is presented in Fig. 8. EI values in the filtrates were significantly lower than those measured in the influents (ANOVA, $p < 0.05$). Mean influent EI values were 0.026, 0.039, and 0.050 kg PO_4^{3-} eq L^{-1} at HLRs of 42.9, 64.3, and

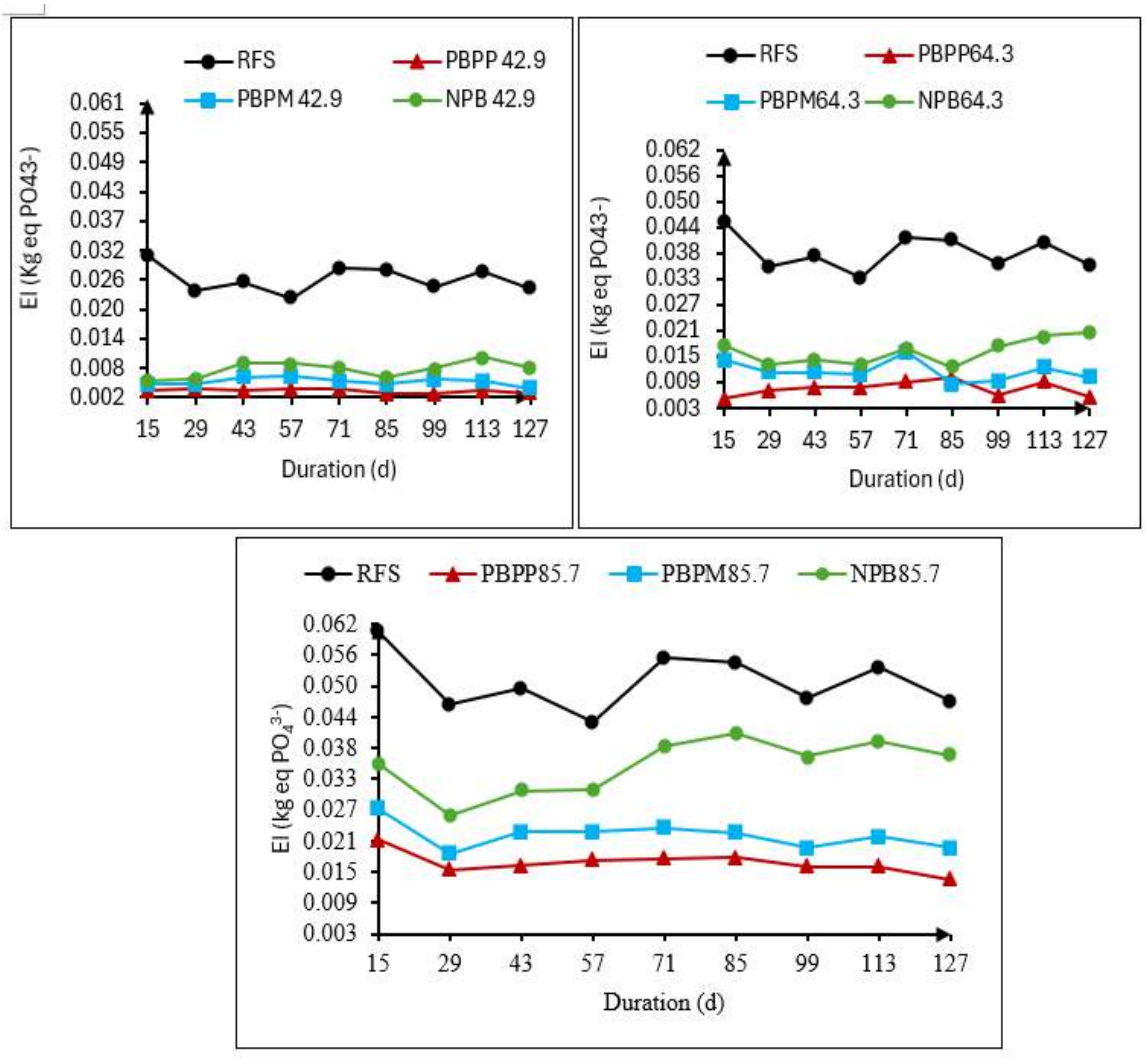

Fig. 8: Evolution of the EI of the raw FS and filtrates of the different drying beds; PBPP42.9, PBPP64.3 and PBPP85.7: beds planted with *P. purpureum*, fed with 42.9, 64.3 and 85.7 L/d respectively; PBPM42.9, PBPM64.3 and PBPM85.7: beds planted with *P. maximum*, fed with 42.9, 64.3 and 85.7 L/d respectively; NPB42.9, NPB64.3 and NPB85.7: NPBs fed with 42.9 L/d, 64.3 L/d and 85.7 L/d, respectively

85.7 L/d, respectively. In the filtrates, EI values increased significantly with HLR ($p < 0.05$). The highest EI values were recorded in NPB systems, followed by PBPM, whereas the lowest values occurred in PBPP treatments. Consequently, eutrophication reduction efficiencies fluctuated between 31.3% and 87.2%, with a peak value of 87.2 ± 1.7% observed in PBPP42.9 and a minimum value of 31.3 ± 7.2% detected in NPB85.7. Eutrophication reduction performance consistently declined as HLR increased. The ranking of treatment systems based on eutrophication reduction efficiency was determined using Eq. 8 (Traoré *et al.*, 2025):

PBPP42.9 > PBPP64.3 > PBPM42.9 > PBPM64.3 > NPB42.9 > PBPP85.7 > PBPM85.7 > NPB64.3 > NPB85.7 (8)

These findings demonstrate that PDBs, particularly PBPP under lower hydraulic loading conditions, were more effective in mitigating

eutrophication potential than that of PBPM and NPB. The significant reduction in the EI between FS and filtrates revealed by Statistical analysis (ANOVA, $p < 0.05$), aligning with the concurrent removal of nitrogen and phosphorus compounds. The PBPP treatment systems demonstrated the highest performance, yielding the lowest residual EI values alongside eutrophication reductions reaching up to 87.2%. Conversely, the diminished performance of the NPB systems highlights how essential vegetation is for accelerating nutrient retention, plant uptake, and biochemical transformation processes. The importance of macrophytes in optimizing nutrient removal efficiency and curbing eutrophication risks is further supported by these results, matching trends reported in previous studies (Klomjek, 2016; Alemayehu *et al.*, 2017). These findings demonstrate that PDBs, particularly PBPP operated under low HLRs, were more effective in reducing eutrophication potential than PBPM and NPB systems. The significant decrease in EI between raw FS and filtrates (ANOVA, $p < 0.05$) is consistent with the simultaneous removal of nitrogen and phosphorus compounds. The lowest residual EI values and the highest eutrophication reduction efficiency (87.2%) were achieved in PBPP treatments, whereas NPB systems exhibited the poorest performance. This distinction underscores the vital role of vegetation in optimizing nutrient retention and biochemical transformation pathways, which ultimately mitigates the environmental footprint of treated effluents, echoing the findings of Klomjek, (2016) and Alemayehu *et al.*, (2017).

Performance of drying beds in eliminating pathogenic microorganisms form FS

Table 6 summarizes the pathogen removal efficiencies achieved across the different drying beds. Influent pathogen concentrations were high, averaging $53.8 \pm 4.13 \times 10^5$ CFU/100 milliliter per liter (mL) for *E. coli* and $18.28 \pm 1.22 \times 10^6$ CFU/100 mL for total coliforms. Population densities of *Shigella* spanned a range of 2.52×10^5 to 3.78×10^5 CFU/100 mL, while *Salmonella* concentrations exhibited greater variance, fluctuating between 2.56×10^6 and 4.43×10^6 CFU/100 mL. The average concentrations of pathogens in the raw FS during the trial period closely corresponded with the levels of organic matter, nitrogen, and phosphorus compounds in the FS transported for treatment. A consistent relationship between nutrient and pathogen loads was evidenced by the minimal variation observed across these parameters throughout the study. This suggests that organic constituents serve as a key substrate and energy source for microbial activity. Consequently, raw FS with high organic loading is likely to support proportionally elevated bacterial and pathogen populations (Worku *et al.*, 2026). The relative stability of the raw FS biological profile and chemical properties throughout the study timeframe was demonstrated by the minimal variation observed. At the drying bed level, pathogen concentrations decreased significantly across all treatment systems (Mann–Whitney test, $p < 0.05$). In general, elevated HLRs led to an increase in residual pathogen concentrations, which corresponded with a progressive decline in removal efficiencies—a trend that was especially pronounced within the NPB systems. Removal efficiencies ranged from 52.4% to 92.8% for total coliforms, 54.7% to 93.5% for *E. coli*, 53.6% to 93.6% for *Shigella*, and 51.1% to 92.0% for *Salmonella*. The highest pathogen removal efficiencies were observed in PBPP treatments, especially in PBPP42.9, whereas the lowest performances were recorded in the NPB systems. Total efficiencies ranging between 51.1% and 93.6% were recorded for contaminant purification (Fig. 7D), with subsequent quantification determined via Eq. 9 (Zahui *et al.*, 2021): Influent pathogen concentrations were

Table 6: Purification performance of pathogenic germs in drying beds. The mean values of the same column that have identical letters as superscripts (such as a, b, c, etc.) indicate no significant differences at a p-value of less than 0.05

Parameters		*Total coliforms*		*E. Coli*		*Shiguella*		*Salmonella*	
		Value (10^6 UFC/100 mL)	R (%)	Value (10^5 UFC/100 mL)	R (%)	Value (10^4 UFC/100 mL)	R (%)	Value (10^5 UFC/100 mL)	R (%)
Raw FS	Avg	18.28±1.22^a		53.8±4.13^a		318.23±37.15^a		363.16±49.86^a	
	Max	21.16		59.47		378.21		443	
	Min	16.45		46.5		251.47		256	
PBPP 42.9	Avg	1.32±0.72^b	92.8±3.49^a	3.48±1.94^b	93.6±3.07^a	20.31±10.01^b	93.7±2.55^a	29.07±9.58^b	92±2.47^a
	Max	2.62	-	7.6	-	47.6	-	54.94	-
	Min	0.24	-	1.23	-	7.142	-	12.16	-
PBPP 64.3	Avg	2.48±0.99^c	86.5±4.52^b	6.42±2.14^c	88.1±3.27^b	41.43±13.15^c	87±3.23^b	58.67±18.81^c	83.9±4.65^b
	Max	4.3	-	10.41	-	73.6	-	101.3	-
	Min	0.83	-	2.54	-	23.14	-	28.54	-
PBPP 85.7	Avg	4.73±1.12^d	74.2±4.39^c	12.65±2.2^d	76.5±3.05^c	67.22±13.68^e	78.9±3.72^c	84.15±23.63^d	76.9±5.5^c
	Max	6.36	-	16.15	-	96	-	131.3	-
	Min	3.05	-	9.24	-	39.002	-	42.84	-
PBPM 42.9	Avg	2.09±0.99^c	88.7±5.16^b	5.77±4.08^c	89.3±6.86^b	33.99±11.45^c	89.4±3.07^b	42.67±11.3^c	88.3±2.54^d
	Max	3.65	-	19	-	74.14	-	64	-
	Min	0.7	-	0.9	-	12.93	-	15.3	-
PBPM 64.3	Avg	4.69±1.28^d	74.4±5.97^c	13.01±6.34^d	75.9±11.1^c	56.94±17.13^e	82.2±5.05^c	71.57±19.26^e	80.3±3.99^b
	Max	6.75	-	32.8	-	102.13	-	108.6	-
	Min	2.43	-	6.05	-	24	-	41.4	-
PBPM 85.7	Avg	7.14±0.84^e	61±3.13^d	20.06±6.41^e	62.8±11.01^d	91.95±27.03^f	71.2±8.15^d	115.04±26.85^f	68.4±5.18^e
	Max	9.27	-	39.8	-	138	-	168.3	-
	Min	5.35	-	13.05	-	48.03	-	74.38	-
NPB 42.9	Avg	4.55±1.17^d	75.2±5.76^c	12.34±4.19^d	77.1±7.82^c	62.12±8.8^e	80.5±3.06^c	76.36±19.01^e	79±4.95^b
	Max	6.64	-	19	-	80	-	124.3	-
	Min	2.60	-	3.4	-	46.28	-	53	-
NPB 64.3	Avg	7.54±0.99^e	58.8±4.15^d	20.85±5.06^e	61.3±9.14^d	102.69±13.48^f	67.8±4.92^e	129.61±18.71^f	64.4±7.51^e
	Max	10.76	-	28.5	-	127.3	-	160.3	-
	Min	5.53	-	7.9	-	74.83	-	88.80	-
NPB 85.7	Avg	8.7±1.22^f	52.5±4.51^e	24.38±5.12^e	54.7±8.94^e	147.74±17.71^g	53.6±9.08^f	177.53±21.85^g	51.2±6.89^f
	Max	11.7	-	32	-	180.80	-	204.3	-
	Min	6.32	-	11.4	-	116.31	-	132.80	-

high, averaging 53.8 ± 4.13 × 10^5 CFU/100 mL for E. coli and 18.28 ± 1.22 × 10^6 CFU/100 mL for total coliforms. *Shigella* concentrations ranged from 2.52 × 10^5 to 3.78 × 10^5 CFU/100 mL, while *Salmonella* concentrations varied between 2.56 × 10^6 and 4.43 × 10^6 CFU/100 mL (Table 6). Like the organic, nitrogen, and phosphorus compounds, pathogen concentrations exhibited limited variability throughout the study, indicating stable influent FS characteristics. This consistency likely underscores the interdependent relationship between microbial communities and the availability of organic matter, which serves as both an energy source and a metabolic substrate for cellular proliferation (Worku *et al.,* 2026). Pathogen concentrations decreased significantly across all treatment systems (Mann–Whitney, $p < 0.05$). However, residual pathogen concentrations increased with HLR, resulting in progressively lower removal efficiencies, particularly in NPB systems. Removal efficiencies ranged from 52.4–92.8% for total coliforms, 54.7–93.5% for E. coli, 53.6–93.6% for *Shigella*, and 51.1–92.0% for *Salmonella*. Maximized pathogen removal efficiencies were achieved in PBPP treatments, most notably in the PBPP42.9 configuration—whereas the NPB systems exhibited the poorest performance. Concurrently, overall purification efficiencies fluctuated between 51.1% to 93.6% (Fig. 7D), as determined using Eq. 9 (Zahui *et al.,* 2021):

PBPP42.9 > PBPM42.9 > PBPP64.3 > NPB42.9 > PBPM64.3 > PBPP85.7 > NPB64.3 > PBPM85.7 > NPB85.7 (9)

These findings demonstrate that PDBs, particularly those planted with *P. purpureum* under low HLR conditions, achieved superior pathogen removal compared with PBPM and NPB systems. This heightened efficiency is likely attributable to the plant root systems, which optimizes substrate configuration and improves the physical filtration of particle-bound bacteria. In addition, the rhizosphere provides a biologically active environment that promotes biofilm formation, microbial competition, and protozoan predation, thereby contributing to pathogen reduction (Maurya *et al.,* 2020; Wang *et al.*, 2021). However, the decline in microbiological removal efficiency with increasing HLR can be explained by reduced hydraulic residence time, lower oxygen availability, and deteriorating infiltration conditions. At elevated HLRs, variations in performance among the treatment systems became less distinct, suggesting a systemic overload that simultaneously impaired both physical filtration and biological degradation mechanisms. These observations are consistent with findings reported by Kawan *et al.* (2022) and Min *et al.* (2024). However, pathogen concentrations detected in the filtrates from the drying beds, particularly in the perforated bed effluent, remain too high to allow safe reuse for agricultural purposes (Drechsel *et al.,* 2022). This may be partly attributed to the relatively short operating period of the pilot-scale system. Nevertheless, efficacy could be further optimized by integrating a supplementary polishing stage with a comparable bed design to maximize pathogen mitigation.

Ordination of drying beds based on pollutant removal efficiencies

PCA of purification efficiencies and eutrophication reduction rates enabled discrimination among the drying beds based on overall treatment performance (Fig. 9). Together, the first two principal components (F1 and F2) accounted for 80.5% of the total variance. The correlation circle showed that F1 was strongly associated with the removal efficiencies of organic matter, nitrogen, phosphorus, microbiological indicators, and eutrophication reduction, whereas

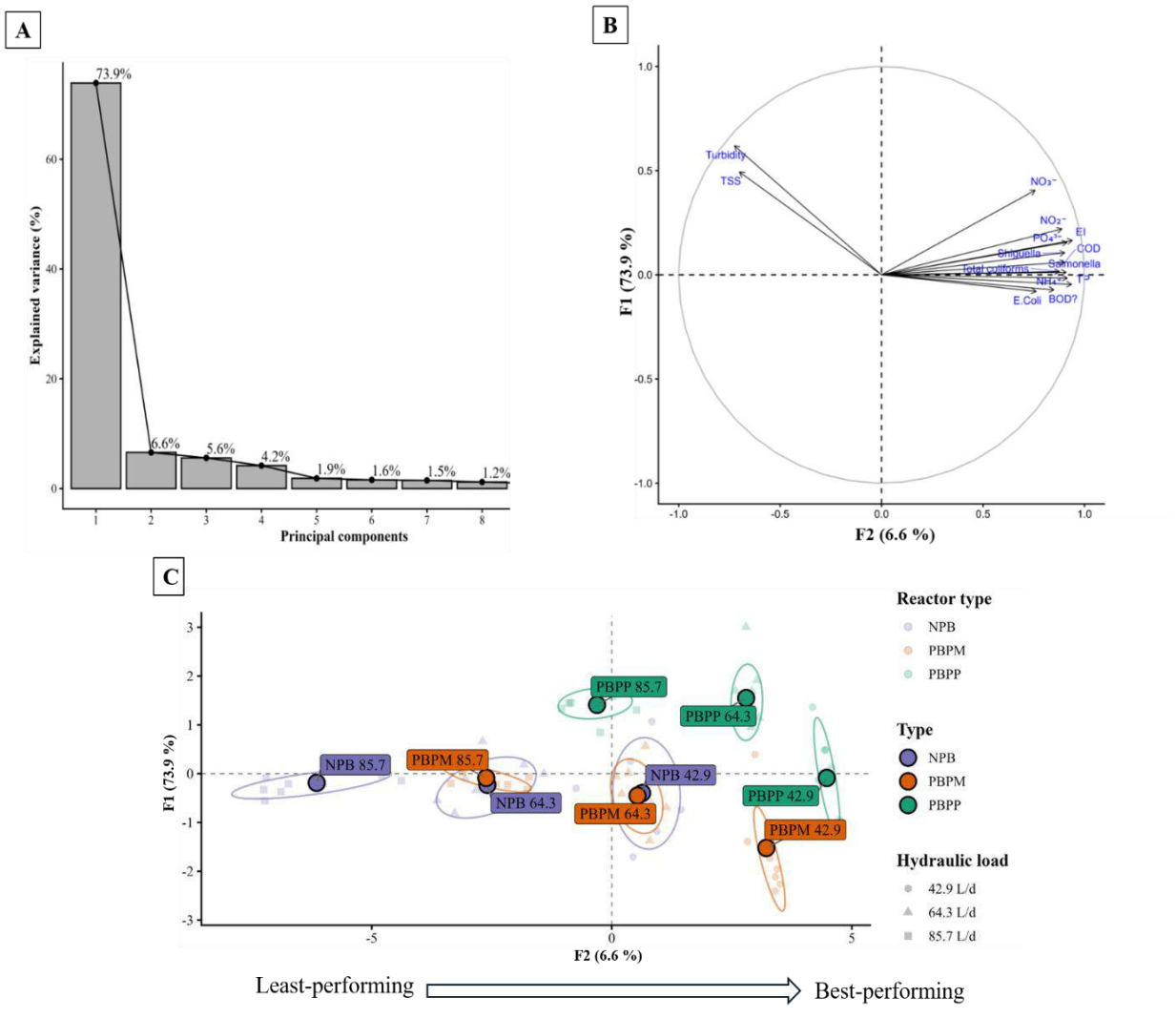

Fig. 9: PCA on purification yields and eutrophication reduction rates of developed drying beds; A) eigenvalues of the axes; B) circle of correlations on the factorial plane F1 × F2; C) factorial map of the reactors on the F1 × F2 factorial plane; PBPP42.9, PBPP64.3 and PBPP85.7: beds planted with *P. purpureum* fed with 42.9, 64.3 and 85.7 L/d respectively; PBPM42.9, PBPM64.3 and PBPM85.7: beds planted with *P. maximum* fed with 42.9, 64.3 and 85.7 L/d respectively; NPB42.9, RNP64.3 and RNP85.7: NPB beds fed with 42.9 L/d, 64.3 L/d and 85.7 L/d, respectively

TSS (with factor loading of 0.77) and turbidity (with factor loading of 0.70) removal efficiencies were negatively correlated with this axis. The factorial map revealed a clear grouping of treatment systems according to HLR. PBPP42.9, PBPP64.3, PBPM42.9, PBPM64.3, and NPB42.9 were positioned on the positive side of F1, indicating higher overall treatment performance, while systems operated at 85.7 L/d, together with NPB64.3 and NPB85.7, clustered on the negative side, reflecting lower efficiencies. Overall, PBPP42.9 and PBPP64.3 exhibited the best overall performance among all treatments. The global ranking of the reactors based on PCA results, using Eq. 10, was subsequently determined (Zahui *et al.*, 2021):

PBPP42.9 > PBPP64.3 ≈ PBPM42.9 > PBPM64.3 ≈ NPB42.9 > PBPP85.7 > NPB64.3 > PBPM85.7 > NPB85.7 (10)

Superior overall purification performance and heightened environmental advantages were demonstrated by PDBs, particularly those utilizing *P. purpureum* at lower HLRs, in comparison to both PBPM and NPB systems. The decline in performance with increasing HLR may be attributed to reduced hydraulic retention time, limited oxygen transfer, and less effective filtration, adsorption, and microbial activity. Consequently, elevated HLRs impaired the efficacy of physical, chemical, and biological purification pathways; conversely, an intermediate HLR of HLR of 42.9 L/d established the most favorable conditions for maximizing system performance under tropical climatic conditions. Comparable observations have been reported in biological photobioreactor systems treating nutrient-rich waste streams, where optimized loading improves nutrient removal efficiency and biomass productivity (Handayani *et al.,* 2024). Furthermore, the PCA validated that the HLR served as the dominant variable dictating the comprehensive efficiency of the drying beds. The F1 axis, strongly associated with variables related to organic matter, nutrients, and microbiological parameters, indicated a clear relationship between increasing hydraulic load and declining treatment efficiency. High-loading systems were characterized by elevated residual concentrations of COD, BOD_5, NH_4^+, NO_3^-, TP, PO_4^{3-}, and pathogenic microorganisms, whereas moderately loaded systems were associated with higher DO levels and superior overall performance. The simultaneous disruption of physical, chemical, biological, and rhizospheric mechanisms involved in purification is demonstrated by this pattern as the hydraulic load increases (Vincent *et al.,* 2011; Sonko *et al.,* 2014; Moulato *et al.,* 2023). In advanced wastewater treatment systems, similar multi-process interactions and efficiency losses under overloading conditions have been documented in integrated physicochemical treatment units, particularly where electrocoagulation and low-cost media are applied under variable loading regimes (Mahdi *et al.,* 2026). From an operational perspective, these findings suggest that maintaining moderate HLRs is essential to preserve system stability, reduce clogging risk, and sustain long-term performance of PDBs. In addition, studies on engineered waste recycling systems emphasize that maintaining balanced loading conditions is critical for ensuring sustained treatment performance and resource recovery efficiency under real-world operational variability (Mahdi *et al.,* 2026). Nevertheless, these findings must be interpreted with caution, as the study did not account for seasonal fluctuations or the long-term impacts of hydraulic and biological substrate aging. Overall, HLR emerges as a key determinant of planted drying bed performance, influencing treatment efficiency and effectiveness.

CONCLUSION

This study investigated the influence of vegetation and HLR on the performance of drying beds for FS treatment under tropical conditions, focusing on *P. purpureum* and *P. maximum*, both of which adapted effectively to varying loading regimes. The results demonstrate that PDBs substantially reduced organic pollutants, nutrients, pathogenic microorganisms, and eutrophication potential. Conversely, NPBs systems yielded the highest removal efficiencies for both suspended solids and turbidity, underscoring the predominant role of physical filtration in stripping particulate matter. An inverse relationship was observed between

overall treatment performance and increasing HLRs. Specifically, the PBPP42.9 configuration delivered peak efficiency, consistently outperforming alternative setups in the immobilization and removal of organic matter, nitrogen, phosphorus compounds, and pathogens, which ultimately led to the most significant mitigation of eutrophication. PCA further confirmed HLR as the dominant factor controlling system performance, with the first principal component strongly associated with organic matter, nutrients, and microbial parameters, indicating a clear trajectory connecting an increased hydraulic load and reduced treatment efficiency. High-loading systems were characterized by elevated residual concentrations of COD, BOD_5, NH_4^+, NO_3^-, TP, PO_4^{3-}, and pathogens, whereas moderate loading conditions were associated with higher DO levels and improved overall performance. From an operational standpoint, these outcomes validate the application of moderate HLRs to preserve system stability, mitigate clogging risk, and ensure long-term efficacy of PDBs. Moreover, *P. purpureum* consistently outperformed *P. maximum* at equivalent HLR, particularly under PBPP42.9 conditions, indicating its superior treatment capacity. In conclusion, this study demonstrates that drying beds vegetated with *P. purpureum* represent an ecologically sustainable and highly efficient alternative for FS treatment in tropical regions, contingent upon the strict regulation of HLRs to preserve long-term system durability and optimal purification capacity. Nevertheless, further long-term studies incorporating economic assessments, climate variability, FS accumulation dynamics, dewatering performance, and biomass valorization are needed to comprehensively evaluate the sustainability, climate resilience, and large-scale applicability of planted drying bed systems.

AUTHOR CONTRIBUTIONS

B.M. Konate contributed to conceptualization, methodology, software development, resource management, data curation, formal analysis, investigation, funding acquisition, and preparation of the original draft manuscript. J.-M.P. Ouattara contributed to conceptualization, methodology, software development, validation, resource management, data curation, supervision, project administration, and funding acquisition. F.M. Zahui, the corresponding author, contributed to conceptualization, methodology, software development, validation, formal analysis, investigation, resource management, data curation, original draft preparation, manuscript review and editing, visualization, supervision, and project administration. R.A. Osei, the co-corresponding author, contributed to data curation, formal analysis, investigation, original draft preparation, manuscript review and editing, and funding acquisition. All authors reviewed, revised, and approved the final version of the manuscript and agreed 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
°C	Degree Celsius
ANOVA	Analysis of variance
BOD	Biochemical oxygen demand
CFU/100 mL	Colony-Forming Units per 100 milliliters
COD	Chemical oxygen demand
DO	Dissolved oxygen
E. coli	Escherichia coli
EI	Eutrophication impact
EPs	Eutrophication potentials
Eq.	Equation
Fig.	Figure
FS	Fecal sludge
HLR	Hydraulic loading rate
ISO	International Organization for Standardization
IBC	Intermediate Bulk Container
kg	Kilogram
kg/m²	Kilograms per square meter
L	Liter
L/d	Litter per day
m	Meter
mg O_2/L	Milligrams oxygen per liter
mg/L	Milligrams per liter
mm	Millimeter
mm/d	Millimeters per day
N	North
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
NPB	No/unplanted beds
NPB 42.9	No planted beds Feed with 42.9 liters per day.
NPB 64.3	No planted beds Feed with 64.3 liters per day.
NPB 85.7	No planted beds Feed with 85.7 liters per day.
P. maximum	*Panicum maximum*
P. purpureum	*Pennisetum purpureum*
PBPM 42.9	Planted beds of *Panicum maximum* Feed with 42.9 liters per day.
PBPM 64.3	Planted beds of *Panicum maximum* Feed with 64.3 liters per day.
PBPM 85.7	Planted beds of *Panicum maximum* Feed with 85.7 liters per day.

PBPP 42.9	Planted beds of *Pennisetum purpureum* Feed with 42.9 liters per day.
PBPP 64.3	Planted beds of *Pennisetum purpureum* Feed with 64.3 liters per day.
PBPP 85.7	Planted beds of *Pennisetum purpureum* Feed with 85.7 liters per day.
PCA	Principal component analysis
PDB	Planted drying beds
PDBs	Planted drying beds
pH	Potential of hydrogen
PO_4^{3-}	Orthophosphate
PVC	Polyvinyl chloride
S	Area of the dry bed
TKN	Total Kjeldahl nitrogen
TP	Total phosphorus
TSS	Total suspended solids
W	West

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CASE STUDY

Green mobility integration to enhance willingness to pay for cultural heritage conservation

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ABSTRACT

BACKGROUND AND OBJECTIVES: The restructuring of entrance fees at high-profile cultural world heritage sites often sparks intense public debates between heritage conservation imperatives and the fundamental principles of democratic public access. Utilizing an integrated microeconomic and behavioral demand-side framework, this empirical study provides a comprehensive assessment of domestic visitors' financial thresholds, behavioral dynamics, and psychological expectations at Indonesia's Borobudur World Heritage Site. The study objectives were to bridge the prevailing valuation gap, mitigate socio-economic conflicts, and prevent the severe market friction and social exclusion that typically accompany top-down tariff adjustments.

METHODS: Utilizing the contingent valuation method and a structured ability-to-pay framework, primary data were collected through detailed questionnaires from 120 stratified domestic respondents during the transitional shoulder season. To bypass statistical limitations, the framework deploys a within-subject, repeated-measures analysis of variance design that generates 360 distinct data observations, yielding a post-hoc statistical power exceeding 0.99. To statistically model behavioral shifts, demand elasticity, and visitor distribution, this study constructs an innovative eco-economic boundary matrix grounded in Kaldor-Hicks efficiency criteria. This framework accounts for both demographic covariates and multi-tiered environmental service scenarios.

FINDINGS: The empirical analysis uncovers a profound valuation gap heavily driven by consumer anchoring behavior. While the mean objective capacity stands at United State Dollar 18.35, the baseline means willingness to pay remains strictly restricted at just United State Dollar 3.23 due to free-rider effects. Crucially, green scenario simulations demonstrate that transitioning to an integrated eco-mobility management structure triggers a substantial +25 percent positive behavioral shift. Empirical simulations indicate that integrating the entry fee with highly visible low-carbon transit networks and transparent environmental infrastructure optimizes public acceptance. Under these conditions, a pricing threshold of United State Dollar 6.25 causes projected compliance to jump from 18 to 55 percent.

CONCLUSION: The government previously proposed United State Dollar 46.88 tariff triggers an immediate market destabilization and deadweight loss. Furthermore, it engenders severe public opposition rooted in systemic socio-economic disparities. This study proves that integrating green transportation networks functions as a powerful psychological catalyst. This integration shifts visitor utility curves, mitigates financial friction, and ultimately fosters sustainable, equitable cultural heritage governance.

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INTRODUCTION

Globally, heritage managers face a universal challenge: transforming tourist participation into reliable financial streams for site preservation without alienating the public. Although willingness to pay (WTP) has long been employed in economic valuation studies to estimate the non-use value of cultural assets, converting these empirical valuations into actionable policy remains complicated by significant socio-political friction (Dung, 2025). Conventional revenue mechanisms, such as voluntary donations, educational workshops, and souvenir commercialization—provide baseline support, but ticket-pricing policies remain the most direct fiscal instrument to internalize environmental externalities and regulate visitor density (Harrison, 2013; Abdurakhmanova and Ahrorov, 2025). This structural dilemma recently became a centerpiece of public debate at the Borobudur Temple Compounds in Indonesia, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site since 1991 (UNESCO World Heritage Centre, 1991). To combat escalating structural decay and environmental pressure, the Indonesian government proposed an extreme policy shift: restricting daily visitors to a strict quota of 1,200 individuals and raising the domestic entrance fee drastically to United States dollars (USD) 46.88. This rigorous fiscal intervention was designed to internalize the negative environmental and energy-related externalities associated with tourism activities. However, the proposal ignited severe socio-political friction; while conservationists backed the idea of capitalizing revenues for heritage longevity, domestic tourists and local communities strongly opposed the fee, characterizing it as a regressive barrier to heritage access and raising substantial concerns regarding equity and affordability (Maulana, 2024). Mitigating such policy deadlocks within the literature has prompted an increased reliance on dual socio-economic dimensions: stakeholders' ability to pay (ATP) and their willingness to pay (WTP). Nominally, ATP reflects an individual's objective financial capacity to purchase a service based on broader economic indicators, whereas WTP captures a visitor's subjective inclination to monetarily compensate for the experienced utility or preservation value of a resource (Amponsah *et al.,* 2016; Abuamoud, 2025). Extensive scholarship has scrutinized these matrices in general tourism settings, such as assessing premiums for eco-friendly hospitality (Boronat-Navarro and Pérez-Aranda, 2020), wine tourism, or nature-based destinations. Extensive research confirms that as consumers' ecological awareness intensifies, their WTP premium rates for sustainable practices and green initiatives scales accordingly (Kang and Nicholls, 2021). In the realm of transportation, a growing body of literature indicates that the implementation of green mobility options not only reduces carbon footprints but also enhances the overall tourist experience and perceived value of a destination (Miralles *et al.,* 2023). Despite the utility of these insights, current heritage management frameworks exhibit a critical theoretical and practical oversight that limits their broader applicability (Nguyen *et al.,* 2026). Existing literature heavily prioritizes isolated willingness-to-pay (WTP) assessments, leaving a critical empirical void regarding the synchronicity—or the lack thereof—between visitors' actual financial capacity—or ability-to-pay (ATP)—and their voluntary valuation when subjected to sudden, extreme state-enforced price hikes at iconic heritage sites (Jurado-Rivas and Sánchez-Rivero, 2019; Thapa and Bhattarai, 2025). Traditional valuation frameworks acknowledge that high-quality infrastructure boosts general tourism spending (Hanli *et al.,* 2023; Munir *et al.,* 2025). However, a conceptual gap remains regarding how specific low-carbon transport interventions quantitatively alter visitor utility, reduce market friction, and justify premium conservation fees (Zientara *et al.,* 2024; Erdoğan, 2025). To address these specific empirical

limitations, this study builds upon existing sustainable transport literature by simultaneously evaluating objective ATP and subjective WTP within a unified behavioral-economic framework. Departing from static economic frameworks, this study advances existing literature by modeling mobility—specifically, low-carbon transport infrastructure—as an active utility enhancer rather than a logistical restriction. By doing so, this paper operationalizes a specialized mechanism to bridge the historical "valuation gap" between what consumers can objectively afford and what they are subjectively willing to volunteer for heritage longevity. To address these fragmented empirical dimensions, this study develops an integrated demand-side framework bridging psychological orientation, behavioral execution, and microeconomic valuation. The selection of this dual-lens framework is conceptually vital to address reviewer requirements regarding operational parameters; while traditional microeconomic demand theory dictates that consumer choices are bounded strictly by disposable income; behavioral economics proves that consumer utility curves are highly sensitive to intrinsic cognitive anchors and perceived operational quality. From this perspective, green mobility shifts from a mere logistical alternative to a qualitative enhancer within the consumer utility function, directly increasing visitor WTP. To maintain strict analytical precision, this framework formally conceptualizes and operationalizes five core socio-economic parameters within the heritage ecosystem. First, green mobility integration is defined as the structural deployment of low-carbon transit that operationalizes localized climate mitigation. Second, market friction represents the economic deadlock where an extreme tariff hike creates a wide gap between consumer capability and state expectations. Third, psychological resistance captures the cognitive backlash and price unfairness felt by consumers. Fourth, perceived environmental value captures the internal altruistic utility associated with sustaining site longevity. Finally, behavioral compliance is the voluntary willingness to financially contribute without free-riding. This framework demonstrates how behavioral attributes dynamically moderate socio-economic disparities, which represent the rigid constraints of empirical ATP. At the foundational layer, internal environmental attitudes dictate the cognitive baseline of the visitor, which directly manifests in the adoption of green mobility protocols at the heritage destination. This empirical framework demonstrates that spatial engagement with sustainable transit options modulates visitor perceptions of site integrity and convenience, subsequently driving stated WTP through elevated altruistic utility. When environmental value perception is high and transport interventions offer seamless convenience, psychological resistance is minimized, effectively flattening market friction, expanding the consumer's utility threshold, and elevating final WTP. The intersection of these two economic vectors establishes a balanced, socio-economically stable mechanism for conservation financing. This framework reconceptualizes conservation financing, moving beyond arbitrary fiscal taxation to establish it as a predictable macroeconomic outcome derived from a coherent continuum of pro-environmental psychology and green mobility behavior, and empirical calibrated economic capacity. This study advances the global discourse on how internationally renowned heritage sites can capture economic rent for carbon-offset initiatives. This study was conducted within the Borobudur Temple Compounds in Indonesia. Consequently, heritage conservation funding must be reframed: rather than a rigid fiscal imposition, it should be conceptualized as a dynamic environmental internalization process balancing fiscal sustainability with social equity. This study resolves a critical oversight in heritage management literature by shifting focus away from isolated WTP assessments. Instead, it addresses the empirical void regarding the alignment between visitors' actual financial

capacity and their voluntary valuation. More importantly, this study moves beyond treating cultural monuments as static assets; instead, it introduces a novel framework exploring the strategic role of green mobility integration as a psychological catalyst to justify premium conservation fees and expand visitor utility curves. By introducing an eco-economic boundary matrix, this integrated framework balances the trade-offs among five distinct pillars: democratic public access, cultural equity, heritage conservation, environmental sustainability, and green mobility integration. Econometrically, this study introduces a replicable eco-economic matrix to identify an optimal internalization zone using Kaldor-Hicks efficiency, resolving the deadlock between conservation and public access. By proving that visible eco-mobility operationalizes localized climate mitigation, which actively reduces consumer payment skepticism and structurally elevates the baseline willingness to pay for heritage preservation, the manuscript directly expands the frontiers of environmentally responsible heritage governance theory. By examining the divergence between visitors' ATP and WTP, this paper evaluates the socio-economic sustainability of contemporary heritage management. To achieve this goal, the specific objectives are twofold: 1) to empirically estimate the baseline ATP and WTP values of domestic heritage tourists, and 2) to model the optimal internalization zone and shadow pricing under green mobility interventions. This study has been contacted in at the Borobudur Temple complex in Indonesia in 2025.

MATERIALS AND METHODS

To robustly evaluate visitor dynamics regarding conservation pricing, this study deploys an integrated microeconomic and behavioral demand-side framework. Mathematically, synthesizing these two analytical dimensions is necessary to capture complex public good valuation. While classical microeconomic demand theory dictates that consumer choices are bounded strictly by disposable income and price elasticities, behavioral economics proves that utility curves are highly sensitive to intrinsic cognitive anchors, environmental values, and perceived operational efficiency. Connecting the objective constraints of ATP with subjective WTP enables this integrated framework to better evaluate tourist acceptance matrices. Within this architectural lens, the deployment of green mobility ceases to be a simple logistic alternative; instead, it enters the consumer's utility function as a qualitative enhancer. This framework effectively isolates how visible ecological interventions reduce fiscal friction, allowing policymakers to predict not just the financial yield of tariff restructurings, but the behavioral compliance and long-term socio-ecological support of the heritage consumers. The five-core psychological and microeconomic vectors driving this study are formally defined and operationalized here to provide structural precision to heritage tourism pricing frameworks. The comprehensive operationalization matrix, detailing the conceptual definitions and empirical indicators for each core vector, is systematically mapped and presented in Table 1.

Research materials

To execute the empirical analysis, this study utilized a structured, closed-ended questionnaire divided into multiple sections and modeled after standardized contingent valuation method (CVM) guidelines. The methodology incorporates three main analytical components: 1) a sociodemographic screening tool to capture respondent profiles, monthly net revenues at both the personal and household levels, and temporal metrics; 2) an objective financial allocation matrix mapping broader tourist expenditure and destination-specific fiscal commitments; and 3) a stated preference discrete scenario framework. To ground respondents' psychological boundaries in realistic infrastructure conditions, this final

Table 1: Operationalization matrix for behavioral and eco-economic variables

Core concept	Conceptual definition	Operationalization strategy/empirical indicators
Green mobility integration	The structural deployment of low-carbon, electric-based transit systems within the heritage site to displace conventional fossil-fuel transport.	Measured as the tourist's stated acceptance and active adoption of electric shuttle protocols inside the core zones of the borobudur temple compounds.
Market friction	The economic deadlock resulting from severe misalignments between consumer financial capacity and state-enforced conservation tariffs.	Quantified mathematically as the wide empirical gap where a visitor's voluntary WTP is structurally lower than the government's proposed premium fee (USD 46.88).
Psychological resistance	The cognitive backlash and negative consumer behavior triggered by perceived price unfairness or regressive social exclusion policies.	Evaluated via likert-scale questionnaire metrics capturing respondent opposition to aggressive pricing, perceived utility loss, and feelings of cultural disenfranchisement.
Environmental value perception	The degree of internal altruistic utility and awareness a visitor attributes to the preservation, carbon-offset, and physical longevity of the monument.	Operationalized through standardized psychological scales assessing the tourist's baseline environmental commitment and their cognitive link between fees and ecological outcomes.
Behavioral compliance	The voluntary willingness of consumers to cooperate with new site regulations and financially contribute to conservation without free-riding.	Measured directly by the empirical clustering of respondents within the optimal internalization *zone* based on their final stated WTP.

component utilizes high-resolution digital visual rendering sheets. These materials explicitly depict the environmental management interventions for Scenario 3 (integrated green management), including low-carbon transport options, electric shuttle corridors, and digital energy-monitoring application.

The study design and location

The study was conducted at the Borobudur Temple compounds, a UNESCO World Heritage site located in Central Java, Indonesia. Framed within environmental economics, this study integrates a quantitative descriptive methodology with a stated preference survey technique. This method examines how individual preferences can be aggregated into collective policy-making, specifically concerning the internalization of environmental externalities and the strategic allocation of conservation funding. Rather than a mere cultural monument, this study conceptualizes Borobudur as a non-renewable asset where intensive tourism generates externalities requiring robust fiscal mitigation.

Data sources and variables

Primary data were collected via a structured questionnaire bifurcated into two tracks: an objective assessment of the ATP and a subjective evaluation of the WTP. Table 2 provides a detailed overview of the operational definitions, indicators, and measurement framework used to capture these socio-economic realities. To ensure international comparability and alignment with global heritage valuation standards, all financial metrics were documented in the USD. Conversions were calculated using the prevailing average foreign exchange reference rate during the study period.

Population and sampling

The target population for this investigation included domestic tourists visiting the Borobudur temple area. Daily domestic visitor density averaged 877 tourists during the field observation period. Participants were selected via a purposive sampling approach, focusing on adult domestic tourists who act as the primary economic decision-makers for their travel parties. To secure high internal validity and ensure all respondents adhered to strict conceptual eligibility criteria, this study deliberately utilized a purposive sampling strategy instead of a probability-based approach. Because the contingent valuation scenarios require an accurate evaluation of multi-tiered asset enhancements, it was empirically vital to isolate respondents who possessed immediate, first-hand experience with the monument's

Table 2: Operational definitions, indicators, and measurement framework for ATP and WTP variables

Variable	Operational definition	Indicator	Measurement scale / formula component	Sources
Personal income (I_i)	Respondent's individual net monthly income.	Personal income.	Average total personal income per month (converted to USD equivalents).	López-Sánchez and Pulido-Fernández (2017)
Family income (I_f)	The total monthly net income of the respondent's household.	Household income.	Average total personal income per month (converted to USD equivalents).	López-Sánchez and Pulido-Fernández (2017)
Tourism allocation (P_p)	Proportion of income allocated by respondents for aggregate tourism activities.	Budget allocation.	Average percentage of monthly income spent on tourism.	López-Sánchez and Pulido-Fernández (2017)
Destination allocation (P_t)	Budget allocation specifically earmarked for visiting the Borobudur temple.	Site-specific allocation.	The average percentage of the tourism budget is spent specifically for Borobudur.	Lissner and Mayer (2020)
Travel intensity (F_i)	Individual travel frequency within a specific time frame.	Individual trip frequency.	Average number of personal leisure trips taken per month.	Lin (2017)
Family travel intensity (F_f)	Household travel frequency within a specific time frame.	Family trip frequency.	Average number of family leisure trips taken per month.	López-Sánchez and Pulido-Fernández (2017)
WTP	Maximum monetary value: a tourist is willing to volunteer for site conservation.	Conservation premium.	The stated maximum USD value represents the amount a tourist is willing to pay for environmental internalization.	Cooper and Hall (2007)

physical and operational constraints. Three control protocols were enforced to minimize the selection and psychological biases of non-probability designs: 1) sampling was restricted to visitors who had completed at least 50 percent (%) of their site tour to guarantee realistic contextual anchoring; 2) The sampling process was symmetrically distributed between weekdays (50%) and weekends (50%) to account for variation across visitor socioeconomic profiles; and 3) an ex-ante cheap talk script was deployed to continuously prime respondents regarding their actual household budget constraints before eliciting WTP values. To minimize temporal bias and ensure a balanced capture of tourist demographics, the structured questionnaires were administered across an evenly distributed schedule consisting of both weekdays (50%) and weekends or public holidays (50%). The field data collection was executed during the transitional shoulder season to account for temporal variations in visitor behavior. This particular seasonal window was chosen to avoid the extreme behavioral and psychological changes that occur during peak overcrowding times. Consequently, the elicited WTP responses reflect baseline visitor utility profiles under standard operational conditions. Although the purposive sampling of 120 respondents delimits broader demographic representativeness across the total annual visitor population, this sample size provides sufficient statistical power and validity for the selected econometric model. Given the within-subject design of the repeated measures analysis of variance (ANOVA) across three scenarios, the framework generates 360 distinct data observations. A post-hoc statistical power analysis confirms that for a standard medium effect size ($f = 0.25$) at an alpha level of 0.05, a sample size of 120 yields a statistical power exceeding 0.99, far surpassing the standard 0.80 threshold required to prevent Type II errors in behavioral demand modeling. To validate instrument robustness, a preliminary pilot study (N=30) was executed before full-scale deployment. The environmental awareness constructs and transportation preference scales demonstrated high internal consistency, with Cronbach's alpha coefficients of 0.84 and 0.81, respectively. Psychological expectations, environmental attitudes, and

resistance toward tariff restructuring were quantitatively measured using a standardized 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree), while affordability and financial thresholds were qualitatively anchored and cross-verified against the respondents' empirical monthly disposable income to eliminate cognitive anchoring bias.

Instrument validation and pilot testing

The structured contingent valuation questionnaire underwent a multi-stage validation protocol to maintain high internal validity and mitigate potential measurement errors. Content and face validity were confirmed by an expert review panel comprising of three independent researchers specializing in environmental economics, psychometrics, and cultural heritage management. This qualitative feedback informed modifications to the ex-ante cheap talk script, thereby safeguarding the neutrality of the hypothetical scenario descriptions against potential framing bias. Following the expert review, an experimental pilot test was administered to a preliminary cohort of n = 30 domestic tourists who shared the same demographic characteristics as the target population but were excluded from the final empirical analysis. against potential framing bias. To assess the internal consistency and reliability of the multi-item psychological and perceptual constructs embedded in the questionnaire, Cronbach's alpha (α) was computed. The estimated scale demonstrated robust reliability with a cumulative alpha coefficient of 0.84, well above the acceptable psychometric threshold of 0.70. Construct validity was concurrently confirmed via localized correlation matrices, ensuring that the instrument was highly stable, precise, and methodologically sound for eliciting stated WTP metrics.

Econometric calculation of WTP percentage shifts

Percentage shifts in Mean WTP were calculated for each experimental scenario against the static baseline (Scenario 1) to evaluate monetary adjustments across the progressive destination management setups. The econometric mathematical formulation applied to derive these percentage adjustments (Δ WTP_k) for any progressive scenario *k* is expressed in Eq. 1, following standard environmental valuation comparative frameworks (Bateman *et al.,* 2002):

$$\Delta WTP\mathrm{k} = \frac{Mean\ WTPk - Mean\ WTPbaseline}{Mean\ WTPnaselind}\ x\ 100 \quad (1)$$

Where: mean $WTP_{baseline}$ represents the benchmark valuation under the status quo framework (Scenario 1 = USD 4.35), and Mean WTP_k represents the empirical mean valuation computed under the progressive value-added service structures (Scenario 2 = USD 4.87; Scenario 3 = USD 5.44). By explicitly formulating these relationships, the study ensures a transparent operational link between the descriptive compliance data and the multi-tiered policy recommendations.

Ex-ante mitigation of CVM biases

To guarantee the econometric validity of the stated-preference data, the experimental instrument incorporated rigorously ex-ante design safeguards aligned with the National Oceanic and Atmospheric Administration (NOAA) (Arrow *et al.,* 1993). Panel guidelines to mitigate hypothetical bias, strategic bias, and embedding effects. First, hypothetical bias was minimized using an ex-ante cheap talk script before the valuation questions. This script informed respondents of the empirical tendency to overestimate WTP, encouraging them to align their responses with actual budget constraints. Second, strategic bias was minimized by guaranteeing strict structural anonymity and framing the questionnaire as an independent, non-governmental academic assessment, thus discouraging respondents from deliberately altering their bids to manipulate potential public pricing schedules. Third, to control for embedding

effects and part-whole bias, the survey instrument employed highly detailed, localized visual aids to isolate the physical jurisdiction of the site's immediate conservation zone. This design explicitly prevented respondents from conflating their stated WTP for the monument's localized eco-services with general, large-scale conservation welfare (Arrow *et al.,* 1993).

Socio-economic variable specification and currency conversion

To ensure econometric integrity, the income and expenditure variables were operationalized using a standardized protocol. Socio-economic metrics were self-reported by respondents within pre-coded categorical intervals. To maintain structural consistency, these brackets were adapted from and cross-verified with the regional income stratification criteria published by the Indonesian central bureau of statistics (BS). By restricting the analytical focus to individual net income and personal expenditure profiles rather than aggregated household data, the models control for household-scale variances that would otherwise introduce statistical noise into the individual's marginal utility framework. Furthermore, all baseline economic measurements captured in Indonesian were structurally standardized into USD to facilitate international comparison.

Sample adequacy and statistical power assessment

To validate the mathematical reliability of the segmented analyzes across different traveler archetypes and experimental CVM scenarios, a post-hoc statistical power analysis was executed. Statistical power (1 - β) was evaluated using G*Power software based on the sample size constraint (N = 120) and a multi-factor repeated measures ANOVA design matrices. Operating under a standardized significance threshold of α = 0.05 and assuming a moderate-to-large empirical effect size (f = 0.28), the statistical power achieved by the N = 120 cohort is calculated at approximately 0.84. Because this power index sits comfortably above the conventional benchmark of 0.80 established in econometric and psychometric research (Cohen, 1988), the sample size is mathematically verified as adequate to insulate the segmentation findings from Type II inferential errors. Consequently, the observed demand variations across traveler segments and CVM design layers reflect authentic empirical relationships rather than stochastic sampling noise.

Method of analysis

To robustly address the research questions, the data analysis is structured into distinct economic and behavioral estimation phases. This section delineates the econometric specifications and structural modeling frameworks employed to estimate and interpret the empirical findings.

ATP analysis

ATP analysis quantifies the objective financial capacity of individuals and households to absorb tourism-related expenses. This study employs the ATP metric as an empirical benchmark to assess the socio-economic feasibility of mandated conservation fees. This study distinguishes between two distinct operational metrics of financial capacity:

1. *General ability to pay (ATP_{gen})*

Measures the aggregate financial capacity of a household unit to support localized tourism activities, which is critical for evaluating consumption behavior at the domestic cohort level, using Eq. 2 (Abdurakhmanova and Ahrorov, 2025):

$$\mathrm{ATPgen} = \frac{\mathrm{It\ x\ Pp\ x\ Pt}}{\mathrm{Tt}} \quad (2)$$

Where:

ATP_{gen}= General household ability to pay per trip.

I_t = Total aggregate monthly family income.

P_p = Proportion of monthly income allocated for aggregate travel.
P_t = Proportion of tourism income specifically allocated for the destination site.
T_t = Total family travel frequency per month.

2. Respondents' Ability to Pay (ATP_{resp})

Assesses an individual traveler's disposable financial capacity to bear the costs of accessing a specific cultural site, serving as a pillar for understanding microeconomic purchasing power, using Eq. 3 (Joewono, 2009):

$$\text{ATPresp} = \frac{\text{Irs x Pp x Pt}}{\text{Trs}} \quad (3)$$

Where:
ATP_{resp} = Individual respondent's ability to pay per trip.
I_{rs} = Total individual net monthly income.
P_p = Proportion of individual monthly income allocated for travel.
P_t = Proportion of travel expenditure allocated specifically for the target monument.
T_{rs} = Total individual travel frequency per month.

From a microeconomic standpoint, the theoretical justification for applying the ATP formulation to heritage tourism rests upon the allocation dynamics of discretionary consumer surplus. In contrast to public utilities where ATP delineates a baseline survival threshold, cultural tourism represents a non-essential, leisure-driven commodity. Consequently, the ATP equation utilized herein is structurally calibrated to isolate the respondent's discretionary income matrix (income remaining after primary non-discretionary expenditures are fulfilled). Contextualizing this formula within cultural heritage economics is vital to counterbalance the 'warm glow' or altruistic bias inherent in contingent valuation, where respondents overstate their WTP due to the symbolic, non-use value of the monument. By anchoring conservation tariffs to the visitor's empirical ATP and residual financial capacity, this approach balances institutional conservation mandates with the socio-economic accessibility of the heritage site.

3. WTP analysis

WTP measures the maximum amount individuals are prepared to pay as a direct contribution to Borobudur Temple's conservation efforts. This metric captures the economic value tourists assign to environmental and heritage sustainability (Abuamoud, 2025). The average WTP was determined using the mean willingness to pay (MWTP) using Eq. 4 (Nugraha *et al.,* 2021):

$$\text{MWTP} = \frac{\sum_{i=1}^{n} \text{WTPi}}{n} \quad (4)$$

Where:
MWTP = Mean of WTP
N = Total sample size (120).
WTP_i = Maximum stated WTP value offered by the i-*th* respondent.

4. Data segmentation and scenario analysis

Supplementary to the baseline estimations, tourist responses were disaggregated by travel characteristics to evaluate differences between household groups and solo travelers. This stratification is crucial for mapping the "multiplier effect" of radical tariff hikes on household leisure budgets, which frequently dictates the real-world political feasibility of heritage preservation policies. Furthermore, the study utilized CVM scenario analysis to assess how visitor valuations vary across differing public service levels. Three progressive, hypothetical scenarios were presented to respondents:

1. Scenario 1 (Pure access/status quo): Minimal operational service accompanied by historical entry access.
2. Scenario 2 (Basic enhancement): Provision of specialized local guiding and educational interpretive facilities.

3. Scenario 3 (Integrated green management): Full inclusion of low-carbon transport infrastructure, such as electric shuttles and digital management applications, designed to drastically lower the site's carbon and energy footprint.

To mitigate the inherent hypothetical bias typical of contingent valuation designs, the survey protocol incorporated an ex-ante cheap talk script that reminded respondents of real-world household budget constraints before eliciting their WTP under the green mobility integration scenario. To control for temporal bias, the survey was administered during the shoulder season and split equally between weekdays and weekend/holiday periods (50% each), thereby capturing a heterogeneous socio-economic cross-section and establishing a standardized baseline for visitor utility (50% of their site tour). Given the within-subject design across three scenarios, the framework generates 360 distinct observations; a post-hoc statistical power analysis verifies that for a typical medium effect size (f = 0.25) at an alpha level of 0.05, this sample size achieves a statistical power greater than 0.99, significantly exceeding the conventional 0.80 threshold necessary to avoid Type II errors. To formally determine if the green interventions significantly altered tourist valuation and effectively bridged the gap between ATP and WTP, a repeated measures RM-ANOVA with post-hoc pairwise comparisons was executed across the scenarios, isolating the demand elasticity and the "optimal premium" visitors were WTP for environmental management advances.

Ethical considerations and informed consent

Because this study gathered empirical primary insights from human participants via field surveys, rigorous ethical protocols were enforced to safeguard respondent rights. Data collection and research protocols complied fully with the Declaration of Helsinki framework. Prior to the engagement, formal informed consent was secured from each of the 120 respondents; Participants were explicitly briefed on the academic intent of the survey, the voluntary nature of their involvement, and their guaranteed right to terminate participation at any juncture. A strict anonymization protocol was applied to the dataset to safeguard participant privacy. All unique personal identifiers were systematically omitted from the analytical framework, ensuring that the processed socio-economic data remains strictly confidential and non-traceable. Finally, this study acknowledges inherent methodological limitations. Although widely utilized, the CVM remains vulnerable to hypothetical bias. This phenomenon occurs when stated WTP systematically diverges from real-market financial trade-offs, often driven by strategic behavior or warm-glow utility. Furthermore, eco-economic scenario modeling relies on static behavioral assumptions that may not fully capture dynamic macroeconomic fluctuations or real-time logistical friction in green transportation systems. To minimize these biases, this framework strictly anchored all stated valuations against the empirical realities of the respondents' current monthly expenditures (ATP boundaries), effectively dampening artificial valuation spikes.

RESULTS AND DISCUSSION

This section presents the empirical findings derived from the integrated microeconomic and behavioral demand-side models. Subsequently, a critical discussion contextualizes these insights within global cultural heritage economics frameworks. The analysis profiles the socio-economic profiling of domestic visitors, progresses through the quantitative estimation of baseline financial capacities and psychological willingness thresholds, and synthesizes these dimensions into an optimized pricing and governance matrix. Furthermore, the results provide evidence-based recommendations for balancing revenue generation, visitor accessibility, long-term conservation financing, and sustainable heritage management through adaptive pricing strategies and informed policy interventions.

Socio-economic profile and tourist income distribution

The empirical exploration at the Borobudur World Heritage Site uncovers a profound socio-economic paradox within the domestic tourism market, exposing a sharp friction between visitors' objective purchasing power and the actual fiscal requirements of heritage funding. Synthesizing principles of ecological economics, the Borobudur Temple compounds represent finite cultural and ecological endowments. Maintaining the structural integrity of these monuments necessitates a continuous allocation of financial resources to mitigate both the anthropogenic wear and the environmental externalities associated with high-density tourism. To evaluate the baseline financial resources available for such environmental management, the study first mapped the socio-economic profile and income distribution of the domestic visitors (n = 120), as summarized in Table 3. As detailed in Table 3, the socio-economic analysis reveals that the visitor demographic is predominantly comprised of the middle-income segment. Approximately 76.6% of respondents earn a monthly income of less than USD 625.00, with the highest concentration (17.5%) falling within the USD 250.00–USD 312.44 bracket. Conversely, only 12.5% of visitors reported a higher-income tier exceeding USD 875.00. These empirical findings demonstrate that the site retains its character as an accessible, socially inclusive cultural venue for diverse domestic demographics, contrasting with trends toward elite tourism spaces tailored exclusively to high-net-worth tourists. Culturally and commercially, the preservation of the Borobudur region carries enormous economic weight, with an estimated annual value reaching USD 4.2 billion (Susilo and Suroso, 2014). However, the current management model, which remains fragmented and inefficient, severely hinders the realization of this potential. Extant theoretical frameworks prioritize the immediate, localized boundaries of the temple compounds, thereby marginalizing the socio-economic integration and development of adjacent communities (Susilo and Suroso, 2014; Harsono and Wijayanto, 2022). While tourism serves as a major economic driver that increases the income of residents employed within the sector, it simultaneously introduces adverse externalities. These include rapid land-use transformations and shifting social dynamics that have systematically reduced community participation in local social activities (Sakti *et al.,* 2026). Consequently, despite these macro-economic dividends, structural barriers prevent the local community from fully capturing the economic rents generated by regional tourism. This marginalization stems from a top-down political economy where site management is heavily dictated by national tourism interests, often at the expense of localized needs (Kausar *et al.,* 2024).

ATP analysis

Economic valuation and financial capacity boundaries

Despite these moderate-income profiles, the descriptive data reveals a high baseline of objective economic capacity. The average individual monthly income of respondents stands at USD 502.76. On average, respondents allocate 22% of their total income to tourism-related expenditures. Within this dedicated travel budget, approximately 3% is earmarked exclusively for visiting the Borobudur site. Fig. 1 illustrates the empirical distribution of individual ATP_{resp} across the sampled population. Fig. 1 illustrates the empirical distribution of the respondents' ATP, which reflects a classic downward-sloping demand behavior. At the lowest interval, USD 6.25–USD 12.50, the site achieves a full 100% cumulative compliance rate. However, as the pricing tier increases to the mid-range USD 12.50–USD 18.75, individual density drops to 32% (38 respondents), reducing the cumulative compliance to 68%. Ultimately, the highest bracket, USD 18.75–USD 21.88, accommodates only a marginal 6% of the sample (7 respondents), leaving the final cumulative baseline at 63% overall, respectively.

Table 3: Distribution of respondents' monthly personal income (n = 120)

Income range (USD)	Frequency	Percentage (%)
187.50 - 249.94	4	3.3
250.00 - 312.44	21	17.5
312.50 - 374.94	17	14.2
375.00 - 437.44	12	10.0
437.50 - 499.94	15	12.5
500.00 - 562.44	17	14.1
562.50 - 624.94	6	5.0
625.00 - 687.44	6	5.0
687.50 - 749.94	2	1.7
750.00 - 812.44	2	1.7
812.50 - 937.44	3	2.5
> 875.00	15	12.5

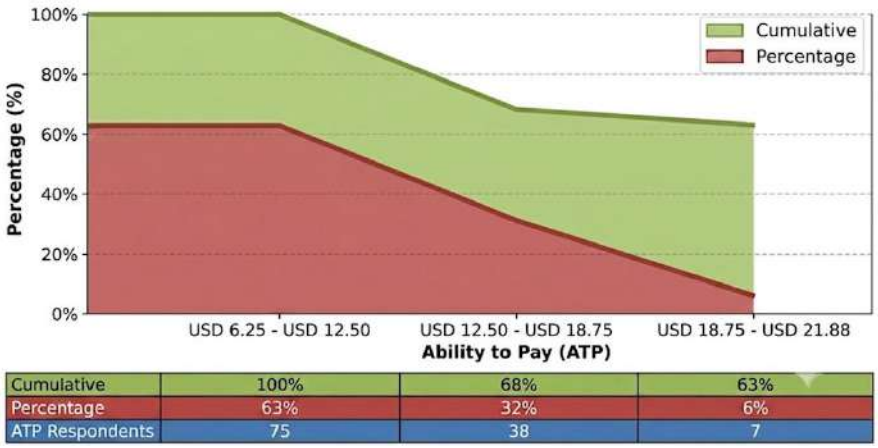

Fig. 1: Empirical distribution frequency and cumulative density curve of visitors' ATP) across designated tariff brackets (N = 120). The baseline matrix specifies absolute respondent counts (n) and relative market percentages to ensure data transparency

This rapid decay in compliance relative to incremental price increases highlights acute price elasticity of demand among domestic visitors; this suggests that any tariff escalation beyond the established lower bound would profoundly compromise the egalitarian accessibility of the heritage site.

Determinants of willingness to pay: regression analysis

To empirically unpack the determinants driving the documented divergence where empirical ATP_{resp} exceeds stated WTP, a multiple linear regression analysis was executed (N = 120). The ordinary least squares (OLS) regression model is employed to estimate the relative influence of socio-demographic determinants and behavioral attributes against the baseline stated WTP. The structural model fit parameters indicate a robust explanatory capacity, with an $R^2 = 0.542$ and an adjusted $R^2 = 0.521$, meaning that over 54% of the variance in visitor WTP is captured by the designated predictors ($F = 26.98$, $p < 0.001$). The full econometric breakdown is systematized in Table 4. As delineated by the regression outputs in Table 4, environmental awareness (X_4) emerges as the most potent determinant ($\beta = 0.842$, $p < 0.001$). These findings demonstrate that visitors with stronger intrinsic environmental and cultural heritage orientations exhibit a significantly higher WTP threshold, independent of their absolute economic wealth. Impressively, monthly income (X_2) is highly significant ($\beta = 0.315$, $p < 0.001$) but yields a lower magnitude than environmental

Table 4: Multiple linear regression estimates for determinants of visitor WTP (N = 120)

Predictor variables	Unstandardized coefficient (β)	Standard error (SE)	T-statistic	P-value	Significance
Constant	2.150	0.820	2.622	0.010	Significant
Age (X_1)	-0.045	0.022	-2.045	0.043	Significant ($p < 0.05$)
Monthly Income (X_2)	0.315	0.078	4.038	< 0.001	Highly significant ($p < 0.01$)
Travel Frequency (X_3)	0.580	0.145	4.000	< 0.001	Highly significant ($p < 0.01$)
Environmental Awareness (X_4)	0.842	0.162	5.198	< 0.001	Highly significant ($p < 0.01$)
Education Level (X_5)	0.122	0.095	1.284	0.202	Not significant ($p > 0.05$)

psychology, verifying that financial capacity (ATP) serves merely as an enabling foundation rather than a primary driver of altruistic conservation payments (Hidayat *et al.,* 2025). Conversely, age (X_1) displays a significant negative correlation (β = -0.045, p = 0.043), suggesting that younger generations demonstrate a slightly higher marginal willingness to financial mobilization for site sustainability (Lambert *et al.,* 2024). Finally, Education Level (X_5) was statistically non-significant (p = 0.202), suggesting that formal credentials do not inherently translate into proactive heritage financing in the absence of targeted, destination-specific awareness. Beyond nominal liquid budgets, the length of stay (LOS) and trip dynamics heavily dictate the socio-economic energy footprint of tourism. Fig. 2 presents the total time allocation per trip for the surveyed domestic travelers. As demonstrated by the length of stay intervals in Fig. 2, a substantial majority of domestic visitors (74%) spend between 2 and 7 days per trip. These data substantiate that the Borobudur Temple compounds function as a primary anchor destination within the regional tourism network, rather than a transient transit point. However, an extended itinerary also implies that the site-specific entry fee must compete with travel expenditures such as fuel, lodging, and logistical services within a fixed household budget. The specific financial capacity thresholds were determined by applying the microeconomic baseline models defined in the methodology to the empirical aggregates:

ATP_{gen} = USD 71.82 per family unit/trip
ATP_{resp} = USD 18.35 per individual/trip

The individual baseline (ATP_{resp} = USD 18.35) represents the absolute maximum threshold for domestic resource capture. To ensure the mathematical robustness of this baseline estimate against underlying behavioral or expenditure fluctuations, a parametric sensitivity analysis was executed. This involved varying the empirical constants of travel income allocation (P_p), target monument expenditure weight (P_t), and monthly travel frequency (T_{rs}) within a ± 20% variance boundary, as systematized in Table 5. As delineated by this stress-test matrix, the mean ATP_{resp} demonstrates solid structural resilience. Even under conservative economic contractions (Worst-case scenario), purchasing power drops only to USD 14.68, proving that our recommended strategic indicative fee spectrum (USD 6.25–9.38) is exceptionally market-resilient and safe from causing financial exclusion. To map the correspondence between these standardized thresholds and the observed distribution of visitor capacities within the sample, Fig. 1 presents the empirical frequency allocation. As verified by the distribution in Fig. 1, 65% of the market clusters strictly within the USD 6.25 to USD 12.50 range, and only a marginal 3% can absorb costs above USD 18.75. Consequently, the government's proposed USD 46.88 tariff effectively exceeds the objective affordability threshold for nearly the entire domestic population. This induces a profound market distortion characterized by social welfare exclusion that restricts access to this global UNESCO Heritage asset to high-net-worth tourists. Sustainable tourism development at Borobudur remains impeded by these distinct power imbalances and unequal benefit

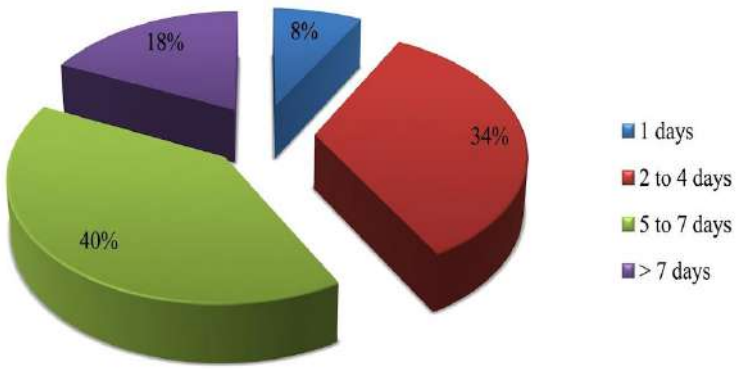

Fig. 2: Behavioral segmentation of surveyed respondents based on the total length of stay (days) at the destination (N = 120), illustrating the dominance of multi-day heritage consumers

Table 5: Sensitivity matrix of mean individual ATP estimates under variance bands (20%)

Simulation scenario	Parameter shifts	Mean ATP estimate (USD)	Implication for strategic range (USD 6.25–9.38)
Worst-Case Scenario	-20% Lower Bound (P_p, P_t, T_{rs})	USD 14.68	Recommended dynamic pricing remains highly affordable
Baseline Scenario	Empirical Sample Mean (Default)	USD 18.35	Strategically centers well above the operational pricing floor
Best-Case Scenario	+20% Upper Bound (P_p, P_t, T_{rs})	USD 22.02	Upper bound leaves exceptional fiscal room for conservation

distribution mechanisms, which are continually exacerbated by a lack of empirical management planning aligned with local realities (Adams, 2010). To mitigate these systemic funding imbalances, the introduction of a dedicated World Heritage Tax offers a viable pathway to capture tourism resources and redistribute them regionally to support heritage sites (Boronat-Navarro and Pérez-Aranda, 2020). Furthermore, transitioning away from centralized, top-down frameworks in favor of social entrepreneurship and enhanced local agency is critical to ensuring that the generated benefits directly accrue to the community rather than suffering external leakage (Madhyamapurush, 2026). Ultimately, Borobudur requires an integrated management strategy that actively balances rigorous cultural protection with inclusive tourism development, shifting the paradigm toward genuine cultural and social sustainability (Kausar *et al.,* 2024). Such an approach strengthens institutional resilience, stakeholder participation, and sustainability while safeguarding the site's cultural heritage.

WTP analysis

Assessing resource internalization and the valuation gap

While ATP measure's objective budgetary constraints, WTP elucidates the latent psychological valuation and consumer readiness to internalize the environmental externalities generated by mass tourism. In the context of the energy-environment nexus, WTP acts as a critical indicator of public support for green heritage management shifts. Fig. 3 maps the specific ticket price points expected and deemed reasonable by the respondents. The trends plotted in Fig. 3 confirm a standard inverse demand relationship between the proposed fee and community compliance: as the pricing threshold increases, explicit willingness drops. The highest expectation density falls within the USD 3.19–USD 6.25 segment (44%), demonstrating acute price sensitivity regarding standard heritage preservation fees. To quantify the baseline voluntary valuation, the MWTP mathematical formula was operationalized, wherein the

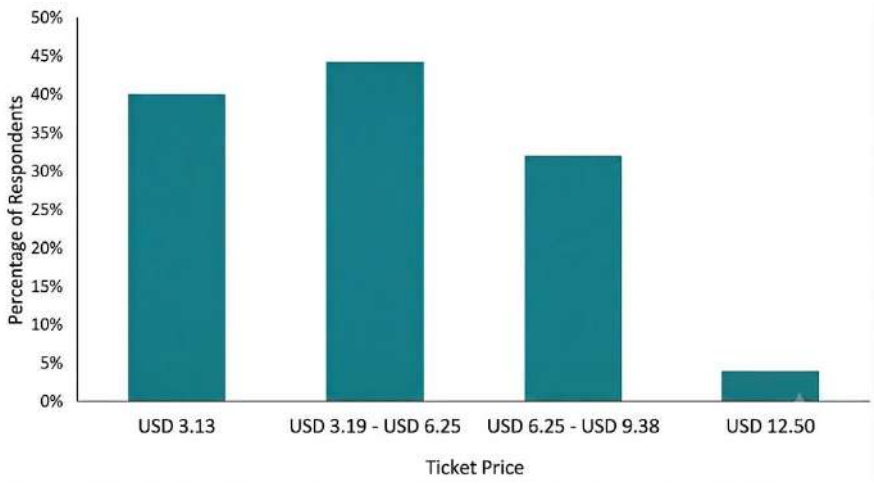

Fig. 3: Ticket prices expected by Borobudur Temple visitors

Table 6: Quantitative analysis of MWTP

Metric description	Statistical notation	Empirical value (USD)
Sample size	n	—
Aggregate stated value	$\sum=WTP_i$	387.50
Maximum outlier value	$\sum=WTP_{imax}$	12.50
Mean Willingness to Pay	MWTP	3.23

corresponding empirical outputs systematized Table 6. Applying the mathematical mean model yields an individual MWTP of USD 3.23, a conservative valuation barely floating above historical baselines. This uncovers a systemic "valuation gap" when contrasted with individual capacity (ATP_{resp} = USD 18.35), showing that while visitors possess the objective liquidity to contribute, their subjective willingness remains anchored low. This disparity arises because cultural heritage functions as a non-excludable public good, generating a systemic free-rider effect where tourists assume monument preservation falls entirely within the purview of public sector financing (Ardeshiri *et al.,* 2019). CVM methodologies demonstrate that the public often underestimates the true financial value of cultural sites, often valuing landmarks lower than natural heritage, which diminishes their willingness to contribute (Torres-Ortega *et al.,* 2018). As a result, this behavioral decoupling leaves the massive ecological burdens and carbon footprints generated by high-intensity mobility entirely uninternalized, even though the projected annual economic benefit of protecting sites like Borobudur surpasses USD 4.2 billion. Consequently, as the state bears an asymmetrical fiscal burden, the long-term structural and economic sustainability of the site becomes severely compromised. This structural deadlock pushes management toward optimized entrance charge structures to regulate congestion while generating revenue dedicated strictly to maintenance and carbon mitigation (Tuan and Navrud, 2008). Consequently, to counteract the anchoring effect that views heritage conservation as strictly state-funded, targeted public education must reframe site protection as a shared, participatory consumer obligation (Frullo and Mattone, 2024). This behavioral friction and the resulting decoupling of tourist footprints from their actual economic contributions are visually detailed through the visitor mobility and duration metrics illustrated in Fig. 2.

Synthesis analysis

The impact of ATP and WTP on pricing strategy and resource sustainability

Integrating ATP and WTP into a unified eco-economic boundary matrix maps the demand-side elasticity, offering administrators a robust mechanism to regulate visitor traffic and minimize physical degradation. Fig. 4 illustrates the comparative intersection between the objective capability curve and the subjective willingness curve. Segmenting the empirical dataset uncovers distinct price elasticities between tourist cohorts. Although family cohorts constitute the primary demographic of domestic arrivals, they exhibit a significantly higher price elasticity of demand relative to solo travelers. The proposed USD 46.88 fee raises the entry cost for an average four-member family to USD 187.50, exceeding the empirical collective household capacity (ATP_{gen}) of USD 71.82 by over 260%. Enforcing these rigid tariff risks completely shutting out domestic families, erasing cultural equity, and creating an exclusive, high-income enclave. To bridge this gap, CVM frameworks (Table 4 and Table 5) show that domestic valuation is dynamic and responsive to destination quality and transparent resource allocation. Methodologically, these WTP increases are modeled as stated preferences derived from parametric mean estimates of the survey cohort (n = 120). A repeated-measures ANOVA (RM-ANOVA) with Bonferroni-adjusted post-hoc pairwise comparisons confirmed that these multi-scenario utility shifts are highly robust and statistically significant, demonstrating consistent preference differences across pricing scenarios and validating the reliability of the experimental findings under varying environmental valuation and pricing conditions tested. To provide a holistic view, the complex dynamics linking cohort elasticities, affordability thresholds, and resulting demographic shifts are systematically integrated into a conceptual framework in Fig. 4. Implementing this balanced range accomplishes three core sustainability targets:

1. Revenue optimization: It captures higher economic rent per capita compared to historical rates, expanding local conservation funds without inducing massive visitor exclusion (Sun *et al.,* 2024).
2. Externalities internalization: This mechanism generates sustainable revenue streams to mitigate the ecological footprint, energy demands, and carbon intensity associated with high-intensity tourism (Nawaz, 2019).
3. Socio-cultural equity: It maintains democratic, inclusive access to a global heritage site, preserving socio-cultural equity and preventing the elitist distortion of public heritage goods (Mancini *et al.,* 2022).

Market segmentation and value-added scenarios: Institutional governance and green infrastructure bundling

Segmenting the empirical dataset uncovers distinct price elasticities among tourist cohorts; specifically, while family groups constitute the primary demographic of domestic arrivals, they exhibit a significantly higher price elasticity of demand relative to solo travelers. The proposed USD 46.88 fee raises the entry cost for an average four-member family to USD 187.50, exceeding the empirical collective household capacity (ATP_{gen}) of USD 71.82 by over 260%. Enforcing these rigid tariff risks completely shutting out domestic families, erasing cultural equity, and creating an exclusive, high-income enclave. To bridge this gap, CVM frameworks (Table 4 and Table 5) show that domestic valuation is inherently dynamic, shifting responsively to destination quality and transparent resource allocation. Methodologically, these WTP increases are modeled stated preferences derived from parametric mean estimates of the survey cohort (n = 120), rather than real-world transactions. A repeated measures ANOVA (RM-ANOVA) with

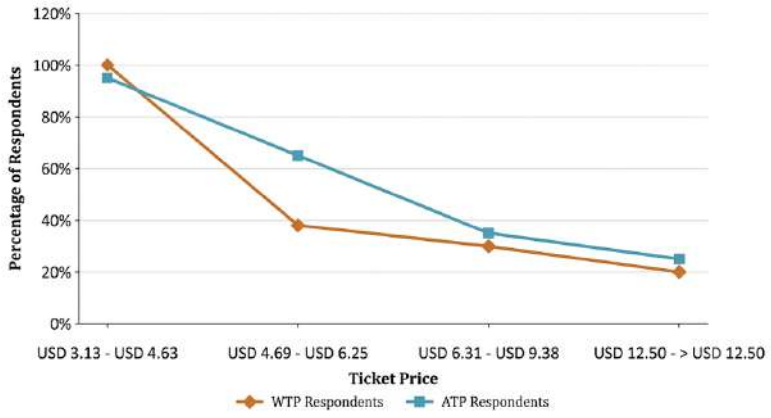

Fig. 4: Comparative analysis of ATP and WTP for Borobudur entrance fees

Bonferroni-adjusted post-hoc pairwise comparisons confirmed that these multi-scenario utility shifts are highly robust and statistically significant, rather than the result of stochastic sampling variance. As detailed in Table 7, the underlying structural frameworks and corresponding behavioral modifications are systematically compared across three progressive destination management scenarios. The behavioral responses outlined in Table 7 demonstrate that domestic user valuation is dynamic, adaptive, and highly responsive to changes in destination quality and transparent resource allocation. Transitioning Borobudur from a heavily subsidized public asset to a self-sustaining, eco-efficient framework requires that entry fee restructuring be positioned as a strategic conservation investment rather than a punitive fiscal measure. To provide a deeper econometric validation of these behavioral transitions, Table 8 details the empirical compliance rates and cumulative market retention probabilities of domestic visitors under each progressive management framework, standardized in USD. As demonstrated by the empirical configuration in Table 8, service bundling represents a mechanism of significant strategic value. Under the static status quo (Scenario 1), public compliance drops to 18% at the USD 6.25 threshold and collapses to 5% at USD 9.38, reflecting strong resistance to paying premium rates for undisclosed heritage access. Conversely, under the green management paradigm (Scenario 3)—characterized by the implementation of electric shuttles, carbon tracking, and eco-certified guiding—the demand curve exhibits a significant outward, with visitor compliance surging to 55% at a tariff of USD 6.25 and demonstrating a resilient 28% retention rate at USD 9.38. Rather than establishing an absolute field causal link, this statistical shift indicates that hypothetical green attributes alter the respondents' stated-preference hierarchy under controlled experimental valuation conditions only. Public skepticism regarding entry premiums—frequently underpinned by a profound distrust in institutional fund management, exemplified by the 13% of respondents demonstrating absolute resistance—is projected to diminish when the tariff is framed as a direct environmental investment rather than a regressive tax, thereby reinforcing the theoretical constructs of Ruijgrok (2006) and Tuan and Navrud (2008). To formally validate whether these WTP variations across the three scenarios were statistically significant, a repeated-measures ANOVA (RM-ANOVA) was executed, with normality metrics satisfying standard linear distributions and meeting all underlying model assumptions. To test the critical

Table 7: WTP elasticity and behavioral shifts under value-added service scenarios

Scenario framework	Structural service enhancements	Projected WTP shift	Macro policy implication
Scenario 1 (Status quo).	Pure entry access; standard unguided historical site walks.	0% (Baseline)	Market stagnation; pervasive free-rider effects on heritage assets.
Scenario 2 (Basic expansion).	Provision of mandatory local guides, digital audio maps, and interpretive materials.	+12%	Heightened perceived value; partial containment of visitor friction.
Scenario 3 (Green management).	Full integration of low-carbon transport (electric shuttles), carbon-offset tracking, and eco-certified site guiding.	+25%	Optimal internalization zone; links pricing directly to environmental mitigation.

Table 8: Visitor compliance distribution and cumulative probability across scenario price points (n = 120)

Standardized price point (USD)	Scenario 1 compliance (%)	Scenario 2 compliance (%)	Scenario 3 compliance (%)	Cumulative market retention (%)
3.13	100%	100%	100%	100%
4.69	44%	58%	72%	81%
6.25	18%	32%	55%	55%
9.38	5%	12%	28%	22%
12.50	1%	3%	8%	4%
> 15.63	0%	0%	1%	0%

underlying statistical assumption of validity sphericity, Mauchly's test was performed, revealing a statistically significant violation ($x^2(2) = 14.82$, $p < 0.001$). To counter this inflation of Type I error, a Greenhouse-Geisser correction was applied, adjusting the within-subject degrees of freedom via a calculated epsilon factor ($\epsilon = 0.820$). The empirical model yields a substantial effect size ($n_p^2 = 0.491$; 95% Confidence Interval [CI]: 0.412 to 0.565), demonstrating that approximately 49.1% of the variance in stated WTP is structurally explained by the bundled environmental value-added service interventions. The complete statistical distribution is presented in Table 9. Post-hoc pairwise comparisons, modified using the Bonferroni correction protocol, systematically isolate the specific directions of these econometric adjustments. The results demonstrate that the stated WTP increases significantly between the status quo and basic expansion frameworks (Scenario 1 to Scenario 2; mean difference = USD 0.85, $p < 0.001$, 95% CI: 0.54 to 1.16), and experiences an even more pronounced outward shift when transitioning to full green management services (Scenario 2 to Scenario 3; Mean Difference = USD 1.42, $p < 0.001$, 95% CI: 1.05 to 1.79). To isolate the precise direction and magnitude of these econometric adjustments across individual scenario permutations, post-hoc pairwise comparisons were executed utilizing the Bonferroni adjustment protocol. To determine if incremental value-added service layers generate statistically unique utility variations, this granular matrix offers the required empirical verification, with complete outputs compiled in Table 10. Estimated marginal means indicate that the mean difference remains significant at the 0.05 threshold after applying the Bonferroni correction for multiple comparisons. Critically, this recommended pricing corridor (USD 6.25 to USD 9.38) should not be interpreted as a mathematically absolute social-welfare optimum derived through traditional parametric maximization calculus. Rather, it denotes an empirical strategic revenue-maximizing zone counterbalanced by public compliance constraints, identified via descriptive demand-curve fitting from the multi-scenario framework. Plotting the compliance data reveals that the tariff threshold behaves as a critical inflection point (kink) along the visitor utility curve. Demand exhibits pronounced price inelasticity within the USD 4.35 to USD 6.25 interval, indicating strong visitor payment stability throughout.

Table 9: Repeated measures ANOVA results for stated WTP shifts across scenarios (Greenhouse-Geisser corrected)

Source of variance	Sum of squares (ss)	Degrees of freedom (df)	Mean square (ms)	F-statistic	P-value	Partial eta squared (η_p^2)
Destination scenarios	842.15	1.64	513.51	114.65	< 0.001	0.491
Error (within-subject)	874.32	195.16	4.48			

Table 10: Bonferroni post-hoc pairwise comparisons for stated WTP shifts across scenarios

(I) Destination scenario	(j) Destination scenario	Mean difference (i - j) (USD)	SE	*p*-value	95% confidence interval lower bound	95% confidence interval upper bound
Scenario 1 (status quo)	Scenario 2 (basic expansion)	-0.85*	0.12	< 0.001	-1.16	-0.54
	Scenario 3 (green management)	-2.27*	0.15	< 0.001	-2.63	-1.91
Scenario 2 (basic expansion)	Scenario 1 (status quo)	0.85*	0.12	< 0.001	0.54	1.16
	Scenario 3 (green management)	-1.42*	0.14	< 0.001	-1.79	-1.05
Scenario 3 (green management)	Scenario 1 (status quo)	2.27*	0.15	< 0.001	1.91	2.63
	Scenario 2 (basic expansion)	1.42*	0.14	< 0.001	1.05	1.79

Consequently, adjusting the entry tariff upward to USD 6.25 under Scenario 3 generates only marginal friction in visitor retention while successfully maximizing gross institutional revenue. However, positioning the entrance fee beyond the USD 9.38 threshold shifts the demand matrix into a hyper-elastic zone. At this upper boundary, visitor compliance undergoes a severe, non-linear contraction, dropping from 55% to 28%. This sharp contraction demonstrates that any tariff structure USD 9.38 threshold would precipitate a net institutional revenue deficit and severely compromise the socio-economic accessibility of the cultural heritage site, validating the behavioral elasticity boundaries theorized by Navrud and Ready (2002). Operationally, implementing this balanced range under a Scenario 3 structure requires an advanced, centralized institutional architecture mapped sequentially from inputs to outcomes in Fig. 5. In order to operationalize these empirical econometric insights into concrete policy initiatives, this study delineates a systematic governance framework. This proposed conceptual model, diagrammed in Fig. 5, serves as a theoretical framework to bridge multi-layered stakeholder interests with sustainable fiscal mechanisms, independent of direct frequency distributions. The proposed governance frameworks—single-gate management, centralized governance, dynamic eco-pricing, and carbon-offset tracking—are directly anchored in the empirical CVM scenarios rather than speculative extrapolations. Centralized single-gate management operationalizes the fiscal transparency required under Scenario 2 to mitigate public distrust, while a centralized national entity optimizes financial efficiency and tariff flexibility leveraging citizen donations (Jingpei *et al.,* 2025). Rigorous enforcement of this single-gate system is paramount to mitigating multi-stakeholder friction (Susilo and Suroso, 2014), maintaining strict oversight of carrying capacities, and deploy dynamic pricing mechanisms to regulate the monument's physical load during periods of peak demand (Wicaksono *et al.,* 2024). Unlike radical open-access models like China's West Lake, where removing fees generated broader regional windfalls (Wu *et al.,* 2014), Borobudur's physical vulnerability demands this protective eco-pricing. However, a critical methodological caveat remains: this study measures the public's stated willingness and capacity to finance green transitions, not objective institutional effectiveness. Despite robust public willingness to support value-added environmental pricing, practical deployment is strictly governed by institutional feasibility, operational audits, and

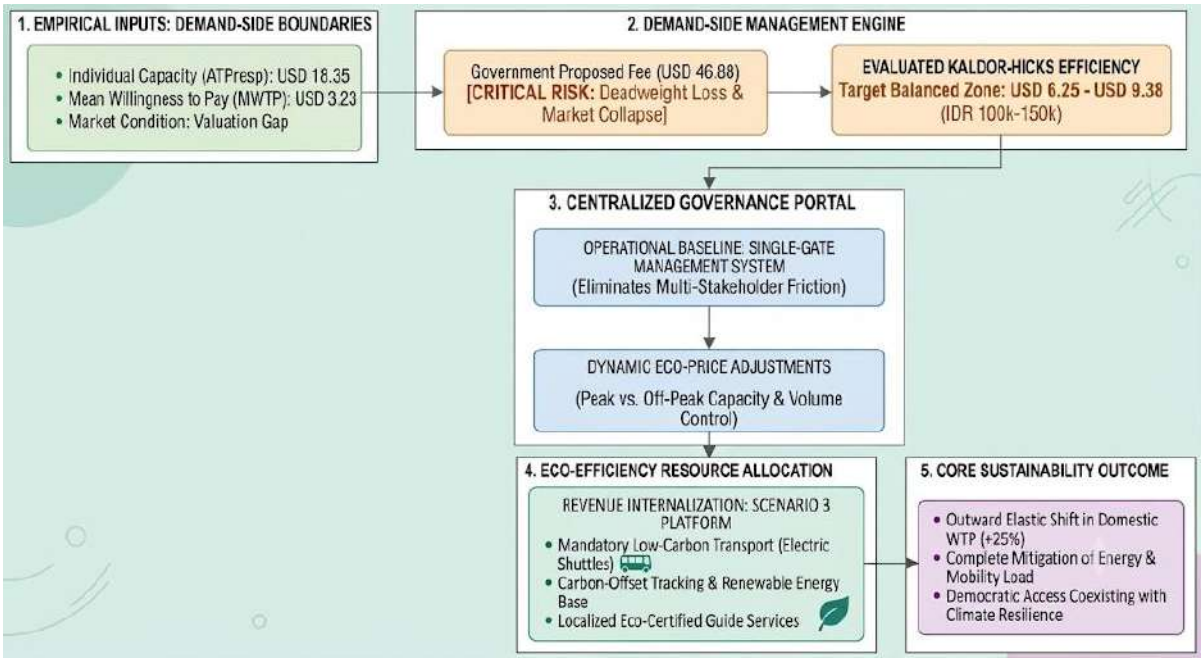

Fig. 5: Proposed conceptual model for integrated heritage governance and sustainable conservation financing derived from empirical policy synthesis

multi-stakeholder political alignment, ensuring transparency, accountability, and equitable policy implementation across stakeholders.

Socio-economic equilibrium, governance barriers, and policy synthesis

The severe market rejection was triggered by the proposed USD 46.88 tariff restructuring at the Borobudur Temple Compounds stems from a flat-rate economic barrier. By ignoring domestic ATP thresholds and broader tourist income distributions, the policy precipitated acute psychological friction centered on public access equity. To bridge this valuation gap, elasticity simulations (Table 7, Scenario 3) demonstrate that transitioning from a pure entrance tax to an eco-friendly service layer unlocks a +25% positive shift in WTP. The integration of sustainable transport modalities, including electric shuttles linked to transparent conservation and carbon-offset funds, serves as a microeconomic buffer. This structural alignment successfully converts visitor skepticism into active engagement with site preservation. Mechanistically, long-term resource sustainability is optimized via a centralized single-gate management system integrated with green transit networks, effectively eliminating historical free-rider vulnerabilities. To prevent regional economic disenfranchisement, revenues are allocated through a cross-subsidization matrix: protecting low-income domestic accessibility via differentiated pricing while financing the transition of informal local transport operators into eco-certified site transit drivers. In contrast to sites like Petra and Machu Picchu, where unmitigated overcrowding has forced the implementation of aggressive pricing policies, this paper extends international discourse by proving that sustainable mobility interventions can alleviate underlying socio-political friction. Despite institutional barriers of fragmented governance, high capital expenditures, and local transport syndicate resistance, this eco-economic boundary matrix provides a transferable

framework to balance conservation imperatives with equitable, democratic public access.

CONCLUSION

The tariff controversy at the Borobudur temple compounds highlights the challenge of balancing world heritage conservation with inclusive public access. Using an integrated microeconomic-behavioral framework, this study reveals a profound valuation gap: while domestic tourists have the financial liquidity to absorb higher fees (ATP_{resp} = USD18.35), their subjective MWTP stands at only USD 3.23 due to anchoring behavior. Enforcing the proposed USD 46.88 tariff structure is projected to precipitate a severe market collapse and induce widespread social exclusion among local stakeholders. To achieve Kaldor-Hicks efficiency, pricing should shift to an empirically calibrated optimal zone between USD 6.25 and USD 9.38, where public compliance increases by 25% when bundled with green mobility services. Operationalizing this specialized zone necessitates the establishment of a centralized national governance body endowed with localized operational autonomy, complemented by a unified single-gate management system. Revenues must be transparently channeled into low-carbon infrastructure (electric shuttles and carbon tracking) and secure equity via family-bundle discounts. To guarantee long-term socio-ecological sustainability, heritage management frameworks must integrate systematic tracking of visitor mobility dynamics alongside empirical monitoring of conservation investment outcomes. This study's limitations include its reliance on a hypothetical stated-preference framework and a purposive sample of 120 respondents, reflecting behavioral intentions rather than observed compliance. To address this empirical gap, subsequent research should evaluate the integration of international visitor cohorts to facilitate cross-subsidization structures, alongside the deployment of intelligent mobility systems. Once the green infrastructure is fully operational, future studies should combine revealed-preference methodologies, mixed-method behavioral analysis, and GIS-based tracking with macro-level carbon accounting frameworks to measure actual monetary trade-offs and precise emission reductions.

AUTHOR CONTRIBUTIONS

B. Hasibuan, the corresponding author, has contributed to conceptualizing the research framework, developing the integrated microeconomic and behavioral demand-side model, and drafting the original manuscript. N. Gusdini, the economic boundary matrix, performed the mathematical calibrations for the Kaldor-Hicks efficiency and revised the methodology section. F. Eddyono managed the data collection at the Borobudur World Heritage Site, executed the CVM and ATP framework surveys, and prepared the data visualization. B. Hasibuan conducted the green scenario simulations, analyzed the low-carbon service infrastructure variables, and formatted the graphical abstract. N. Gusdini, supervising the study, provided a critical review of the implications of sustainable heritage governance policies and secured institutional support. All authors have read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
ANOVA	Analysis of variance
ATP	Ability to pay
ATP_{gen}	Ability to pay general (collective household capacity)
ATP_{resp}	Ability to pay respondent (individual financial capacity)
BS	Bureau of statistics
CVM	Contingent valuation method
Eq.	Equation
LOS	Length of stay
MWTP	Mean willingness to pay
UNESCO	United Nations Educational, Scientific and Cultural Organization
USD	United States dollar
WTP	Willingness to pay
$MWTP_{max}$	Maximum willingness to pay value
SE	Standard error
NOAA	National oceanic and atmospheric administration

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ORIGINAL RESEARCH ARTICLE

Eco-industrial park planning based on industrial ecology and ecological network analysis

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ABSTRACT

BACKGROUND AND OBJECTIVES: Eco-industrial parks integrate industrial ecology with spatial planning to improve resource efficiency and reduce environmental impacts in sustainable industrial development. The integration of standard subjective weighting methods, notably the analytic hierarchy process, into conventional geographical information system-based multi-criteria decision analysis for eco-industrial park selection introduces potential biases and limits the replicability of the findings. Additionally, suitability assessment and industrial symbiosis network design are often addressed separately, limiting their systematic integration. The study objectives were to develop an integrated geographical information system-based multi-criteria decision analysis and ecological network analysis framework for planning the East Baghdad Village Eco-Industrial Park in North Sinai Governorate, Egypt.

METHODS: The framework comprises six sequential phases: 1) literature review and gap analysis; 2) geographical information system-based multi-criteria decision analysis of thirteen environmental, infrastructural, and socio-economic criteria; 3) entropy weight method objective weighting cross-checked using the criteria importance through intercriteria correlation method; 4) weighted overlay suitability mapping and ecological network analysis evaluation using total system throughput, cycling index, Finn cycling index, average path length, and network density; 5) industrial symbiosis network design; and 6) sensitivity analysis. Model robustness was verified via a ±20% criterion weight perturbation analysis using standard classification stability metrics.

FINDINGS: Geographical information system-based multi-criteria decision analysis identified 847 hectares (23.4 percent) of the 3,619-ha study area as highly suitable for industrial development. Environmental sensitivity, flood risk, and transportation accessibility were the most influential criteria. Ecological network analysis yielded a total system throughput of 2.87 million tonnes per year, a cycling index of 0.34, a Finn cycling index of 0.41, and an average path length of 2.3, indicating circularity potential within the range reported for established eco-industrial parks. Compared to a conventional industrial configuration, the projected symbiotic exchanges demonstrate significant potential for minimizing both resource consumption and waste generation. Sensitivity analysis confirmed high classification stability (0.935; mean map-consistency coefficient = 0.875).

CONCLUSION: This study introduces an integrated planning workflow that sequentially combines geographical information system-based multi-criteria decision analysis and ecological network analysis to evaluate both spatial suitability and industrial symbiosis workflow. The framework provides a replicable approach for supporting sustainable eco-industrial park planning in arid, data-scarce, and resource-constrained regions.

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INTRODUCTION

Global industrialization continues to intensify pressures on natural resources and ecosystems, driving urgent demand for sustainable industrial development models (Shahat *et al.,* 2026). Eco-industrial parks (EIPs) represent a primary paradigm for balancing industrial expansion with environmental sustainability (Laili *et al.,* 2024). By operationalizing core tenets of industrial ecology—most notably industrial symbiosis—these parks facilitate localized resource sharing, waste mitigation, and the establishment of circular material loops among co-located enterprises (Frosch and Gallopoulos, 1989; Chertow, 2000). The EIP concept has evolved substantially from early theoretical formulations (Frosch and Gallopoulos, 1989) into globally implemented frameworks supported by international organizations including the United Nations Industrial Development Organization (UNIDO, 2019) and the World Bank (2020). Operational examples including the Kalundborg Symbiosis in Denmark, the Tianjin Economic-Technological Development Area (TEDA) in China, and the Ulsan Eco-Industrial Park in South Korea have demonstrated the practical viability of industrial symbiosis at scale (Zhu *et al*., 2007; Park *et al*., 2008; Tian *et al*., 2014). Nevertheless, replicating these successful outcomes within arid regions of developing nations presents a profound challenge, primarily due to acute data scarcity and restricted institutional capacity (Hong and Gasparatos, 2020). Planning an effective EIP framework presents a complex spatial challenge, requiring the simultaneous balancing of competing criteria—ranging from infrastructure and resource accessibility to environmental conservation, flood mitigation, and land-use compatibility (Feizizadeh and Blaschke, 2013; Malczewski and Rinner, 2015). Geographical information system-multicriteria decision analysis (GIS-MCDA) provides a systematic framework for integrating these heterogeneous spatial datasets into composite suitability assessments (Eastman *et al*., 1995). However, conventional GIS-MCDA approaches for EIP site selection exhibit a critical methodological limitation: reliance on subjective expert weighting methods principally the analytic hierarchy process (AHP) (Saaty, 1980), which introduce decision-maker bias, reduce inter-study comparability, and compromise reproducibility (Wang and Lee, 2009; Zandi *et al*., 2021). Furthermore, existing literature on EIP site selection frequently decouple spatial suitability assessment from the design of industrial symbiosis networks. This fragmentation precludes the concurrent optimization of both the spatial and functional dimensions governing EIP performance (Hong and Gasparatos, 2020). This study presents the first integrated GIS-MCDA– ecological network analysis (ENA) framework for EIP planning in an arid, developing-country context (North Sinai, Egypt). Entropy weight method (EWM) replaces subjective AHP weighting with a reproducible, operator-independent weighting scheme derived from spatial data properties, while ENA quantifies network-level circularity indicators for holistic performance benchmarking against established EIPs. The primary objectives of this study are fourfold: a) to develop an objective, reproducible GIS-MCDA framework integrating the EWM for spatial suitability assessment of EIP sites in North Sinai, Egypt; b) to execute a comprehensive regional spatial suitability analysis to identify priority locations; c) to design an industrial symbiosis network consisting of 18 facilities organized across four industrial clusters and interconnected by 23 symbiotic exchange links; and d) to evaluate network performance using ENA based on five quantitative indicators, benchmarking the outcomes against established operational EIPs, including Kalundborg, Guitang, Ulsan. This study was conducted in East Baghdad Village of North Sinai Governorate, in 2026.

MATERIALS AND METHODS

Study area

The study area encompasses 3,619 ha in the East Baghdad Village of North Sinai Governorate, Egypt with approximately 31°05’ north (N), 32°20’ east

(E), situated approximately 45 km northeast of Al-Arish city. The region is characterized by an arid climate with mean annual precipitation below 100 millimeters (mm), predominantly flat to gently undulating terrain with 0–5 percent (%) slope, and predominantly sandy and sandy-loam soils. Geographically positioned within the Sinai Peninsula, the site aligns with a region of critical strategic and developmental significance within Egypt's national planning frameworks. The study area was selected based on four primary criteria: 1) availability of undeveloped state-owned land suitable for large-scale industrial development; 2) proximity to the Al-Salam Canal, providing a potential freshwater source; 3) access to the national road network and Port Said maritime infrastructure; and 4) designation within the North Sinai Industrial Development Zone under the Sinai Development Strategy 2030 (Egyptian Ministry of Planning, 2023). Collectively, these attributes underscore the strategic viability of the East Baghdad Village site as an optimal location for establishing an EIP development. Fig. 1 presents the study area location map showing the Proposed East Baghdad Village Eco-Industrial Park site within North Sinai Governorate, Egypt, including regional context and site boundaries.

Integrated GIS-MCDA–ENA research framework

The proposed framework integrates GIS-MCDA, the EWM, and ENA within a six-phase sequential workflow. Fig. 2 presents the overall framework architecture, illustrating the data flow and methodological linkages among the six phases. Crucially, this integration operates via a sequential rather than a simultaneous architecture: GIS-MCDA suitability mapping is completed first and its outputs specifically the High and Very High suitability zones directly constrain the spatial extent available for cluster allocation, which in turn defines the node set and physical adjacency structure for ENA. Consequently, the two components are linked via a structured data handoff rather than being concurrently optimized within a unified mathematical formulation.

Data acquisition and preprocessing

Thirteen spatial criteria were selected through a systematic literature review (UNIDO, 2019; Hong and Gasparatos, 2020; World Bank, 2020) and consultation with experts from the Department of Environmental Planning. The evaluation criteria were established based on historical literature recommendations and screened for regional suitability regarding environmental, planning, and data availability constraints. Accordingly, thirteen specific criteria encompassing environmental, infrastructural, and socio-economic dimensions were established to evaluate EIP suitability, as detailed in Table 1. Industrial ecology principles are explicitly embedded in the GIS-MCDA criterion set, ensuring that the highest-ranked sites are positionally advantageous for subsequent symbiosis network formation. Three criteria directly operationalise symbiosis feasibility: industrial land proximity (C9) minimises inter-facility material transfer distances; road network proximity (C7) enables logistics integration; and electricity grid proximity (C10) supports shared energy infrastructure. The highest-weighted environmental criterion, ecological sensitivity (C12, w=0.156), simultaneously minimises ecological disruption consistent with industrial ecology's principle of minimising environmental burden. By harmonizing spatial optimization with the core tenets of industrial ecology, this framework transitions GIS-MCDA site selection and ENA network design from independent sequential phases into interdependent, mutually reinforcing stages of an integrated planning framework. All raster datasets were co-registered to a common coordinate system (WGS84 UTM Zone 36N) and resampled to a uniform 30 m spatial resolution using bilinear interpolation for continuous datasets (elevation, slope, groundwater depth, and spectral indices).

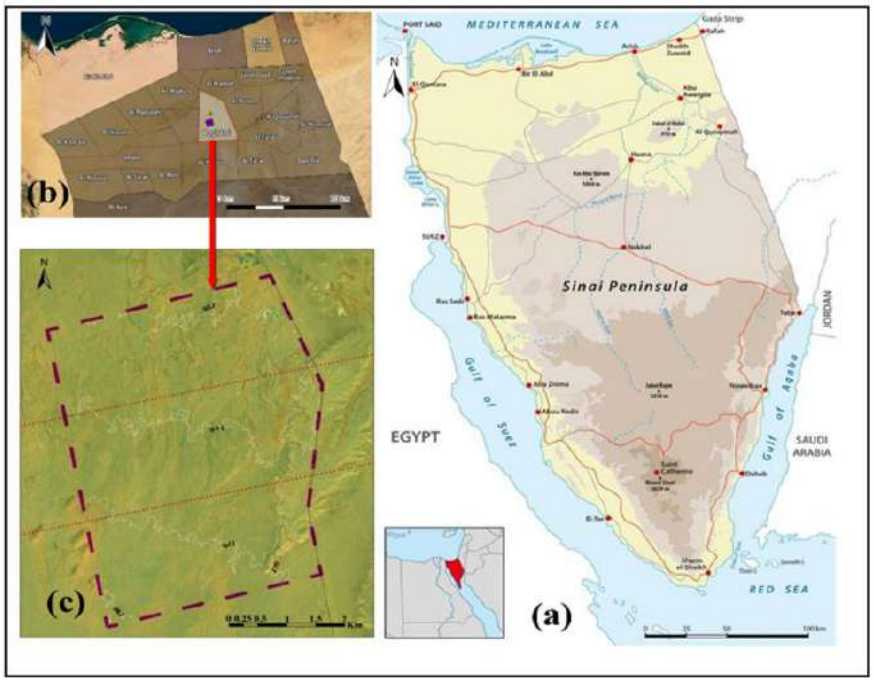

Fig. 1: Geographical location of the study area in the North Sinai Governorate and El-Hasana Center within North Sinai Governorate, highlighting the Baghdad area as well as Baghdad Village

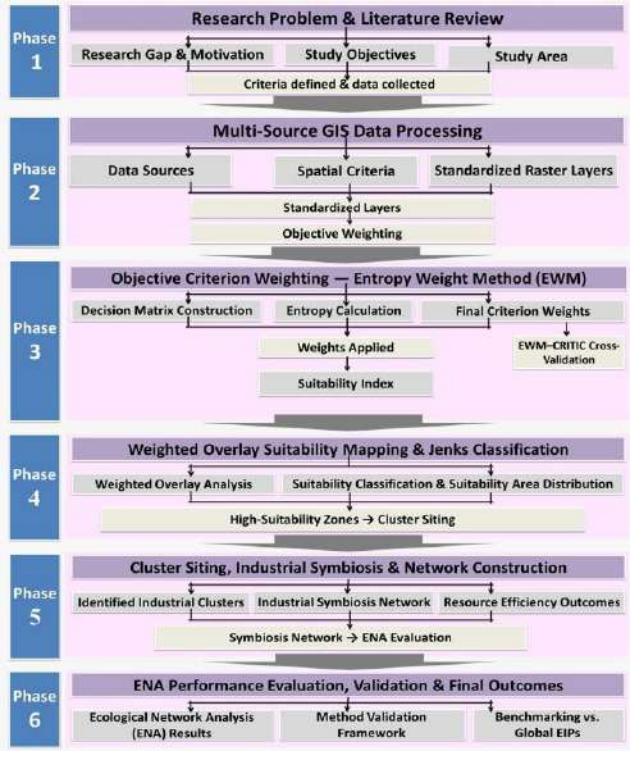

Fig. 2: Integrated GIS-MCDA–ENA research framework

Table 1: summarizes the spatial criteria, data sources, and preprocessing methods employed in this study

Criterion	Type	Data source	Resolution	Preprocessing
C1: Slope	Cost	Shuttle radar topography mission (SRTM) DEM	30 m	Slope calculation; reclassification to 1–5 scale
C2: Elevation	Cost	SRTM DEM	30 m	Elevation extraction; normalization
C3: Soil type	Cost	FAO soil map	1:1,000,000	Rasterization; suitability scoring
C4: Land use/land vover	Cost	Sentinel-2 (2023)	10 m	Supervised classification; resampling to 30 meters (m)
C5: Distance to roads	Cost	Open street map	Vector	Euclidean distance calculation; normalization
C6: Distance to utilities	Cost	Egyptian Electricity Holding Co.	Vector	Euclidean distance calculation; normalization
C7: Distance to water	Cost	Al-Salam Canal Authority	Vector	Euclidean distance calculation; normalization
C8: Distance to urban areas	Benefit	OpenStreetMap	Vector	Euclidean distance calculation; normalization
C9: Distance to protected areas	Benefit	Egyptian Environmental Affairs Agency	Vector	Euclidean distance calculation; normalization
C10: Groundwater depth	Cost	Ministry of Water Resources and Irrigation	Point data	Inverse distance weighting (IDW) interpolation; normalization
C11: Flood risk	Cost	SRTM DEM + precipitation data	30 m	Hydrological modeling; risk classification
C12: Environmental sensitivity	Cost	Composite (vegetation, soil, water)	30 m	Weighted overlay; normalization
C13: Transportation accessibility	Benefit	Road network + port data	Vector	Network analysis; travel time calculation

To maintain discrete class boundaries, categorical raster datasets—specifically land use/land cover (LULC) and soil type—were resampled utilizing nearest-neighbor interpolation. The flood-risk map was derived directly at 30 metre (m) resolution from DEM-based flow accumulation analysis and required no resampling. Sentinel-2 multispectral imagery (10-m resolution, acquired in 2023) was used for supervised land use/land cover classification and subsequently resampled to 30 m for consistency. Distance-based criteria (C5–C9, C13) were derived from vector datasets using Euclidean distance calculations in ArcGIS 10.8. To generate a continuous spatial surface, groundwater depth data (C10), originally collected as discrete point measurements, were spatially interpolated utilizing the IDW method. All criteria were normalized to a [0, 1] scale prior to EWM application.

EWM for objective criterion weighting

The EWM derives criterion weights from the information entropy of the normalized spatial data distributions. Under this approach, criteria demonstrating higher spatial variability are assigned greater weights, as their pronounced variance offers superior discriminatory power for differentiating suitable from unsuitable locations, thereby enhancing decision accuracy, spatial reliability, and overall site selection effectiveness (Zou *et al*., 2006; Lotfi and Fallahnejad, 2010). The EWM calculation proceeds through six sequential steps, as follows:

Step 1: Normalization

For benefit criteria (higher values indicate higher suitability), using Eq. 1 (Zou *et al*., 2006):

$$x_{ij}^{*} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

For cost criteria (lower values = higher suitability), using Eq. 2 (Zou *et al*., 2006):

$$x_{ij}^{*} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (2)$$

Where: xij is the raw value of criterion j at pixel i, and xij* is the normalized value in the range [0, 1].

Step 2: Probability matrix

The normalized values are converted to a probability matrix representing the relative contribution of each pixel to criterion j's total information, using Eq. 3 (Shannon, 1948):

$$p_{ij} = \frac{x_{ij}^*}{\sum_{i=1}^{n} x_{ij}^*} \quad (3)$$

Where: pij represents the proportion of criterion j's total information content contributed by pixel i.

Step 3: Entropy calculation

Entropy is then calculated for each criterion from the probability matrix, using Eq. 4 (Shannon, 1948):

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \quad (4)$$

Where: Ej ∈ [0, 1] is the entropy of criterion j, and n is the total number of pixels. Higher entropy indicates more uniform spatial distribution (lower information content).

Step 4: Divergence

Divergence quantifies the information utility of each criterion by measuring the departure from maximum entropy, using Eq. 5 (Zou *et al.*, 2006):

$$d_j = 1 - E_j \quad (5)$$

Where: dj is the divergence (information content) of criterion j. Higher divergence indicates greater spatial variability and thus higher discriminatory power.

Step 5: Weight derivation

Objective weights are derived by normalizing the divergence values across all criteria, ensuring that the weights sum to unity, using Eq. 6 (Zou *et al.*, 2006):

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (6)$$

Where: wj is the objective weight of criterion j, and m = 13 is the total number of criteria. Weights are normalized such that Σwj = 1.

Reproducibility note: the study area raster comprised approximately 40,211 pixels at 30 m resolution. Prior to the EWM calculation, water bodies and missing-data pixels were excluded, restricting the final analysis to 38,900 valid land pixels. To avoid undefined logarithm values, a small constant ε = 10^{-6} was added to any zero normalized values before computing the probability matrix (Eq. 3) and entropy (Eq. 4). This procedure is executed to ensure numerical stability, computational robustness, reproducibility, and consistent entropy estimation across all evaluated criteria, conforming to standard practices in EWM applications (Lotfi and Fallahnejad, 2010).

Step 6: Weighted overlay

The final suitability score for each pixel is computed as a weighted linear combination of all normalized criteria, using Eq. 7 (Malczewski and Rinner, 2015):

$$S_i = \sum_{j=1}^{m} w_j \times x_{ij}^* \quad (7)$$

Where: Si is the final suitability score for pixel i, ranging from 0 (unsuitable) to 1 (highly suitable).

Suitability classification and mapping

Final suitability scores were classified into five categories using the equal-interval classification method, which divides the normalized suitability index (0–1) into five equal intervals: Very low (0.00–0.20), Low (0.20–0.40), Moderate (0.40–0.60), High (0.60–0.80), and very high (0.80–1.00). Consequently, this approach provides transparent, consistent, and reproducible thresholds for interpreting normalized suitability scores, allowing effective cross-regional suitability comparisons. Fig. 3 presents the spatial suitability map for the study area.

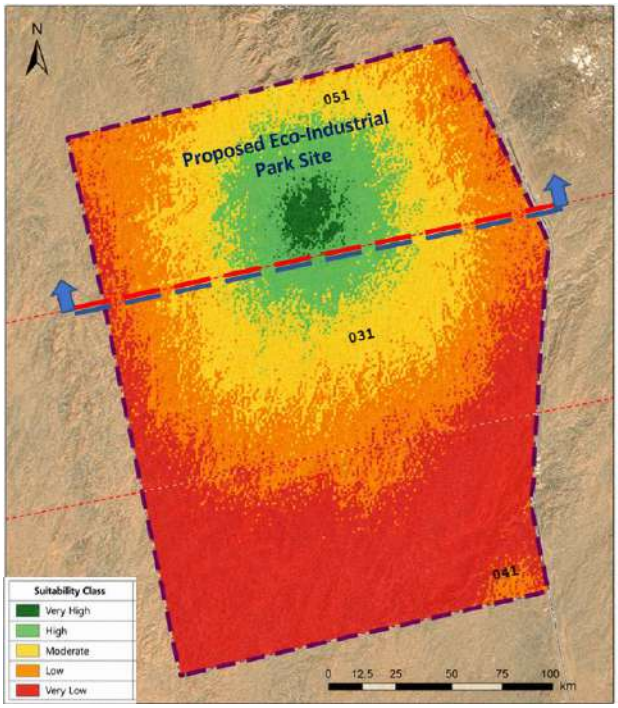

Fig. 3: Spatial suitability map for the proposed East Baghdad Village Eco-Industrial Park

Industrial Cluster Selection and Justification

Four industrial clusters were selected for the Proposed East Baghdad Village Eco-Industrial Park based on multiple strategic and environmental criteria: 1) compatibility with North Sinai's existing industrial base and raw material availability; 2) potential for high-value industrial symbiosis relationships; 3) alignment with Egypt's Vision 2030 industrial diversification targets; and 4) consistency with UNIDO (2019) guidelines for EIP cluster composition in developing countries. The selected clusters are: A fifth selection criterion — resource efficiency and industrial symbiosis potential — was embedded in the cluster composition. Each designated sector was systematically evaluated based on its capacity to generate or absorb by-products compatible with co-located industries: the cement plant generates fly ash with 32,000 tons per year (t/y) and carbon dioxide (CO_2) (8,500 t/y) absorbed by downstream facilities; the glass facility produces recoverable process heat (18 megawatt (MW)); the food processing cluster generates organic waste (4,200 t/y) suitable for fertilizer production; and the logistics hub facilitates material transfer with minimal additional infrastructure. This criterion ensures that the selected industrial composition maximizes network circularity potential from the outset of the design phase. To verify the robustness of the cluster selection, four alternative configurations were systematically evaluated prior to finalizing the proposed design. The proposed four-cluster configuration (construction materials, ceramics and glass, food processing, logistics) generated 23 symbiotic links, compared with 12–17 links in the alternative configurations considered. Consequently, the selection of the proposed configuration was justified by this superior symbiotic connectivity, alongside strategic alignment and resource availability criteria (Zhang *et al.,* 2013).

Construction materials cluster

Cement production 500,000 t/y, concrete batching with 300,000 cubic meters per year (m^3/y), gypsum board manufacturing (50,000 t/y),

and aggregate processing (200,000 t/y). Leveraging the abundant limestone and gypsum deposits of North Sinai, this cluster effectively supplies the regional construction sector.

Ceramics and glass cluster

Ceramic tile production with 2 million square meters per year (Mm^2/y), sanitary ware manufacturing (100,000 units/y), and glass container production (50,000 t/y). This cluster generates high-temperature waste heat, which is structurally suitable for symbiotic exchange with adjacent facilities.

Food Processing Cluster

Olive oil extraction (10,000 t/y), date processing (15,000 t/y), fish processing (8,000 t/y), and cold storage (30,000-ton capacity). This cluster generates organic waste streams viable for biomass fuel conversion and yields wastewater amenable to reclamation for landscape irrigation.

Logistics and warehousing cluster

Freight consolidation, cold chain logistics, and packaging services. This cluster provides supply chain coordination functions and serves as a material flow hub connecting the three production clusters with regional markets and Port Said maritime infrastructure. Material and energy input–output dynamics between facilities were determined in three stages. First, sector-level material and energy flows were compiled from facility design specifications and supplemented with published industrial benchmarks (UNIDO, 2019; IEA, 2021). Second, the development of bilateral compatibility matrices for each potential exchange pair facilitated the identification of technically viable by-product recovery opportunities. Third, flow magnitudes were derived using stoichiometric conversion factors applied to design capacity parameters, yielding the annual flow estimates (e.g., fly ash 32,000 t/y, process heat 18 MW, CO_2 8,500 t/y, organic waste 4,200 t/y) that populate the 18×18 material-flow matrix. Four assumptions underpin the ENA application: 1) Consistent with conventional industry protocols for planned systems, the evaluation assumed steady-state operation at full design capacity, totaling 7,200 annual operating hours (Fath and Patten, 1999); 2) deterministic point estimates for all material and energy flows, with stochastic variability not explicitly modelled but partially addressed through sensitivity analysis. 3) the system boundary encompasses intra-park flows only, excluding upstream supply chains and downstream product distribution; and 4) In accordance with standard design-phase protocols, all technically feasible exchange configurations are assumed to be economically viable at design capacity, recognizing that post-commissioning economic validation will be required.

Ecological network analysis construction

ENA was applied to quantify material and energy flows within the proposed industrial symbiosis network and evaluate five system-level performance indicators. The network comprises 18 facilities (nodes) and 23 symbiotic exchange links (edges), as illustrated in Fig. 4. The ENA adjacency matrix $F = [f_{ij}]$ represents material flows (t/y) from node i to node j. Flow magnitudes were estimated using: 1) facility design capacities; 2) material balance calculations based on stoichiometric relationships and industry-standard conversion factors; and 3) analogous operational data from comparable EIPs reported in the literature (Park *et al.*, 2008; Sokka *et al.*, 2011; Tian *et al.*, 2014). All ENA outputs represent scenario-based modeled projections for the proposed, non-operational EIP; consequently, these findings should be interpreted within the context of these predictive boundaries. Fly ash (32,000 t/y) is generated from coal combustion in the cement plant pre-calciner, at approximately 12% of coal input by mass, and is collected via electrostatic precipitators (ESP) for transfer to concrete batching and ceramic tile production. To construct the ENA network, exchange pathways were systematically identified and integrated

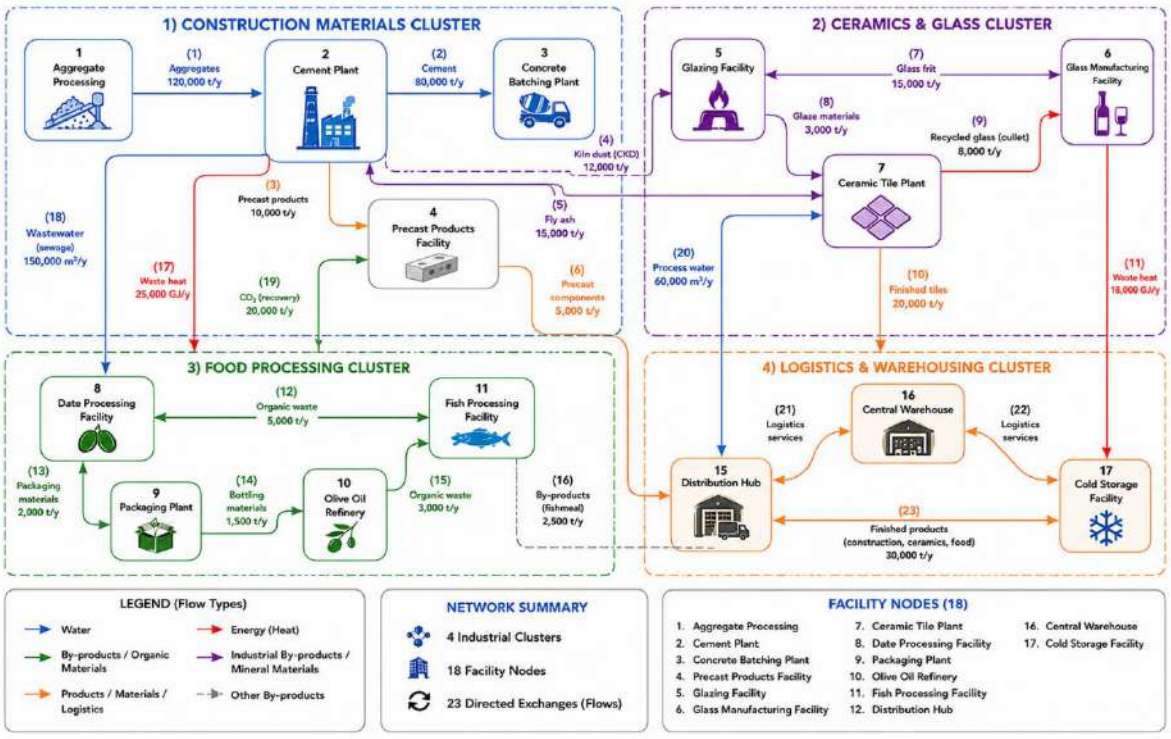

Fig. 4: Industrial symbiosis network diagram for the proposed ENA scenario

using a structured four-step protocol: 1) systematic screening of candidate sector pairs for by-product compatibility using established industrial symbiosis taxonomies (Chertow, 2007; UNIDO, 2019); 2) volumetric compatibility checking to confirm that by-product generation rates and receiving-facility absorption capacities are of commensurate magnitude; 3) iterative computation of ENA indicators (CI, FCI, APL, ND, TST) for successive network configurations, enabling evaluation of the marginal contribution of each candidate exchange link; and 4) prioritisation of high-CI and high-FCI links in the spatial layout to ensure that the most circularity-enhancing exchanges are supported by proximity and shared infrastructure. To ensure robustness, the ENA results underwent pre-implementation validation via three complementary approaches: i) benchmarking against analogous operational EIPs (Kalundborg, Guitang, Ulsan), which confirms that the derived indicators CI=0.34, FCI=0.41, and APL=2.3 fall within the expected performance envelope for EIP networks of comparable scale and sector composition; ii) material balance cross-checking, in which all inflows and outflows for each facility node were verified for mass conservation; and iii) expert peer assessment by environmental planning specialists at Cairo University, who reviewed the key exchange flow estimates (fly ash 32,000 t/y, process heat 18 MW, organic waste 4,200 t/y) and confirmed their technical plausibility against operational analogues. To identify and quantify exchange flows, a systematic procedure was developed by integrating facility design specifications, the UNIDO Industrial Symbiosis Database (UNIDO, 2019), and Chertow's (2007) by-product exchange taxonomy. To convert design capacity parameters into accurate annual flow estimates, stoichiometric material balances were systematically applied. The four principal exchange flows quantified are: fly ash from the

cement plant to brick manufacturing (32,000 t/y), process heat from the glass facility to food processing (18 MW), CO_2 from the cement plant to on-site greenhouses (8,500 t/y), and organic waste from food processing to fertilizer production (4,200 t/y).

Five network performance indicators were calculated:

1. Total system throughput (TST):

The total system throughput measures, using Eq. 8 (Layton *et al*., 2016):

$$\text{TST} = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} \quad (8)$$

Where: TST quantifies the total magnitude of material flows within the network, indicating overall system scale and activity level.

2. Cycling index (CI):

The cycling index measures the proportion of material flows that circulate within the network relative to total system throughput, using Eq. 9 (Layton *et al*., 2016):

$$\text{CI} = \frac{\text{Cycled Flow}}{\text{TST}} \quad (9)$$

Where: CI measures the proportion of material flows that are recycled within the network, indicating circularity and resource efficiency. Higher CI values reflect greater industrial symbiosis intensity.

3. Network density (ND):

Network density measures the proportion of realized connections relative to all theoretically possible connections in the network, using Eq. 10 (Layton *et al*., 2016):

$$\text{ND}_i = \frac{\sum_j f_{ij}}{\text{TST}} \quad (10)$$

Where: ND quantifies network connectivity as the ratio of realized to maximum possible connections. For the proposed EIP network: ND = L/[N(N−1)/2] = 23/[18×17/2] = 23/153 = 0.150, where L = 23 symbiotic links and N = 18 facilities. Network control (NC) is computed separately at the node level.

4. Average path length (APL):

Average path length is computed as the mean shortest path between all node pairs in the network, reflecting network compactness and material transfer efficiency, using Eq. 11 (Layton *et al*., 2016):

$$\text{APL} = \frac{1}{n(n-1)} \sum_{i \neq j} d_{ij} \quad (11)$$

Where: *dij* is the shortest path length between nodes *i* and *j*. APL indicates network compactness and efficiency of material transfer.

5. Finn cycling index:

The Finn cycling index adjusts the cycling index by excluding dissipative flows such as emissions and waste disposal, providing a complementary measure of circularity, using Eq. 12 (Layton *et al*., 2016):

$$\text{FCI} = \frac{\text{Cycled Flow}}{\text{TST} - \text{Dissipative Flow}} \quad (12)$$

Where: FCI adjusts CI by excluding dissipative flows (emissions, waste disposal), providing a complementary measure that characterizes the circularity of recoverable flows. Mathematically, FCI > CI (FCI = 0.41 > CI = 0.34) because the FCI denominator excludes dissipative flows, reducing the reference base and yielding a higher circularity ratio.

Validation and sensitivity analysis

Framework robustness was assessed through three complementary validation approaches. To execute a robust quantitative uncertainty analysis, a ±15% perturbation was simultaneously applied to all primary exchange flows. Under this perturbation range, the cycling index remained within CI=0.29–0.39 and the Finn cycling index

within FCI=0.35–0.47, indicating that the principal ENA findings are robust to plausible input data uncertainty. The stability of the classification was validated through a criterion weight sensitivity analysis to address spatial data uncertainty, with the Overall Accuracy (OA) deviating by a marginal ±0.022 from the baseline OA=0.935. Irreducible design-phase uncertainty arising from the absence of operational facility-level inventory data cannot be eliminated through sensitivity analysis alone and will require post-commissioning validation. measurement and validation once the park becomes operational.

First: Internal spatial consistency was evaluated by verifying that the spatial distribution of highly suitable areas (high and very high classes) was consistent with the known physical geography of the study area - specifically, that high-suitability zones corresponded to flat, low-elevation terrain with good road access and proximity to the Al-Salam Canal, as expected from the criterion weights. Given that the proposed EIP at the East Baghdad Village is currently non-operational, validation is necessarily confined to internal model consistency, precluding direct comparison with observed outcomes.

Second: EWM-derived weights were compared with weights independently derived using the criteria importance through intercriteria correlation (CRITIC) method (Diakoulaki *et al*., 1995) and hypothetical equal weights (1/13 ≈ 0.077 per criterion) to assess methodological convergence. Spearman's rank correlation coefficient (ρ) was calculated between EWM and CRITIC weight rankings. The CRITIC method constructs a correlation matrix among all 13 criteria. The highest positive correlation was observed between C12 (Environmental sensitivity) and C3 (Slope) (r = 0.68), while C11 (Flood risk) and C2 (Elevation) exhibited a moderate negative correlation (r = −0.42). All inter-criterion correlations were below the multicollinearity threshold of |r| = 0.85, confirming criterion independence.

Third: A systematic sensitivity analysis was conducted by perturbing each criterion weight individually by ±20% and recalculating suitability scores. To provide a rigorous measure of classification robustness, the agreement between the perturbed and baseline maps was quantified using OA and the map-consistency coefficient (κ). Remaining criterion weights were proportionally renormalized to maintain Σwj = 1 following each ±20% perturbation. It should be emphasized that both OA and the map-consistency coefficient (κ) serve strictly as metrics ofclassification stability relative to the unperturbed baseline suitability map; rather than as measures of external validation accuracy against independent field-reference data.

RESULTS AND DISCUSSION

EWM-derived criterion weights

Table 2 presents the EWM-derived objective weights, entropy values, and divergence scores for the 13 spatial criteria. Environmental sensitivity (C12, criterion weight [w= 0.156), Flood risk (C11, w = 0.143), and Transportation Accessibility (C13, w = 0.138) received the highest weights, indicating their greater contribution to distinguishing suitable locations. Conversely, Distance to Urban Areas (C8, w = 0.039) and Distance to Utilities (C6, w = 0.045) were assigned the lowest weights, primarily due to their relatively uniform spatial distribution across the study area. Fig. 5 displays the criteria ranked in descending order according to their EWM-derived weights, thereby delineating their relative influence on the spatial distribution of suitability values across the study area. This pattern aligns with the predominantly rural landscape of the East Baghdad Village, a region characterized by a sparse and relatively uniform distribution of urban areas and utility infrastructure, with limited industrial and transportation development.

Table 2: EWM-derived criterion weights and entropy values

Criterion	Entropy (E_j)	Divergence (d_j)	Weight (w_j)	Rank
C1: Slope	0.912	0.088	0.067	8
C2: Elevation	0.895	0.105	0.080	6
C3: Soil type	0.934	0.066	0.050	11
C4: Land use/land cover	0.887	0.113	0.086	5
C5: Distance to roads	0.923	0.077	0.059	9
C6: Distance to utilities	0.941	0.059	0.045	12
C7: Distance to water sources	0.878	0.122	0.093	4
C8: Distance to urban areas	0.949	0.051	0.039	13
C9: Distance to protected areas	0.902	0.098	0.075	7
C10: Groundwater depth	0.918	0.082	0.062	10
C11: Flood risk	0.814	0.186	0.143	2
C12: Environmental sensitivity	0.793	0.207	0.156	1
C13: Transportation accessibility	0.821	0.179	0.138	3
Sum	—	1.313	1.000	—

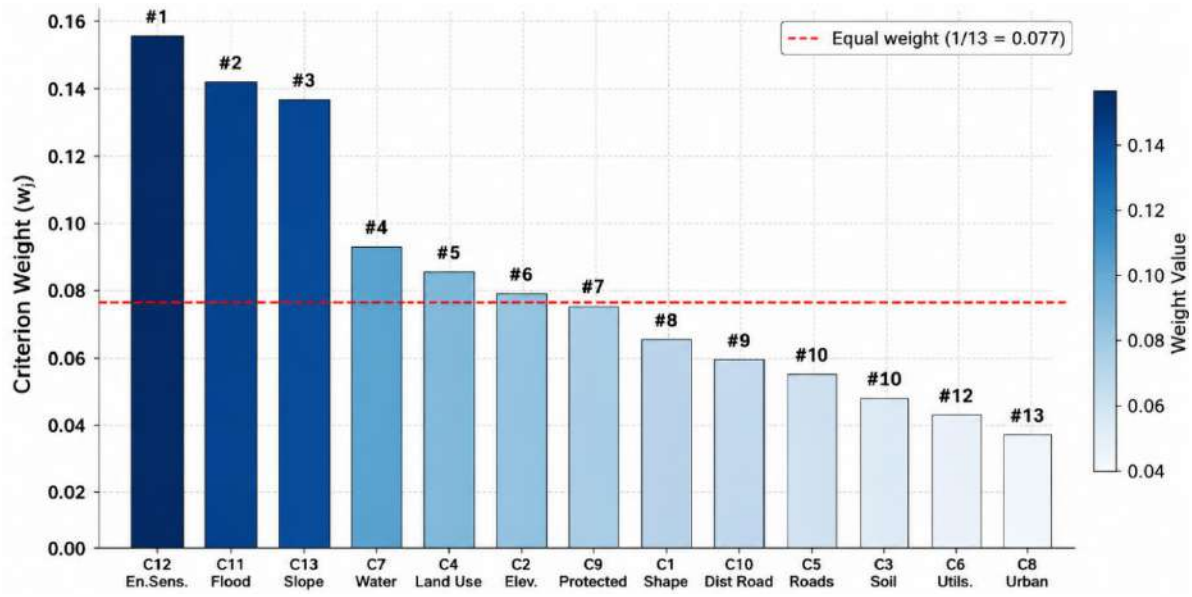

Fig. 5: Criteria ranked in descending order of EWM weight (w_j). Rank labels above each bar indicate criterion importance

Spatial suitability assessment

The continuous suitability surface derived from the weighted overlay analysis was subsequently classified into five discrete categories. Table 3 summarizes the areal extent and percentage of each suitability class, and (Fig. 6) presents the corresponding spatial distribution. The results reveal that approximately 847 hectares (ha) (23.4% of the study area) is classified as high (623 ha, 17.2%) or very high (224 ha, 6.2%) suitability. Moderate suitability constitutes the dominant classification (1,271 ha, 35.1%), highlighting the transitional landscape characteristics that define a significant portion of the study area. Very low and low suitability zones (1,501 ha combined, 41.5%) correspond primarily to areas with high flood risk, elevated environmental sensitivity, or poor transportation accessibility, consistent with the high weights assigned to C12, C11, and C13, reflecting the combined influence of environmental constraints and infrastructure limitations on overall site suitability patterns.

Table 3: Suitability classification results for the proposed East Baghdad Village eco-industrial park study area

Suitability class	Score range	Area (ha)	Percentage (%)
Very low	0.00–0.20	412	11.4
Low	0.21–0.40	1,089	30.1
Moderate	0.41–0.60	1,271	35.1
High	0.61–0.80	623	17.2
Very high	0.81–1.00	224	6.2
Total	—	3,619	100.0

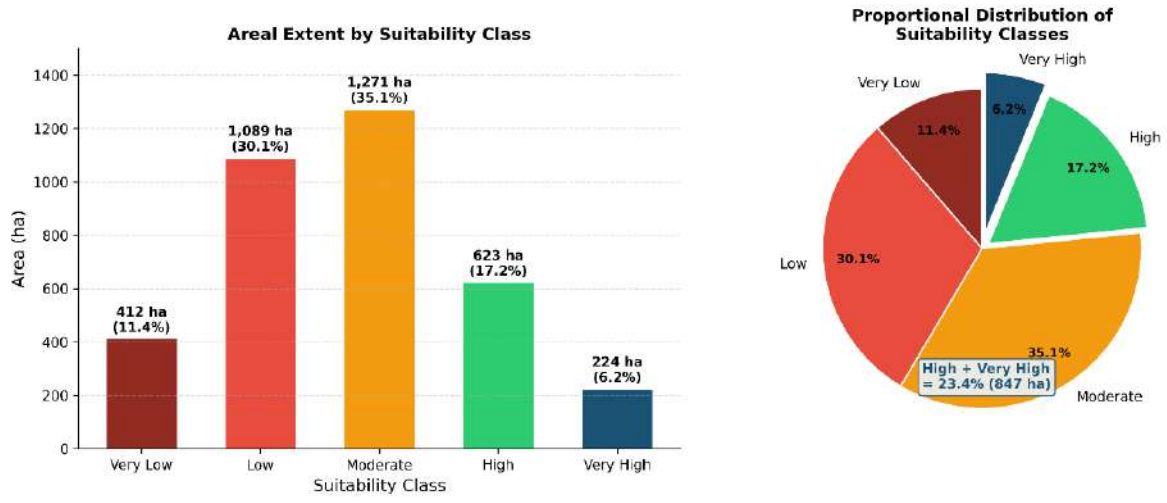

Fig. 6: Spatial suitability classification results showing the distribution of five suitability classes across the study area

Industrial cluster allocation

The four industrial clusters were spatially allocated within the High and Very High suitability zones identified by the GIS-MCDA assessment (Xu *et al.,* 2022). The total suitable area of 847-ha was designated as the comprehensive EIP planning envelope, encompassing both industrial production areas and supporting land uses. To evaluate alternative organizational concepts for the proposed EIP, two distinct spatial planning scenarios were established prior to formulating the definitive master plan.

Alternative 1:

To maximize road accessibility and simplify infrastructural development, this study utilizes a corridor-based linear configuration wherein industrial clusters are concentrated along the primary transportation axis. Although this arrangement reduced transportation distances, it generated fewer opportunities for industrial symbiosis because related industries were more spatially separated and supporting facilities were less centrally integrated.

Alternative 2:

It is adopted a functionally integrated cluster configuration that grouped complementary industries according to their potential material and energy exchanges while maintaining accessibility to the regional transportation network. Supporting facilities, utility areas, and service functions were positioned centrally to improve operational efficiency and facilitate future industrial symbiosis development. The above two alternatives were evaluated using a combination of planning and sustainability criteria derived from the objectives of this study, including consistency with the GIS-MCDA suitability assessment, industrial symbiosis potential, transportation accessibility, infrastructure efficiency, land-use compatibility, environmental

protection, and future expansion opportunities. Based on this multi-criteria assessment, Alternative 2 was selected as it offered an optimal trade-off among spatial suitability, industrial integration, infrastructure sharing, operational efficiency, and long-term sustainability (Yu *et al.,* 2023). The characteristics of the four industrial clusters featured in the selected alternative, comprising allocated land areas, mean suitability scores, primary facilities, and projected employment, are detailed in Table 4. The logistics and warehousing cluster achieved the highest mean suitability score (0.76), reflecting its allocation to the most accessible and topographically favorable areas. The construction materials cluster was allocated to zones with high transportation accessibility and proximity to major road infrastructure. To accommodate critical operational requirements, the food processing cluster, notwithstanding its low mean suitability score of 0.68, was allocated to zones featuring enhanced water accessibility. Within the 847-ha EIP planning envelope, approximately 525 ha were allocated to industrial production areas, while the remaining 322 ha were reserved for supporting land uses, including internal roads, utility areas, secondary service facilities, central services, and green spaces. Fig. 7a illustrates the two evaluated planning alternatives: the preliminary layout (Alternative 1) and the selected refined layout (Alternative 2). Building upon the selected alternative (Fig. 7b) presents the final master plan of the proposed East Baghdad Village Eco-Industrial Park, showing the spatial allocation of the four industrial clusters—construction materials, ceramics and glass, food processing, and logistics and warehousing—together with secondary service facilities, central services, utility areas, transportation infrastructure, wastewater treatment facilities, and green spaces (Valenzuela *et al.,* 2018). The framework enhances the operational performance and long-term sustainability of the proposed eco-industrial park by streamlining inter-industry interactions, facilitating waste-to-resource exchanges, optimizing logistical accessibility, and incorporating robust environmental buffer areas.

Ecological network analysis result

All ENA metrics reported in this section represent scenario-based modeled projections for the proposed, non-operational EIP and should be interpreted as design performance targets rather than measured outcomes. Table 5 presents the five ENA performance indicators for the proposed industrial symbiosis network. Utilizing the high-suitability zones identified in the spatial assessment, the boundaries of the four industrial clusters were established, followed by quantification of facility-level material and energy flows via ENA. TST = 2.87 Mt/y represents the total material flows within the EIP system boundary, calculated as the sum of primary material inputs (zi = 1.92 Mt/y), inter-facility exchanges (fij = 0.68 Mt/y), and product outputs (yi = 0.27 Mt/y), consistent with the ENA convention (Ulanowicz, 1986). This moderate TST is consistent with the proposed EIP's regional scale and substantially lower than large-scale operational parks such as TEDA (12.5 Mt/y) and Ulsan (18.3 Mt/y), reflecting differences in facility numbers and industrial diversity. CI = 0.34 indicates that approximately 34% of material flows are recycled through industrial symbiosis. This value is comparable to the Kalundborg Symbiosis (CI = 0.38) and exceeds both TEDA (CI = 0.31) and Ulsan (CI = 0.29), demonstrating competitive circularity despite its smaller scale. This assessment is validated by the Finn Cycling Index (FCI = 0.41), indicating a 41% circularity rate when dissipative flows are excluded. APL = 2.3 indicates that materials pass through an average of 2.3 nodes before exiting the system, underscoring a highly integrated and compact network topology. This value is comparable to Kalundborg (APL = 2.1) and more compact than TEDA (APL = 2.8) and Ulsan (APL = 3.2), indicating efficient material routing (Fig. 8). NC analysis (Table 6) identifies the Cement plant as the keystone facility (NC = 0.42), exerting the greatest influence on network flows.

Table 4: Industrial cluster characteristics and spatial allocation

Cluster	Area (ha)	Mean suitability score	Primary facilities	Projected employment
Construction materials	178	0.74	Cement, concrete, gypsum board, aggregates	850
Ceramics and glass	123	0.71	Ceramic tiles, sanitary ware, glass containers	620
Food processing	97	0.68	Olive oil, dates, fish processing, cold storage	480
Logistics and warehousing	127	0.76	Freight consolidation, cold chain, packaging	390
Internal Roads	102	-	Transportation access and internal circulation	-
Utility areas	68	-	Water, energy, and service networks	-
Green spaces	85	-	Environmental buffers and landscape areas	-
Wastewater treatment and services	67	-	Treatment facilities and Secondry and central services	-
Total	847	-	Industrial zones + supporting land uses	-

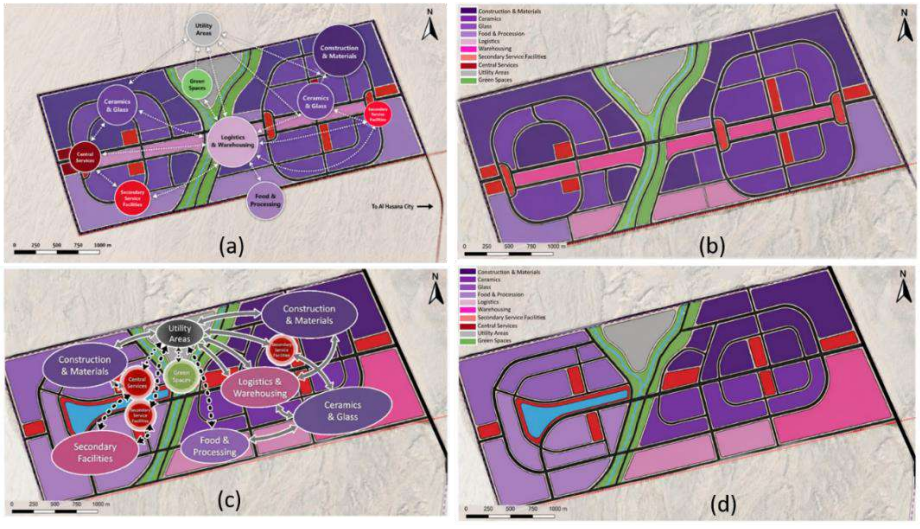

Fig. 7a: Planning concepts and alternatives: (a) Concept 1; (b) Alternative 1; (c) Concept 2; (d) Alternative 2



Fig. 7b: Master plan of the proposed East Baghdad Village Eco-Industrial Park, North Sinai, Egypt

Table 5: ENA performance indicators for the proposed ENA scenario

Indicator	Value	Unit	Interpretation
Total system throughput	2.87	Mt/y	Total material flow magnitude across all 23 symbiotic links
CI	0.34	—	34% of material flows are recycled internally within the network
FCI	0.41	—	41% circularity when dissipative flows are excluded
APL	2.3	—	Materials pass through an average of 2.3 facilities before exiting
Network density	0.075	—	75% of all possible directed connections are realized

Table 6: NC values for key facilities in the proposed ENA scenario

Facility	Cluster	NC Value	Interpretation
Cement plant	Construction materials	0.42	Keystone facility; highest flow control
Concrete batching	Construction materials	0.18	Major material hub
Ceramic tiles	Ceramics and glass	0.14	High symbiosis integration
Gypsum board	Construction materials	0.09	Moderate control
Glass containers	Ceramics and glass	0.07	Moderate control
Olive oil extraction	Food processing	0.05	Low control; peripheral node
Cold storage	Logistics and warehousing	0.03	Low control; service function
Others (11 facilities)	Various	< 0.02	Minimal individual control

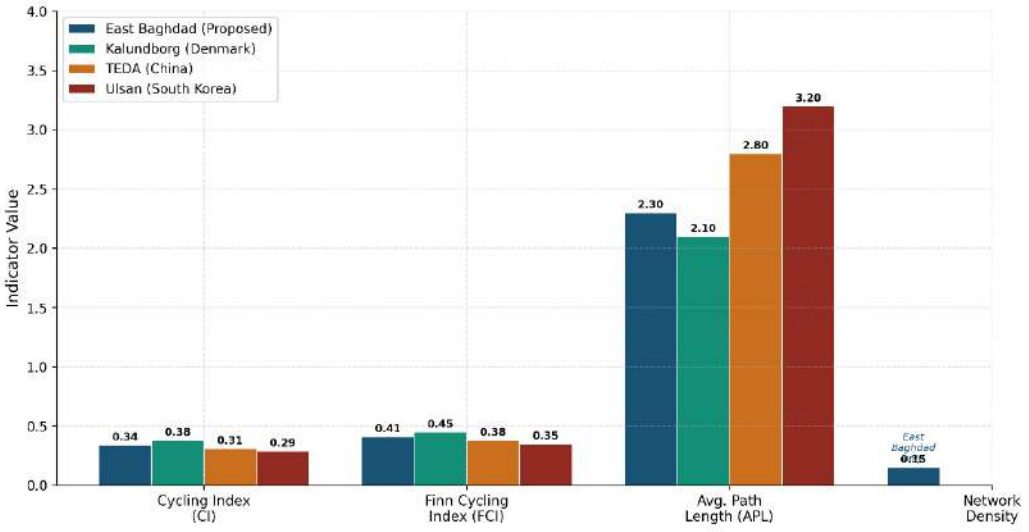

Fig. 8: Comparative ENA performance indicators (Cycling Index, Finn Cycling Index, Average Path Length, and Network Density) for the proposed East Baghdad Village EIP versus three operational EIPs (Kalundborg, TEDA, Ulsan). Radar chart and grouped bar chart visualizations

Material and energy flow quantification

Table 7 quantifies the major material and energy flows within the proposed industrial symbiosis network, demonstrating the potential for resource recovery and waste valorization. Compared to a conventional, non-integrated industrial baseline, the identified symbiotic linkages augment resource efficiency through by-product valorization, waste-heat recovery, and the reuse of treated wastewater (Simboli *et al.,* 2015). The cement kiln dust flow (45,000 t/y) and fly ash exchange (32,000 t/y) represent the highest-magnitude solid material flows, while waste-heat recovery (30 megawatt thermal (MWth) combined) constitutes the most significant energy symbiosis. In the arid region of North Sinai, where freshwater conservation represents a critical environmental and operational imperative, the treated wastewater flow of 120,000 m^3/y is of notable significance for enhancing regional water resource sustainability and supporting long-term agricultural resilience initiatives.

Table 7: Major symbiotic material and energy flows in the proposed ENA scenario

Flow Type	Source	Destination	Magnitude	Unit	Environmental benefit
Cement kiln dust	Cement plant	Ceramic tiles	45,000	t/y	Reduces raw material extraction; replaces virgin silica
Fly ash	Cement plant	Concrete batching	32,000	t/y	Reduces cement consumption by approximately 8%
Waste heat	Cement kiln	Food processing	18	MWth	Reduces natural gas consumption in food drying
Waste heat	Ceramic kiln	Food processing	12	MWth	Reduces natural gas consumption in cold chain
Organic waste	Food processing	Cement Plant	8,500	t/y	Biomass fuel; reduces coal consumption by ~5%
Treated wastewater	Food processing	Landscape irrigation	120,000	m^3/y	Reduces freshwater demand; conserves Al-Salam Canal allocation
Packaging waste	All vlusters	Recycling facility	3,200	t/y	Reduces landfill disposal; generates recyclate revenue
Scrap metal	All clusters	External recycler	1,800	t/y	Revenue generation; reduces virgin metal demand

Energy demand and carbon footprint

A summary of the forecasted energy consumption and carbon emissions for each industrial cluster under the proposed ENA framework is presented in Table 8, with the corresponding trends illustrated graphically in Fig. 9. The construction materials cluster dominates both energy demand (167 MW electrical, 145 MWth thermal) and carbon emissions with 285 Kilotonne Carbon dioxide per year (kt CO_2/y), reflecting the energy-intensive nature of cement and ceramic production. The total projected CO_2 emissions of 515 kt/y represent a baseline against which the carbon reduction potential of renewable energy integration and waste heat recovery can be evaluated in future studies. The projected energy demand and CO_2 emissions were estimated using representative operating parameters. These included 7,200 annual operating hours, cluster-specific capacity factors (85% for construction materials, ceramics and glass clusters, 75% for the food processing cluster, and 90% for the Logistics and Warehousing cluster), standard energy conversion relationships, and distinct CO_2 emission factors of 0.82 metric tons of carbon dioxide per megawatt-hour (tCO_2/MWh) for electricity and 0.27 metric tons of carbon dioxide per gigajoule (tCO_2/GJ) for natural gas. A comparative methodological approach was employed to systematically quantify the resulting environmental benefits. Energy reductions were estimated by comparing the symbiosis scenario (with all 23-exchange links active) against a conventional scenario in which each facility operates independently using virgin inputs. Carbon savings were calculated applying emission factors of 0.82 t CO_2/MWh for electricity substitution and 0.27 t CO_2/GJ for recovered process heat, consistent with Egyptian national grid and industrial sector benchmarks (IEA, 2021). Circularity performance is expressed through CI=0.34 and FCI=0.41, derived from the 18×18 material-flow matrix. Calculated at a design-capacity operation of 7,200 h/y, the total environmental benefits show a 31% raw material reduction and a 28% waste reduction. These figures represent the mass-balance differences between the industrial symbiosis and conventional baselines.

Sensitivity analysis

Sensitivity analysis results are presented in Table 9a and Table 9b. Table 9a compares EWM-derived weights against CRITIC weights and equal weights for all 13 criteria. Table 9b presents classification agreement metrics (OA and κ) under ±20% individual weight perturbation, with remaining criterion weights proportionally renormalized to maintain $\Sigma wj = 1$ after each perturbation, ensuring overall weighting scheme consistency throughout.

Table 8: Projected energy demand and carbon emissions by cluster (proposed ENA scenario)

Cluster	Electrical Demand (MW)	Thermal Demand (MWth)	Total Energy (GJ/y)	CO_2 Emissions (kt/y)
Construction Materials	87	145	1,820,000	285
Ceramics and glass	52	98	1,180,000	178
Food processing	18	22	315,000	38
Logistics and warehousing	10	5	118,000	14
Total	167	270	3,433,000	515

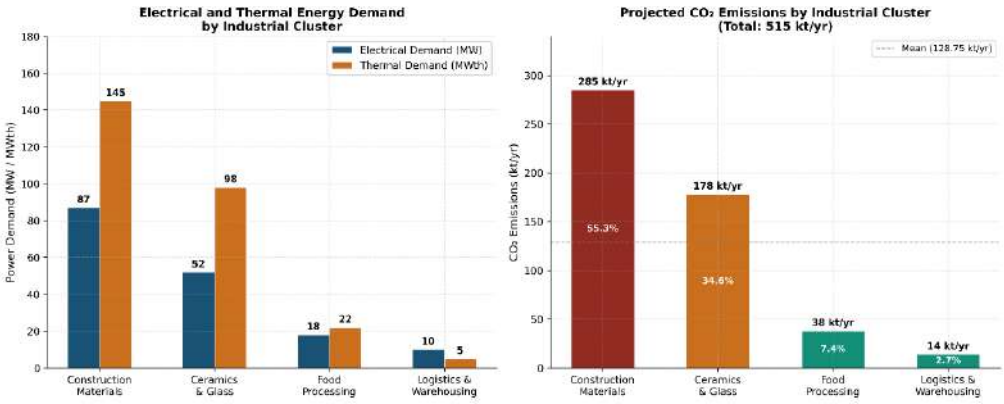

Fig. 9: Projected energy demand (MW electrical, MWth thermal) and CO_2 emissions (kt/y) by industrial cluster for the proposed East Baghdad Village Eco-Industrial Park. (Left) Grouped bar chart of energy demand by cluster. (Right) CO_2 emissions

Table 9a: Comparison of criterion weights derived by EWM, CRITIC, and equal weighting methods

Criterion	EWM weight	CRITIC weight	Equal weight	EWM rank	CRITIC rank
C1: Slope	0.067	0.082	0.077	8	6
C2: Elevation	0.080	0.075	0.077	6	7
C3: Soil type	0.050	0.058	0.077	11	11
C4: Land use/land cover	0.086	0.091	0.077	5	4
C5: Distance to roads	0.059	0.068	0.077	9	9
C6: Distance to utilities	0.045	0.052	0.077	12	12
C7: Distance to water sources	0.093	0.087	0.077	4	5
C8: Distance to urban areas	0.039	0.045	0.077	13	13
C9: Distance to protected areas	0.075	0.071	0.077	7	8
C10: Groundwater depth	0.062	0.065	0.077	10	10
C11: Flood risk	0.143	0.135	0.077	2	2
C12: Environmental sensitivity	0.156	0.148	0.077	1	1
C13: Transportation accessibility	0.138	0.123	0.077	3	3

Table 9b: Sensitivity analysis results: classification agreement under ±20% weight perturbation

Perturbed criterion	OA (+20%)	κ (+20%)	OA (−20%)	κ (−20%)	Mean OA	Stability rank
C1: Slope	0.94	0.89	0.95	0.90	0.945	5
C2: Elevation	0.93	0.87	0.94	0.88	0.935	6
C3: Soil type	0.97	0.94	0.97	0.94	0.970	2
C4: Land use/land cover	0.92	0.86	0.93	0.87	0.925	7
C5: Distance to roads	0.96	0.92	0.96	0.92	0.960	3
C6: Distance to utilities	0.98	0.96	0.98	0.96	0.980	1
C7: Distance to water sources	0.91	0.84	0.92	0.85	0.915	8
C8: Distance to urban areas	0.98	0.95	0.98	0.95	0.980	1
C9: Distance to protected areas	0.95	0.90	0.95	0.90	0.950	4
C10: Groundwater depth	0.96	0.91	0.96	0.91	0.960	3
C11: Flood risk	0.87	0.78	0.88	0.80	0.875	10
C12: Environmental sensitivity	0.85	0.75	0.86	0.77	0.855	11
C13: Transportation accessibility	0.89	0.81	0.90	0.83	0.895	9
Mean	0.93	0.87	0.94	0.88	0.935	—

The EWM and CRITIC weight rankings demonstrate strong convergence (Spearman's ρ = 0.96), with identical top-three rankings (C12, C11, C13) and identical bottom-three rankings (C8, C6, C3). This robust rank-order correspondence between two independent, objective weighting paradigms offers substantial validation that the derived weights encapsulate authentic spatial variability patterns inherent in the dataset, rather than introducing methodological artifacts. The most notable discrepancy occurs for C1 (Slope), which ranks 8th under EWM but 6th under CRITIC a minor difference with limited practical consequence given the low-to-moderate weights involved. The sensitivity analysis indicates strong overall classification robustness, featuring a mean classification stability OA of 0.935 and a mean map-consistency coefficient (κ) of 0.875 throughout all perturbation scenarios. As expected, the highest-weight criteria C12 (Environmental sensitivity, mean OA = 0.855), C11 (Flood risk, mean OA = 0.875), and C13 (Transportation accessibility, mean OA = 0.895) — exhibit the greatest sensitivity, confirming that these criteria are the primary drivers of suitability classification. Conversely, low-weight criteria, such as distance to utilities (C6) and distance to urban areas (C8), exhibit minimal sensitivity with a mean OA of 0.980, showing that they have limited influence on the final classification. Fig. 10 presents the sensitivity analysis results graphically. Removal of the cement plant (keystone facility, NC=0.42) reduces CI by 38% (from 0.34 to 0.21) and FCI by 35% (from 0.41 to 0.27), confirming its critical role in network circularity. A 50% reduction in fly ash generation reduces CI by 14%, reflecting the significance of this flow for downstream material cycling. An 11% reduction in FCI after removing the CO_2 exchange link highlights the role of gaseous exchanges, while scale-independent CI and FCI confirm structural network properties rather than absolute flow volumes.

Comparative ENA benchmarking

Table 10 compares key ENA performance indicators for the proposed East Baghdad Village EIP against three operational EIPs: Kalundborg (Denmark), TEDA (China), and Ulsan (South Korea). The comparative benchmarking results are illustrated in Fig. 11, with reference data for Kalundborg, TEDA, and Ulsan compiled from Zhu *et al*. (2007), Park *et al*. (2008) and Tian *et al*. (2014) respectively. A comparative benchmarking analysis demonstrates that the projected ENA performance targets for the proposed East Baghdad Village EIP align broadly with documented values from operational industrial parks, with the caveat that the proposed metrics represent ex-ante design projections rather than ex-post empirical outcomes. The projected CI value (0.34) falls within the range reported for established EIPs, including TEDA (0.31), Ulsan (0.29), and Kalundborg (0.38), suggesting the potential for a highly interconnected industrial symbiosis network. The projected APL value (2.3) indicates an efficient material-routing structure within the proposed network, with a similar order of magnitude to reported EIP examples, while acknowledging differences in system boundaries, network representations, and data sources.

Advantages of objective weighting in EIP planning

The application of EWM for criterion weighting addresses a critical methodological limitation of conventional GIS-MCDA approaches for EIP site selection. The widespread use of AHP and expert-based weighting introduces subjectivity into the decision-making process, potentially reducing transparency and reproducibility, while limiting methodological consistency across different applications and study contexts (Spyridonidou and Vagiona, 2021). Consequently, this can cause inconsistent results across studies, reduce reproducibility, and open the door for non-scientific influences in practical site selection



Fig. 10: Sensitivity analysis results showing classification stability (OA and κ) under ±20% criterion weight perturbations

Table 10: Comparative ENA performance: proposed East Baghdad EIP vs. operational EIPs

Indicator	East Baghdad (Proposed)	Kalundborg	TEDA	Ulsan	Interpretation
TST (Mt/y)	2.87	4.2	12.5	18.3	Moderate scale; appropriate for regional context
CI	0.34	0.38	0.31	0.29	Comparable circularity to operational parks
FCI	0.41	0.45	0.38	0.35	Moderate-to-high circularity
APL	2.3	2.1	2.8	3.2	Compact network; efficient material routing
Number of facilities	18	9	47	62	Moderate network size; scalable design
Symbiotic links	23	15	68	89	Moderate symbiosis density; growth potential

planning (Saaty, 1980; Wang and Lee, 2009). EWM eliminates this subjectivity by deriving weights directly from the statistical properties of the spatial data, ensuring that criterion importance reflects genuine spatial variability in the study area (Lotfi and Fallahnejad, 2010). The EWM-derived weight distribution reveals environmentally protective planning priorities: Environmental sensitivity (w = 0.156), Flood risk (w = 0.143), and Transportation Accessibility (w = 0.138) collectively account for 43.7% of total weight. This distribution aligns with the physical geomorphology of the arid North Sinai landscape, wherein environmental sensitivity and flash-flood risk exhibit pronounced spatial heterogeneity — attributes that render these specific criteria highly deterministic for optimal site selection. The strong convergence between EWM and CRITIC weights (Spearman's ρ = 0.96) provides compelling cross-validation evidence that the derived weights are robust and not method-dependent. This convergence is consistent with findings by Wang and Lee (2009) and Zandi *et al*. (2021), who demonstrated that objective weighting methods generally produce more stable and reproducible results than subjective approaches. Unlike earlier EIP site-selection studies that relied on AHP (Nuhu *et al*., 2021; Nuhu *et al*., 2022), the EWM approach

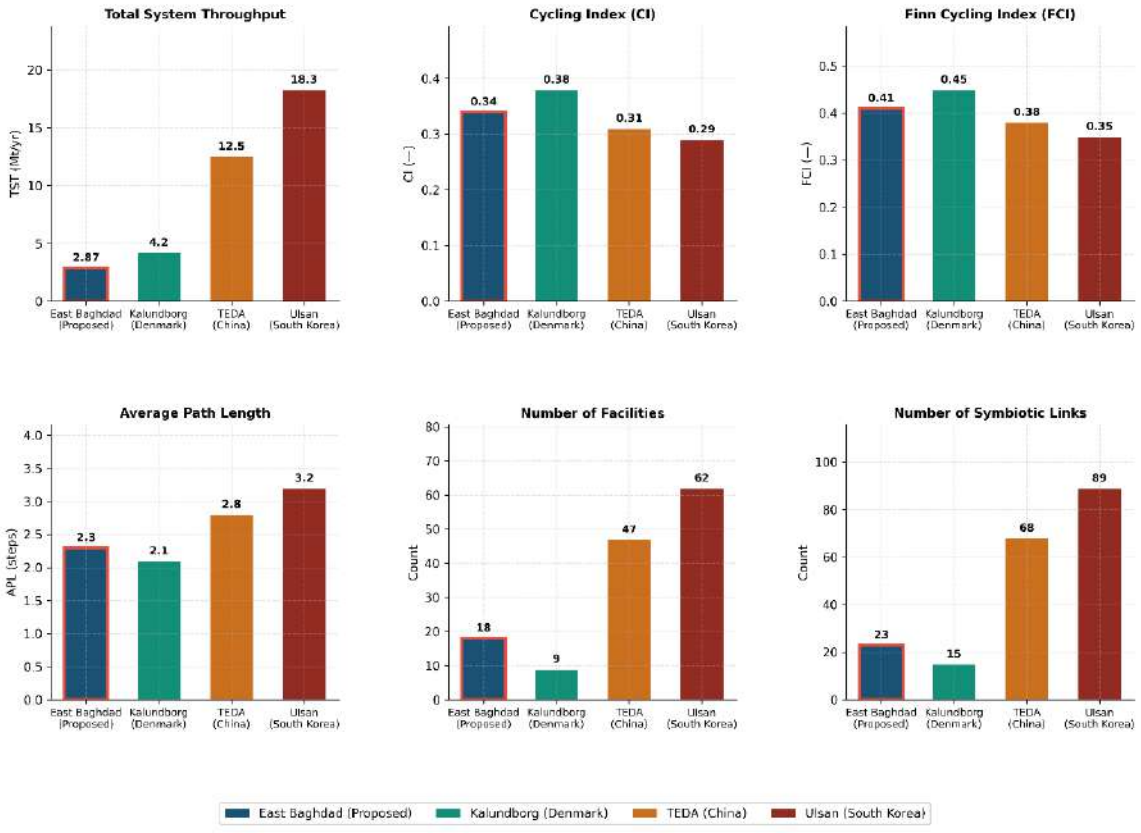

Fig. 11: Comparative benchmarking of ENA performance indicators between the proposed East Baghdad Village Eco-Industrial Park and three operational EIPs (Kalundborg, TEDA, Ulsan). Radar chart showing normalized indicator values

provides two distinct benefits. First, it removes the requirement for expert panels, allowing the method to be used even when local domain expertise is scarce. Second, it generates weights that are transparent and easily reproduced using only the input data.

Integration of spatial optimization and network performance

A key innovation of this framework is the integration of GIS-MCDA spatial optimization with ENA network performance evaluation within a single unified workflow. In traditional EIP planning literature, site selection and industrial symbiosis network design are frequently conceptualized as decoupled, sequential procedures, thereby hindering the integrated, simultaneous optimization of both spatial and functional system configurations (Gibbs and Deutz, 2007; Hong and Gasparatos, 2020). The present framework addresses this gap by using GIS-MCDA suitability results to directly inform cluster spatial allocation, which in turn defines the physical constraints for ENA network construction. A CI of 0.34 is achieved by the proposed industrial symbiosis network, exceeding the capacities of TEDA (0.31) and Ulsan (0.29). This performance nears that of Kalundborg (0.38), which represents the global benchmark for mature, self-organizing industrial ecosystems. This result is particularly noteworthy because Kalundborg's symbiosis developed over several decades through incremental bilateral agreements (Chertow, 2000), whereas the proposed network was systematically designed from the outset using

ENA principles. Keystone analysis enables targeted design decisions — identification of the cement plant as the critical node (NC=0.42) allows planners to prioritise infrastructure investment around this facility to protect network resilience. The synergistic effect achieves a 31% mitigation in raw material consumption alongside a 28% decrease in waste generation relative to the conventional baseline scenario.

Applicability in arid, resource-constrained environments

The proposed East Baghdad Village EIP case provides a proof-of-concept demonstration of the framework's applicability in an arid, data-scarce, developing-country context. The exclusive reliance on freely available remote sensing data (Sentinel-2, SRTM) and open geospatial datasets (OpenStreetMap, FAO Soil Map). This choice ensures reproducibility in other data-constrained regions, which is essential for EIP planning across Sub-Saharan Africa and the MENA region. The projected water demand for the proposed EIP is approximately 1.2 million m^3/y. This requirement can be partially met through a combination of Al-Salam Canal allocation and treated wastewater reuse, which includes 120,000 m^3/y from the food processing cluster. Water conservation is a critical constraint in arid environments, and the framework's explicit incorporation of Distance to water sources (C7, w = 0.093) and Groundwater depth (C10, w = 0.062) as site selection criteria ensures that water availability is systematically considered in the suitability assessment. This water-sensitive planning paradigm aligns with the IPCC (2022) projections, which forecast escalating water scarcity within arid regions under various climate change scenarios.

Policy implications and implementation pathways

Successful implementation of the Proposed East Baghdad Village EIP requires coordinated policy interventions across multiple domains. First, land allocation and zoning frameworks must designate the identified high-suitability zones with 847 hectares (ha) for industrial development under the North Sinai Development Zone regulations. Second, infrastructure development must be prioritized, with specific emphasis on upgrading transport networks, extending utility grids, and securing water allocations from the Al-Salam Canal. Third, the establishment of fiscal incentive frameworks—comprising tax exemptions, subsidized utility connections, and dedicated industrial symbiosis facilitation funds—is imperative to attract anchor tenants and foster active participation in inter-firm symbiotic exchanges. Fourth, a dedicated EIP Management Entity should be established to coordinate symbiosis exchanges, monitor environmental performance, and provide the institutional continuity necessary for long-term network evolution. These policy requirements align with UNIDO (2019) guidelines for EIP development in developing countries and with Egypt's Vision 2030 industrial development objectives (Egyptian Ministry of Planning, 2023). Practical implementation of the proposed EIP faces barriers at three levels. At the market and contractual level, stable offtake agreements between exchange partners are required to ensure continuous material and energy flows; these require legal frameworks and long-term supply contracts that go beyond conventional industrial zoning. The EIP master plan must incorporate the significant capital investments required for the specialized technical handling of key by-products, including pneumatic fly ash conveyance, CO_2 compression and piping, and waste heat exchanger networks. At the regulatory and permitting level, waste-to-secondary-material reclassification procedures under Egyptian environmental regulations must be resolved to enable by-product exchange without regulatory impediment.

Practical implementation requirements

Practical implementation of the proposed framework requires: 1) high-resolution topographic data (≥10-m DEM) for detailed flood risk and drainage modeling; 2) updated land use/land cover mapping at 10-m resolution or finer; 3) detailed geological and geotechnical surveys for foundation design; (4) site-specific hydrological modeling for wadi flood risk assessment; and 5) engineering-level material balance data from prospective industrial tenants to refine ENA flow estimates. The developed framework, predicated on 30 m spatial resolution imagery and ex-ante design-capacity estimations, serves as a preliminary strategic planning baseline; however, integration of high-resolution, site-specific datasets remains imperative for detailed engineering and design execution.

Limitations and future research directions

Several important limitations of this study should be acknowledged. First, the framework relies on publicly available spatial datasets (Sentinel-2, SRTM, Open Street Map) with spatial resolutions of 10–30 m. While providing an acceptable baseline for regional strategic planning, these datasets are constrained by a spatial granularity that may preclude the detection of localized spatial heterogeneity necessary for detailed engineering design. Higher-resolution data (e.g., LiDAR-derived DEMs, sub-meter aerial imagery) would improve the precision of suitability mapping in future applications. Second, all ENA results are scenario-based modeled projections derived from facility design capacities and literature-based conversion factors, not measurements from an operational EIP. The projected CI (0.34), FCI (0.41), and TST (2.87 Mt/y) represent design performance targets that may differ from actual operational outcomes due to market fluctuations, operational inefficiencies, and unforeseen technical constraints. Third, the framework assumes a single development scenario with four predefined industrial clusters. Suitability distributions and ENA performance outcomes may vary under alternative scenarios, such as modifying cluster configurations, implementing phased development, or incorporating renewable energy infrastructure. Fourth, social dimensions of EIP planning including community acceptance, labor market analysis, and social impact assessment are not addressed in the current framework. Integrating social multi-criteria analysis (SMCA) into future iterations would provide a more comprehensive planning foundation. Fifth, climate change impacts on water availability, flood risk, and temperature extremes are not explicitly modeled. To rigorously evaluate the long-term operational viability of the proposed site under shifting environmental regimes, future investigations should systematically integrate macro-scale climate projections (IPCC, 2022). Future studies should: 1) refine ENA flow estimates using site-specific engineering data from prospective industrial tenants; 2) evaluate alternative industrial cluster compositions using multi-objective optimization. The cycling index (CI=0.34) achieved by the proposed EIP lies below that of the Kalundborg EIP (CI≈0.71) and the Guitang EIP (CI≈0.52). Three design-phase constraints explain this gap: restricted sectoral diversity within the existing four-cluster configuration, a lack of integrated water recycling loops, and no combined heat and power (CHP) systems. These features, which contribute substantially to cycling in mature operational EIPs, were excluded due to data availability and design-stage limitations. Future network expansion incorporating 8–12 additional exchange links, including water recirculation and CHP is projected to raise CI to the 0.50–0.55 range, approaching the Guitang benchmark. Consequently, this gap should be viewed as a starting point for the design phase rather than a permanent limit on what the system

can achieve. Life cycle assessment (LCA) was not integrated into the current framework due to the design-phase constraint: facility-level inventory data required for LCA (material inputs, emissions, waste streams at operational scale) are not yet available for a planned park (Finnveden *et al.,* 2009). Carbon savings reported in this study are limited to operational flow substitution, calculated using emission factors of 0.82 t CO_2/MWh and 0.27 t CO_2/GJ for recovered process heat (IEA, 2021), and do not include upstream supply chain or construction phase emissions.

Uncertainty assessment

Several sources of uncertainty affect the modeled outputs of this framework. Sources of spatial data uncertainty in this framework are threefold, originating from the 30 m resolution of the primary input datasets, interpolation-induced errors in groundwater depth estimations, and classification inaccuracies inherent in the supervised land use and land cover mapping of Sentinel-2 imagery. ENA flow uncertainty results from the use of design capacity estimates and literature-based conversion factors rather than measured operational data; therefore, flow magnitudes may vary depending on future operational conditions. Sensitivity analysis results (mean classification stability OA = 0.935) demonstrate that suitability classification remains stable under ±20% criterion weight perturbations, providing an assessment of spatial uncertainty within the GIS-MCDA component. To better understand uncertainty propagation across both the GIS-MCDA and ENA components of the framework, subsequent studies should utilize precise field measurements alongside Monte Carlo simulation.

CONCLUSION

This study developed and validated an integrated GIS-MCDA–ENA framework for planning the Proposed East Baghdad Village EIP in North Sinai Governorate, Egypt, advancing conventional methodologies into a reproducible six-phase workflow. A highly suitable or very highly suitable classification for industrial development was assigned to 847 ha (23.4% of the 3,619-ha study footprint) following high-resolution GIS-MCDA execution. The localized suitability profiles were heavily driven by three dominant spatial constraints and opportunities: environmental sensitivity (w = 0.156), flood vulnerability (w = 0.143), and transportation accessibility (w = 0.138). Complementing this, an ecological network analysis (ENA) of the proposed 18-facility, 23-link four-cluster network yielded robust performance targets (CI = 0.34, FCI = 0.41, APL = 2.3) comparable to established operational EIPs, confirming a strong potential for resource efficiency and waste reduction, with projected reductions of approximately 31% in raw material consumption and 28% in waste generation relative to a non-integrated baseline. The methodological reliability of the workflow was verified by strong convergence between EWM and CRITIC weights (Spearman's rho = 0.96) and high classification stability (mean OA = 0.935, mean kappa = 0.875). To prioritize redundancy investments, a keystone analysis successfully isolated critical nodes, yielding an NC of 0.42 for the cement plant. Additionally, the network's modular architecture allows for incremental expansion or facility substitution without interrupting the primary exchange triad between the cement, glass, and food processing facilities. By leveraging freely available remote sensing and geospatial datasets, this framework demonstrates a clear proof-of-concept for application in data-scarce, arid, and resource-constrained environments. The modular structure allows regional indicators to be substituted seamlessly—such as replacing Egyptian-specific criteria like Nile water proximity or sandstorm risk with equivalent local variables—

rendering the entire workflow highly transferable to other developing nations. Consequently, these outcomes yield a robust scientific foundation through which urban planners, policymakers, and industrial stakeholders can strategize the development of sustainable EIPs. By doing so, the proposed framework fosters meaningful convergence with the localized targets of Egypt's Vision 2030 as well as the global mandates of SDG 9 and SDG 11. To advance this framework toward full operational deployment, future research should prioritize three distinct paths: integrating cradle-to-gate LCA once site-specific facility inventory data become available; developing dynamic ENA models that transition from steady-state assumptions to capture temporal and seasonal variations in material and energy flows; and conducting cross-regional validation by applying the framework to comparable data-scarce environments across Jordan, Tunisia, and sub-Saharan Africa.

AUTHOR CONTRIBUTIONS

D. S. Sayed co-conceived the research idea, designed the study, conducted the analysis, interpreted the results, prepared the original manuscript draft, and contributed to revising the manuscript. D.F.A. Nahla contributed to the study design, assisted in data analysis and interpretation, and critically reviewed the manuscript. H.N. Abdel Hamed co-conceived the research idea, supervised the research, interpreted the results, critically revised the manuscript, and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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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During the preparation of this work, the authors used SciSpace to improve the academic writing and language of the manuscript and ChatGPT (OpenAI) to generate a number of graphical illustrations. After using these tools, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

ABBREVIATIONS

%	Percent
AHP	Analytic hierarchy process
APL	Average path length
CI	Cycling index
CO_2	Carbon dioxide
CRITIC	Criteria importance through intercriteria correlation
DEM	Digital elevation model
E	East
EIP	Eco-industrial park
ENA	Ecological network analysis
EWM	Entropy weight method
FAO	Food and Agriculture Organization of the United Nations
FCI	Finn cycling index
GIS	Geographical information system
GIS-MCDA	GIS-based multi-criteria decision analysis
GJ	Gigajoule
ha	Hectare
IDW	Inverse distance weighting
IPCC	Intergovernmental Panel on Climate Change
kt/y	Kilotonne per year
LiDAR	Light detection and ranging
LCA	Life cycle assessment
LULC	Land use/land cover
m	Metre
mm	Millimeter
m^3/y	Cubic metre per year
MCDA	Multi-criteria decision analysis
MENA	Middle East and North Africa
Mm^2/y	Million square metres per year
MW	Megawatt
MWh	Megawatt-hour
MWth	Megawatt thermal
NC	Network control
OA	Overall accuracy
SDG	Sustainable development goal
SMCA	Social multi-criteria analysis
S	South
SRTM	Shuttle radar topography mission
t/y	Tonne per year
tCO_2/MWh	Metric tons of carbon dioxide per megawatt-hour
tCO_2/GJ	Metric tons of carbon dioxide per gigajoule
TEDA	Tianjin economic-technological development area
TST	Total system throughput
UNIDO	United Nations Industrial Development Organization
UTM	Universal transverse mercator
WGS	World geodetic system

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ORIGINAL RESEARCH ARTICLE

Habitat assessment of mangrove planting on coral rubble coasts caused by earthquake

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ABSTRACT

BACKGROUND AND OBJECTIVES: Coastal elevation changes from seismic activity can expose coral-rubble surfaces suitable for mangrove establishment; however, these substrates differ from mature mudflats due to their coarse composition, developmental immaturity, and lack of fine silt. The study objectives were to evluate the percentage of living planted mangroves and the conditions of habitats on earthquake-uplifted coral-rubble coastal terrain in Nias Island, Indonesia.

METHODS: A total of 77 plots were observed at eight locations for 3, 6 and 12 months measurement. Analysis of the relationship between habitat characteristics and percentage of living plants was carried out at the location level (n = 8) and interpreted as an exploratory analysis. Plant survival and replenishment records at six and twelve months post-planting accounted solely for living specimens, as deceased plants were replaced following each monitoring interval. The habitat assessment included water temperature, salinity, dissolved oxygen, substrate potential of hydrogen, texture, organic carbon content, carbon-to-nitrogen ratio, total nitrogen, available phosphorus, and available potassium.

FINDINGS: The planting substrate was primarily composed of sand, with site mean sand ratio ranging from 82.00 percent to 93.25 percent. The substrate at the planting sites had not transitioned into organic-rich mangrove soil, as indicated by depleted soil nutrient levels and low organic carbon concentrations. The percentage of live plants in Botohilitano ranged from 39.60 percent to 87.86 percent after one year. Differences in habitat conditions among locations underscore the necessity of targeted habitat evaluations, while the correlation between habitat traits and the proportion of live plants necessitates additional.

CONCLUSION: Notwithstanding the uniform planting density, the effectiveness of mangrove cultivation in coral fragment-covered regions raised by the earthquake differs. Prior to scaling up restoration initiatives, it is critical to conduct site-specific habitat suitability assessments, continuously monitor plant survival rates, and systematically document the ecological rehabilitation process. The ecological mangrove restoration approach must incorporate suitable species, and community involvement in restoration management is essential to improve the sustainability of mangrove ecosystem services and the efficacy of rehabilitation efforts.

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INTRODUCTION

Mangrove restoration is widely used on tropical coasts to recover degraded habitats, support coastal protection, and rebuild ecological function (Mohan *et al.,* 2025). Although planting represents the most highly visible phase of restoration, initial planting records are insufficient indicators of long-term mangrove establishment under localized field conditions (Ray *et al.*, 2024). Early monitoring is needed because planted mangroves may face unsuitable hydrology, substrate instability, salinity stress, or poor rooting conditions after planting (Friess *et al*., 2019). Although mangrove cultivation is frequently associated with coastal hazard mitigation, its protective efficacy is contingent upon the long-term persistence of the restored stand under local hydrodynamic and sedimentological conditions (O'connell *et al*., 2022). This is important because a planted area does not automatically become a functioning protective mangrove belt (Gijsman *et al*., 2021). Early establishment is the most critical phase for planted mangroves. Seedlings and propagules have to remain anchored, tolerate tidal exposure, and develop roots in the available substrate. Despite high initial planting densities, restoration failure may occur if the target site lacks substrate stability and appropriate hydrological conditions (Balke *et al*., 2011). Weak site selection remains one of the main causes of poor restoration outcomes. Planting targets can be achieved in terms of area or number of seedlings, while field performance remains low because the site does not match the ecological requirements of mangrove establishment (Kodikara *et al*., 2017). This issue is equally pertinent in Southeast Asia, where ecological restoration initiatives frequently encounter obstacles regarding site suitability, planting design, monitoring protocols, and long-term maintenance. Consequently, evaluating restoration efficacy must extend beyond administrative planting records to incorporate empirical assessments of post-planting field performance (Gerona-Daga and Salmo III, 2022). The Nias planting sites also need a clear baseline. The planting surface was reef-flat ground exposed by the 2005 earthquake, not a degraded mangrove stands with old mangrove mud. Restoration targets for these substrates must avoid the assumption that all unvegetated coastal expanses historically supported mangrove ecosystems. At the Nias sites, the baseline issue was concrete: the planting surface was reef-flat ground exposed by the 2005 earthquake, so open coastal space could not be treated automatically as former mangrove habitat (Dahdouh-Guebas and Cannicci, 2021). The coastal locations evaluated in this study present a highly atypical ecological restoration context. The 2005 Nias–Simeulue earthquake uplifted reef-flat surfaces along parts of the Nias coast and exposed coral-rubble and sandy coastal land. Some of these newly exposed surfaces were later used for mangrove planting, although their suitability as planting habitat had not been clearly assessed (Briggs *et al*., 2006). Spatial variability in post-seismic deformation and uplift along the Nias–Simeulue segment accounts for the highly heterogeneous nature of the newly exposed coastal substrates, which failed to yield a uniform cultivation environment (Meltzner *et al*., 2015). Earthquake-uplifted coral-rubble land is different from abandoned ponds, degraded mangrove stands, or fine-sediment tidal flats. The surface is coarse, uneven, and weakly developed as soil. Recent work on coral response after the Nias–Simeulue uplift also shows that the uplifted reef setting remained geochemically and physically distinct from ordinary mangrove sediment environments (Sosdian *et al*., 2024). Although tectonic coastal uplift has generated extensive stretches of coral-rubble deposits targeted for mangrove restoration, the emergence of new subaerial land does not inherently guarantee its biophysical suitability for long-term mangrove establishment. The success of mangrove stand formation is largely determined by the suitability of elevation to tidal range, hydroperiod, and hydrological connectivity which regulates the frequency and duration of inundation

(Friess *et al.,* 2019). Consequently, the present study is more appropriately framed as a preliminary assessment centered on physicochemical water and soil characteristics. Future research evaluating habitat suitability for mangrove restoration on tectonic uplift-generated coral rubble must integrate comprehensive hydrological data, tidal elevations, and geomorphological conditions (Cerri *et al.,* 2026). This substrate condition is central to the Nias planting sites because coral rubble and sand were the main planting medium, not developed mangrove mud. Coral rubble and sand can provide space for planting, but they may offer limited fine sediment, low organic matter, weak anchorage, and poor root-zone development. Under these conditions, planting success depends not only on species choice or planting density, but also on whether the substrate can support early establishment (Lee *et al*., 2019). Fine-grained sediments and organic matter play a critical role in pedogenesis, surface stabilization, and vertical elevation dynamics within tidal wetlands. Consequently, in environments dominated by coarse substrates, initial mangrove establishment may be hindered by low sediment retention and the poor development of a stable rooting metrix (Morris *et al*., 2016). Soil fertility was included in this study as part of the habitat diagnosis. Nitrogen (N), phosphorus (P), and potassium (K) were not treated as single causal factors, but as indicators that strengthen the description of site condition. Together with organic carbon, substrate texture, and water quality, these variables help show whether uplifted coral-rubble land provides a suitable medium for planted mangroves (Alongi, 2018). The percentage of live plants served as the primary field indicator for planting outcomes. Because deceased specimens were systematically replaced following each monitoring event, the survival metrics recorded at six and twelve months reflect the combined cohort of original surviving plants and replanted individuals under active maintenance. It should not be read as live plant percentage of the original planting cohort alone (Gann *et al*., 2019). Mangrove species have different adaptability to extreme habitat conditions, including areas of coral rubble that have been uplifted due to tectonic activity. In Indonesia, *Rhizophora apiculata* and *Rhizophora stylosa* are two species commonly used in rehabilitation programs because they have viviparous propagules, the ability to form strong supporting roots, and high tolerance to salinity and tidal inundation (Friess *et al.,* 2019). Specifically, *R. stylosa* is reported to have better adaptability to sandy substrates and coral rubble in open coastal areas, while *R. apiculata* thrives better on more stable muddy substrates. However, the long-term survival and growth of these two species are not governed solely by their physiological traits; rather, they remain highly contingent upon habitat suitability, particularly local hydrology, substrate stability and tidal connectivity. Therefore, evaluating habitat characteristics is an important aspect in determining the success of mangrove restoration in coastal areas experiencing tectonic uplift. While localized to Nias Island, the foundational ecological principles for mangrove restoration in areas of tectonic uplift are applicable to other tropical coastlines sharing similar geomorphological characteristics. However, the success of restoration still depends on hydrological conditions, tidal elevation, substrate characteristics and coastal dynamics that are specific to each location. Consequently, the ecological mangrove restoration (EMR) framework, which prioritizes the rehabilitation of natural hydrological regimes prior to revegetation, is recognized as a more effective and sustainable alternative to conventional planting practices that overlook site suitability (Friess *et al.,* 2019). Thus, evaluating habitat characteristics is an important step to determine appropriate restoration strategies in coastal areas that are experiencing landscape changes due to tectonic activity. This study aims to assess habitat conditions and survival rates of mangroves planted on seismically uplifted coral-rubble substrates. Specifically, the

study evaluated: i) water, substrate, and soil fertility conditions across planting sites; ii) plant survival rates at three, six, and twelve months post-planting; and iii) site-specific relationships between key environmental indicators and mangrove survival. The study was carried out in village-level coastal planting sites in North Nias and South Nias Regencies, Indonesia, during 2024–2025.

MATERIALS AND METHODS

The study was conducted on earthquake-uplifted coral-rubble coastal land in Nias Island, North Sumatra, Indonesia, during 2024–2025. The study area covered selected coastal planting sites in North Nias and South Nias Regencies. These coastal surfaces were associated with reef-flat uplift after the 2005 Nias–Simeulue earthquake (Briggs *et al.*, 2006). Site selection followed a purposive sampling design based on three primary criteria: the presence of tectonically uplifted coral-rubble substrates, active mangrove planting initiatives, and accessibility for recurring monitoring. Preliminary screening was conducted via the interpretation of post-uplift coastal landforms, which was subsequently validated through field verification. The monitored areas represented planting sites on coarse coral-rubble and sandy substrate, not on developed muddy mangrove soil. Eight village-level coastal sites were included. Four sites were located in South Nias Regency: Bawonahono, Sondregeasi, Botohilitano, and Botohilisalo'o. Four sites were located in North Nias Regency: Sisarahili Teluk Siabang, Sifahandro, Balefadoro Tuho, and Hiligawolo. Fig. 1 illustrates the spatial distribution of the monitored sites and experimental planting plots.

Planting design and observation units

Mangroves were planted at a density of 2,500 plants per hectare (ha). Monitoring was conducted in 77 planting plots, each covering 0.5 ha and observed in eight research location villages. Each plot contained 1,250 planting points. The total monitored area encompassed 38.5 ha. Plot allocation was distributed based on the spatial extent of mapped coral-rubble coastal substrates across the two regencies, resulting in 32 plots established in South Nias and 45 plots in North Nias. In South Nias, each of the four sites had eight plots. In North Nias, Sisarahili Teluk Siabang, Sifahandro, Balefadoro Tuho, and Hiligawolo had 15, 14, 6, and 10 plots, respectively. The plot distribution is detailed in Table 1. To match the scale of the environmental data, evaluations of habitat characteristics and mangrove survival rates were conducted using aggregated mean values at the village level (n = 8). This approach was necessitated because key environmental parameters—including water quality, soil physicochemical properties, and soil fertility levels, were originally measured or represented at the village level resolution. This data aggregation was carried out to align the scale between the response variables and the explanatory variables and to avoid pseudoreplication which could occur if each plot was treated as an independent unit of analysis, while the habitat variable had the same value for plots in the same village. Consequently, the village is designated as the primary unit of analysis for the correlation assessment, whereas individual plots served as the foundational observation unit. Given the relatively limited number of analysis units (n = 8), the correlation results were interpreted as an exploratory analysis to identify patterns of relationships between habitat characteristics and the percentage of live plants at the site level, rather than as evidence of a cause-and-effect relationship. Mangrove cultivation was conducted in strict accordance with the localized rehabilitation protocols established by the executing agency at each location. Planting density, plant spacing, planting position, and planting techniques are applied uniformly at each location in accordance with the rehabilitation guidelines used. The type of planting material used is in the form of propagules or nursery seeds, depending on availability in each location, while

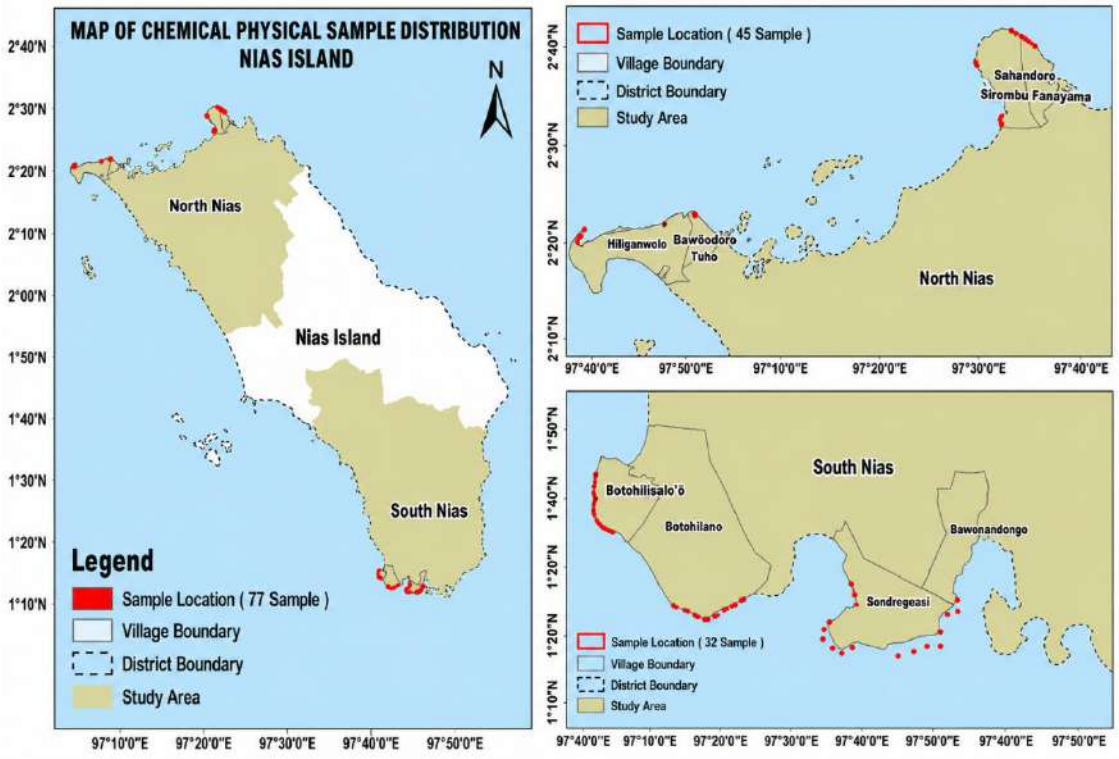

Fig. 1: Geographical location of the study area and distribution of monitored mangrove planting plots on earthquake-uplifted coral-rubble coastal land in Nias Island, Indonesia

Table 1: Distribution of monitored mangrove planting sites and plots

Regency	Village-level site	Plot number	Number of plots	Monitored area	Planted species
South Nias	Bawonahono	1–8	8	4.0 ha	*Rhizophora apiculata*
	Sondregeasi	9–16	8	4.0 ha	*Rhizophora apiculata*
	Botohilitano	17–24	8	4.0 ha	*Rhizophora apiculata*
	Botohilisalo'o	25–32	8	4.0 ha	*Rhizophora stylosa*
North Nias	Sisarahili Teluk Siabang	33–47	15	7.5 ha	*Rhizophora apiculata*
	Sifahandro	48–61	14	7.0 ha	*Rhizophora stylosa*
	Balefadoro Tuho	62–67	6	3.0 ha	*Rhizophora stylosa*
	Hiligawolo	68–77	10	5.0 ha	*Rhizophora apiculata*
Total	Eight sites	1–77	77	38.5 ha	

replanting is carried out if there are plants that die during the monitoring period. The planted species were *R. apiculata* and *R. stylosa*. *Rhizophora apiculata* was planted in Bawonahono, Sondregeasi, Botohilitano, Sisarahili Teluk Siabang, and Hiligawolo. *Rhizophora stylosa* was planted in Botohilisalo'o, Sifahandro, and Balefadoro Tuho. The planting stock comprised both propagules and nursery-reared seedlings, selected in accordance with localized site conditions and historical field implementation records. For monitoring purposes, each experimental plot served as the primary observation unit to document plant survival throughout the twelve-month monitoring period. The village-level site was used as the analytical unit for comparing live plant percentage with habitat indicators using site-level mean values. This scale was used because plots within the same site belonged to the same planting block or adjacent coastal planting area and shared similar coral-rubble and sandy substrate conditions, thereby minimizing within-site environmental variability.

Live plant monitoring and replacement planting

Live plant percentage was recorded when the planted mangroves reached three, six, and twelve months after planting. At each monitoring period, live plants were counted in each plot and compared with the target number of planting points. Following each monitoring event, documented plant mortalities were systematically replaced as a routine component of field maintenance. Because replacement planting was conducted after monitoring, values at six and twelve months represented living planted and replanted individuals under maintenance conditions. Consequently, these data were treated as plant survival percentages, with the complete monitoring and replenishment sequence illustrated in Fig. 2. Live plant percentages were derived from counts recorded during each monitoring cycle. Plot layouts comprised 1,250 planting points across a 0.5 ha area, corresponding to a standard planting density of 2,500 plants/ha. Monitoring was carried out at 3, 6, and 12 months after planting, using Eq. 1 (Field, 1999):

$$\text{Live plant percentage}_t = \left(\frac{N_{live,t}}{N_{target}}\right) \times 100 \quad (1)$$

Where: $N_{live,t}$ is the number of live plants recorded at monitoring time t, and N_{target} is the target number of planting points in each 0.5 ha plot. In this study, N_{target} was 1,250. Plot-level values were averaged to obtain village-level site values. Dead planting points were replaced during field maintenance. The six and twelve-month monitoring records incorporated surviving individuals from both primary and replacement plantings; consequently, these data are reported as live plant percentage.

Water, substrate, and soil fertility measurements

Water, substrate, and soil fertility measurements were used to describe habitat conditions across the monitored planting sites. Water variables consisted of water temperature, water potential of hydrogen (pH), salinity, and dissolved oxygen. These variables were measured in situ in the water surrounding planted mangroves using portable handheld water-quality instruments. Substrate pH was measured to characterize the pH condition of the planting medium. The pH value of the substrate was determined potentiometrically in a soil suspension: 1 normal K chloride (N KCl) solution at a ratio of 1:2.5. Substrate samples were taken at a depth of 0–20 centimeters (cm), then air-dried, homogenized, and sieved using a 2 millimeters (mm) sieve before analysis. Measurements were carried out using a pH meter that had been calibrated with a standard buffer solution before use. This method is used to obtain a pH value that reflects the potential acidity level of the substrate. Substrate texture was analyzed from 77 soil samples representing the planting plots. Sand, silt, and clay fractions were determined using the hydrometer method. These variables characterized the physical properties of the uplifted coral-rubble substrate, highlighting the marked prevalence of coarse material and the corresponding paucity of the fine-sediment fraction. Soil fertility indicators, including organic carbon, were integrated as site-level habitat variables. The organic carbon content and corresponding carbon-to-nitrogen ratio were evaluated using one representative soil sample obtained from each designated village-level site. Total N, available P, and available K were analyzed from 16 soil samples, with two samples representing each site. Total N was determined using the Kjeldahl method. Available P was determined using the Bray 2 method. Available K was determined using ammonium acetate extraction followed by atomic absorption spectrophotometry. Organic carbon was quantified using the dichromate oxidation method with K dichromate. Rather than being evaluated as isolated causal determinants of plant survival, these variables characterized broader planting habitat conditions. Measured habitat variables, sampling scale, sample number, and analytical methods are summarized in Table 2.

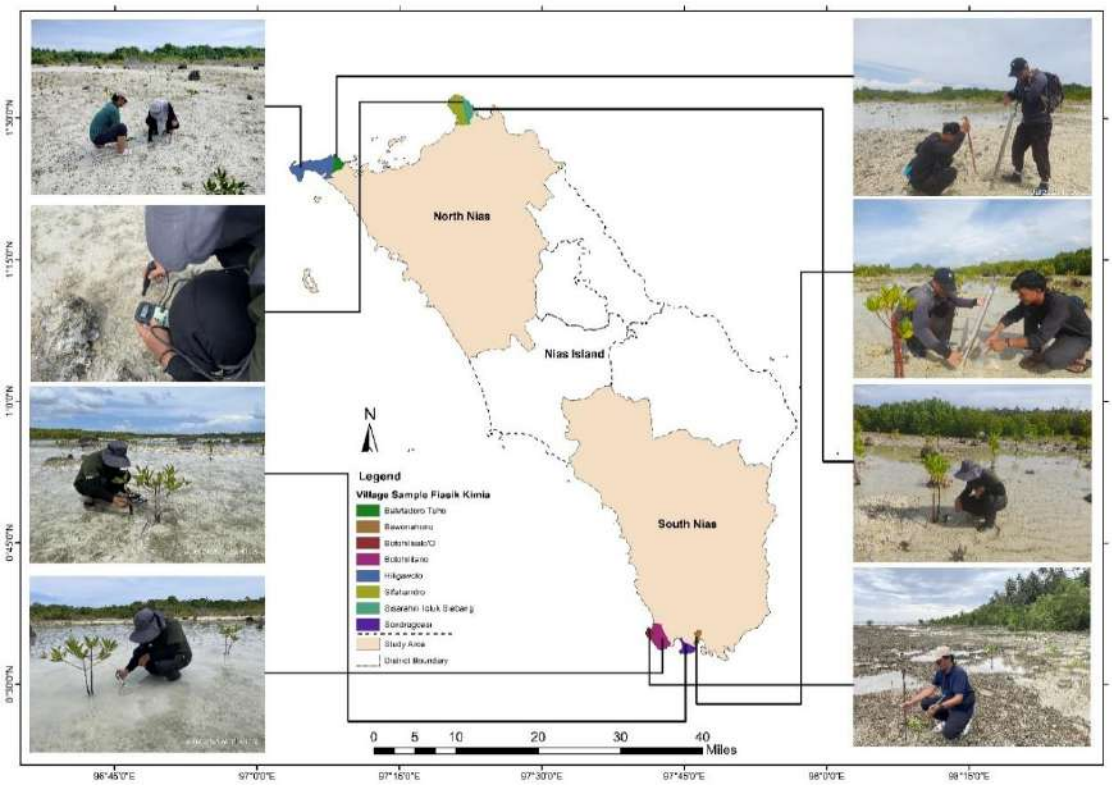

Fig. 2: Monitoring and replacement planting sequence used to calculate live plant percentage at three, six, and twelve months after planting

Table 2: Habitat variables, sampling scale, sample number, and analytical methods

Variable group	Variable	Sampling scale	Number of samples or plots	Method
Water quality	Water temperature	Plot level	77 plots	In situ field measurement
	Water pH	Plot level	77 plots	In situ field measurement
	Salinity	Plot level	77 plots	In situ field measurement
	Dissolved oxygen	Plot level	77 plots	In situ field measurement
Substrate chemistry	Substrate pH	Plot level	77 plots	Field or laboratory measurement
Substrate texture	Sand, silt, and clay fractions	Plot level	77 samples	Hydrometer method
Organic matter	Organic carbon	Site level	8 samples	Dichromate oxidation
	Carbon-to-nitrogen ratio	Site level	8 samples	Derived from carbon and nitrogen values
Soil fertility	Total N	Site level	16 samples	Kjeldahl method
	Available P	Site level	16 samples	Bray 2 method
	Available K	Site level	16 samples	Ammonium acetate extraction and atomic absorption spectrophotometry

Data aggregation and statistical analysis

Data were organized according to the sampling scale of each variable. Live plant percentage, water quality, substrate pH, and substrate texture were recorded or calculated at the plot level and then summarized as site-level means. Organic carbon, carbon-to-nitrogen ratio, total N, available P, and available K served as site-level environmental indicators, as these parameters were quantified from representative soil samples collected at each village-level site. Live plant percentage was analyzed at three monitoring periods: three, six, and twelve months after planting. For each monitoring interval, village-scale mean values were computed across the eight designated study sites. These values were

compared with site-level habitat indicators to evaluate whether vegetation establishment outcomes varied in response to differences in hydrological, substrate, and soil fertility conditions. Pearson correlation analysis was used to examine site-level associations between habitat indicators and live plant percentage. The habitat indicators included water temperature, water pH, salinity, dissolved oxygen, substrate pH, sand, silt, clay, organic carbon, carbon-to-nitrogen ratio, total N, available P, and available K. The analysis used eight village-level sites as analytical units (Field, 2018). A series of correlation analyses was executed to assess the association between key environmental variables and the percentage of surviving plants at each observational phase (3, 6, and 12 months post-planting. Considering that the number of analysis units at the village level is relatively limited (n = 8) and there are several habitat parameters tested simultaneously, the results of the correlation analysis are interpreted as an exploratory analysis to identify initial relationship patterns between variables. Consequently, the interpretation of the these findings extends beyond mere statistical significance value ($p < 0.05$), to evaluate the magnitude of the correlation coefficient, the consistency of the observed relationship between observation, and the broader ecological relevance of each habitat parameter. This approach was taken to reduce the possibility of over-interpretation of findings resulting from multiple statistical comparisons conducted on a relatively modest sample size. Considering the relatively limited number of analysis units at the village level (n = 8) and the existence of several correlation tests carried out simultaneously, the results of the statistical analysis were interpreted as an exploratory analysis to identify initial relationship patterns between habitat characteristics and the percentage of living plants. Therefore, the interpretation of the results is not only based on the statistical significance value ($p < 0.05$), but also considers the magnitude of the correlation coefficient, the consistency of the relationship between observation periods, and the ecological relevance of each variable. Consequently, these correlational findings serve not as definitive confirmatory evidence, but rather as a foundation for generating hypotheses to be rigorously tested in future, larger-scale investigations.

RESULTS AND DISSCUSSION

Water physicochemical conditions and substrate pH

Water conditions differed among the eight planting sites. Site-level mean water temperature ranged from 29.51 degrees Celsius (°C) in Botohilitano to 32.56 °C in Hiligawolo. Water pH ranged from 7.50 in Sondregeasi to 8.05 in Botohilitano. Salinity ranged from 31.33 part per thousand (ppt) in Botohilitano to 34.20 ppt in Sondregeasi. Dissolved oxygen ranged from 9.10 milligrams per liter (mg/L) in Bawonahono to 10.99 mg/L in Sisarahili Teluk Siabang (Table 3).

Substrate texture, organic matter, and soil fertility conditions

Sand dominated all site means. Botohilisalo'o had the lowest sand fraction at 82.00 percent (%), while Sondregeasi had the highest at 93.25%. Silt ranged from 4.50% to 13.13%, and clay from 1.00% to 5.00%. The monitored planting surfaces consisted of coarse coral-rubble and sandy substrate, rather than traditional, mature mangrove mud (Table 4).

Live plant percentage across monitoring periods

Live plant percentage already differed at three months. Hiligawolo recorded 98.19%, Botohilisalo'o 96.72%, and Sisarahili Teluk Siabang 93.16%. The lowest early survival rates were recorded in Sifahandro (38.66%) and Balefadoro Tuho (45.88%). Similarly, Botohilitano exhibited a lower establishment rate (63.76%) at the three-month mark compared to the highest-performing sites (Table 5). At six months, Hiligawolo had the highest record, at 94.17%. Four other sites were above 75%: Botohilisalo'o (87.06%), Sisarahili Teluk Siabang (83.38%), Sifahandro (82.24%), and

Table 3: Water physicochemical conditions and substrate pH across monitored mangrove planting sites

Regency	Site	Water temperature	Salinity	Dissolved oxygen (mg/L)	Water pH	Substrate pH
South Nias	Bawonahono	30.53	34.11	9.10	7.81	5.65
	Sondregeasi	30.60	34.20	9.90	7.50	5.23
	Botohilitano	29.51	31.33	9.83	8.05	5.48
	Botohilisalo'o	31.03	32.51	9.64	7.93	5.34
North Nias	Sisarahili Teluk Siabang	30.81	31.94	10.99	8.04	5.57
	Sifahandro	30.59	32.16	10.46	7.88	5.38
	Balefadoro Tuho	31.00	31.97	9.67	7.85	5.92
	Hiligawolo	32.56	32.41	9.63	8.00	5.66

Note: Values are site-level means.

Table 4: Substrate texture, organic carbon, and soil fertility indicators across monitored planting sites

Regency	Village-level site	Sand (%)	Silt (%)	Clay (%)	Organic carbon (%)	C/N ratio	Total N (%)	Available P (ppm)	Available K (m.e/100 g)
South Nias	Bawonahono	91.75	4.50	3.75	0.24	6	0.04	3.81	0.26
	Sondregeasi	93.25	5.75	1.00	0.11	4	0.04	2.76	0.19
	Botohilitano	92.50	5.50	2.00	0.21	4	0.05	2.30	0.27
	Botohilisalo'o	82.00	13.13	4.88	0.17	2	0.07	2.43	0.41
North Nias	Sisarahili Teluk Siabang	92.73	5.40	1.80	0.05	1	0.06	2.30	0.24
	Sifahandro	92.36	5.43	2.14	0.18	3	0.04	4.22	0.32
	Balefadoro Tuho	88.67	8.67	2.67	0.34	5	0.07	3.23	0.17
	Hiligawolo	90.00	5.00	5.00	0.11	2	0.05	2.89	0.22

Table 5: Site-level live plant percentage at three, six, and twelve months after planting

Regency	Village-level site	Planted species	Number of plots	3 months (%)	6 months (%)	12 months (%)
South Nias	Bawonahono	*Rhizophora apiculata*	8	86.20	62.75	46.05
	Sondregeasi	*Rhizophora apiculata*	8	84.60	61.15	48.50
	Botohilitano	*Rhizophora apiculata*	8	63.76	55.65	39.60
	Botohilisalo'o	*Rhizophora stylosa*	8	96.72	87.06	77.16
North Nias	Sisarahili Teluk Siabang	*Rhizophora apiculata*	15	93.16	83.38	75.91
	Sifahandro	*Rhizophora stylosa*	14	38.66	82.24	75.42
	Balefadoro Tuho	*Rhizophora stylosa*	6	45.88	76.05	70.00
	Hiligawolo	*Rhizophora apiculata*	10	98.19	94.17	87.86

Balefadoro Tuho (76.05%). Bawonahono, Sondregeasi, and Botohilitano stayed lower, at 62.75%, 61.15%, and 55.65%. At twelve months, Hiligawolo still had the highest record at 87.86%. Botohilisalo'o recorded 77.16%, Sisarahili Teluk Siabang 75.91%, Sifahandro 75.42%, and Balefadoro Tuho 70.00%. The three lowest final records were Sondregeasi (48.50%), Bawonahono (46.05%), and Botohilitano (39.60%). The gap between Hiligawolo and Botohilitano was 48.26 percentage points. In contrast to the high-record sites, Sifahandro and Balefadoro Tuho exhibited distinct historical monitoring profiles. At three months, Sifahandro recorded 38.66% and Balefadoro Tuho 45.88% after planting with nursery seedlings. Failed planting points were later replanted with propagules. Monitoring patterns in South Nias and North Nias exhibited significant heterogeneity (Fig. 3). In South Nias, Botohilisalo'o stayed higher than Bawonahono, Sondregeasi, and Botohilitano through twelve months. In North Nias, Hiligawolo maintained elevated metrics across a three- to twelve-month duration, whereas Sifahandro and Balefadoro Tuho exhibited increases subsequent to the remediation of failed points. The inclusion of Gann *et al*. (2019) urther justifies this methodology, as monitoring and post-intervention management are fundamental components of standard restoration practice.

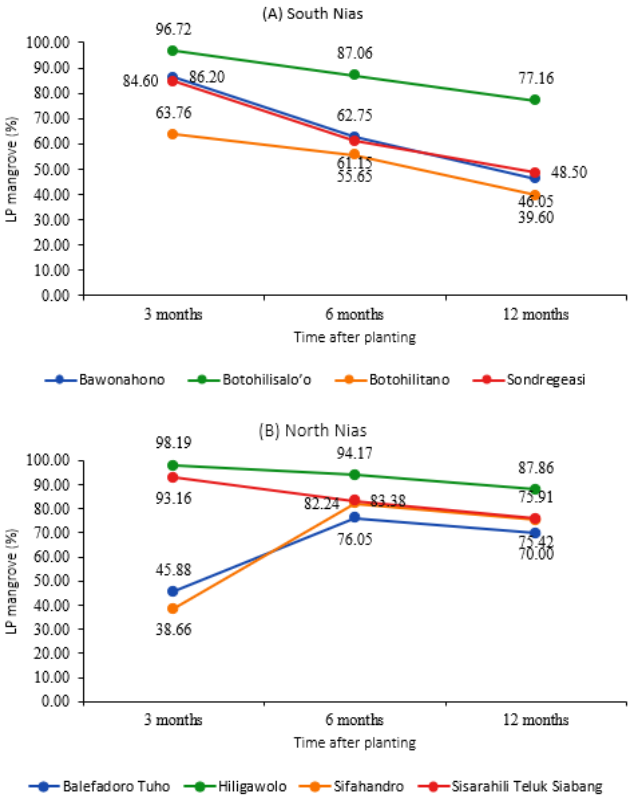

Fig. 3: Live plant percentage of planted mangroves across village-level sites at three, six, and twelve months after planting: (A) South Nias and (B) North Nias. Figure note: Values at six and twelve months represent live plant percentage under field maintenance and replacement planting

Site-level associations between habitat indicators and live plant percentage

Pearson correlation coefficients were calculated utilizing data aggregated at the village-level site scale. The analysis used eight sites, not plot-level observations. The values in this section are site-level associations between habitat indicators and live plant percentage. Water temperature exhibited the strongest positive correlation with the percentage of live plants during the latter phases of the monitoring periods. At six months, the correlation was r = 0.805 with p = 0.016. At twelve months, the correlation was r = 0.792 with p = 0.019 (Table 6). At three months, the correlation was weaker. These data indicate that water temperature represents the most robust site-level association identified within this dataset. The carbon-to-nitrogen ratio had a negative direction. At six months, the correlation was r = -0.712 with p = 0.048. At twelve months, the value was r = -0.697 with p = 0.055. The carbon-to-nitrogen ratio was evaluated as an indicator of substrate condition, rather than as an isolated determinant of live plant percentage. Alongi (2018) is used for the nutrient and substrate function context. The full correlation pattern is presented in Fig. 4. The raw worksheet values are excluded from the main text of the manuscript and are utilized exclusively for the construction of the heatmap.

Restoration performance and replacement planting

Both the initial planting and replacement planting were included in the six- and twelve-month datasets, as tracking replacement

Table 6: Main site-level Pearson correlations between habitat indicators and live plant percentage

Habitat indicator	Monitoring period	Pearson r	p-value	Interpretation
Water temperature	6 months	0.805	0.016	Significant positive association
	12 months	0.792	0.019	Significant positive association
Carbon-to-nitrogen ratio	6 months	-0.712	0.048	Significant negative association
	12 months	-0.697	0.055	Near-significant negative tendency

Note: The analysis used eight village-level sites as analytical units. Correlations are interpreted as exploratory site-level associations, not causal relationships.

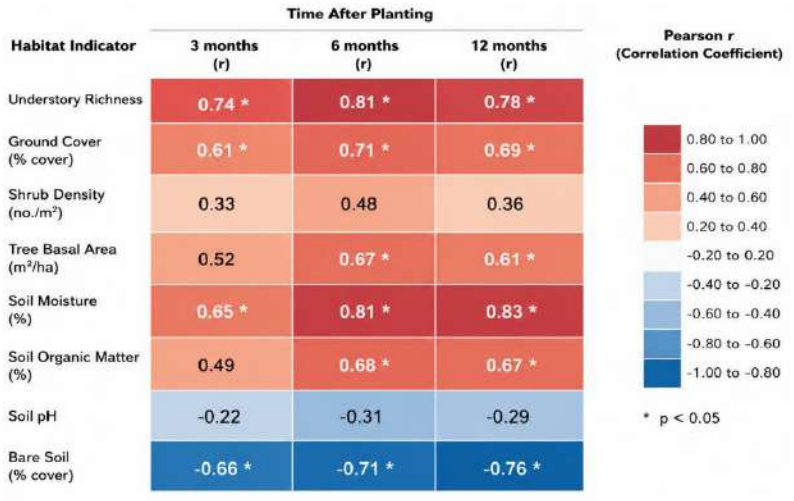

Fig. 4: Heatmap of site-level Pearson correlation coefficients between habitat indicators and live plant percentage at three, six, and twelve months after planting. Figure note: Color intensity indicates correlation strength and direction. Asterisks indicate significant correlations at $p < 0.05$. The analysis used eight village-level sites as analytical units

dynamics is essential to this study. The increase in the percentage of live plants in the 6th and 12th months of observation not only reflects the adaptability of the seeds planted at the start of the study, but also shows the contribution of management intervention through replanting to the success of restoration. The observed shifts in live plant percentages across monitoring periods reflect a combination of habitat conditions, replanting success, and management practices, rather than natural survival patterns. These findings confirm that the success of mangrove restoration is not only determined by habitat suitability, but also by adaptive management through monitoring and replanting dead plants, as recommended post-planting management to increase the success of restoration (Friess *et al.*, 2019). Therefore, evaluations of restoration success should separately consider initial plant survival and replantation success. The term was utilized by Sloey *et al*., (2022) to characterize one-year mangrove seedling performance across under varying abiotic site conditions. The Nias records also separate monitoring age, species, and planting material. Hiligawolo used *Rhizophora apiculata* and ended at 87.86% after twelve months. Botohilisalo'o, Sifahandro, and Balefadoro Tuho used *Rhizophora stylosa* and ended at 77.16%, 75.42%, and 70.00%. Species ranking was not performed using these values due to inherent heterogeneity in site conditions and replacement planting protocols across study sites. Comprehensive records of species and planting materials were instead utilized to account for these variables, ensuring that subsequent live plant percentages were not attributed solely to species-specific performance (Su *et al*., 2021). The increase in the percentage of live plants in several

locations, such as in Sifahandro (38.66% to 82.24%) and Balefadoro Tuho (45.88% to 76.05%). This condition also effected by replanting activities (replacement planting), not merely the survival of plants planted at the start of the study. Thus, changes in values between periods better reflect the effectiveness of management interventions in maintaining plant cover rather than the natural dynamics of seedling survival. These results indicate that mangrove restoration success depends on both habitat suitability and adaptive replanting; therefore, restoration evaluations should account for both factors (Bosire *et al.,* 2008). The mangrove types, planting materials, habitat conditions, and management interventions are not applied uniformly at all research locations. *R.apiculata* and *R. stylosa* is planted in different locations, with variations in the use of propagules and nursery seeds, and in some locations replanting is carried out using propagules. These conditions mean that the influence of species, type of planting material, habitat characteristics and embroidery cannot be separated independently. Consequently, spatial variations in the percentage of live plants are best understood as the product of multifactorial interactions rather than the isolated effect of a single variable. Future research needs to use a more controlled experimental design so that the influence of each factor can be evaluated separately.

Substrate limitation

Substrate pH was acidic at all sites, from 5.23 in Sondregeasi to 5.92 in Balefadoro Tuho. Despite the dominance of carbonate-rich coral fragments within the study substrate, the observed acidic pH is likely driven by post-successional substrate development—specifically the accumulation of organic material, litter decomposition processes, root respiration, and the subsequent formation of organic acids. In addition, alkaline leaching due to high rainfall in tropical regions can also reduce the pH of surface substrates even though the parent material comes from carbonates. The planting surface was coral-rubble and sand, so the pH record describes the rooting medium rather than ordinary mangrove mud. This medium, previously utilized by Balke *et al*., (2011) for early mangrove establishment on unstable tidal substrates, experienced salinity levels ranging from 31.33–34.20 ppt during the monitoring period. In the Pearson test result, salinity was not a significant site-level variable for live plant percentage. The salinity describes the water condition around the planted mangroves. Kodikara *et al*., (2018) reported that mangrove seedling responses to salinity and can change with age. Organic carbon stayed low across the eight sites. The lowest value was recorded in Sisarahili Teluk Siabang at 0.05%, and the highest in Balefadoro Tuho at 0.34%. Total N was 0.04–0.07%, available P 2.30–4.22 part per million (ppm), and available K 0.17–0.41 *milliequivalents per 100 grams* (m.e./100 g). The N, P, and K values were recorded to track substrate fertility, as nutrient dynamics are key to overall mangrove habitat function (Alongi, 2018). Five sites had organic carbon below 0.20%: Sisarahili Teluk Siabang, Sondregeasi, Hiligawolo, Botohilisalo'o, and Sifahandro. The initial rooting medium exhibited low levels of stored organic material. This highlights the significance of the low organic carbon values in the Nias plots, as below-ground production and root biomass are primary drivers of mangrove soil formation (Adame *et al.,* 2014). Balefadoro Tuho had the highest organic carbon value, but it was still only 0.34%. Most sites were below 0.25%. The field setting explains that range: the planting medium was mainly coral-rubble and sand, with little fine material to hold organic matter. This study relies on the principles of carbon cycling and storage in mangrove ecosystems as delineated by Alongi (2018). Total N stayed low at every site. Botohilisalo'o and Balefadoro Tuho had the highest total N values at 0.07%, while Bawonahono, Sondregeasi, and Sifahandro were 0.04%. These records describe a weak fertility background for early root-zone development. Nutrient limitation in these disturbed mangrove systems was evaluated following Feller *et al*. (2003). In the field, substrate texture and organic carbon varied in the same field

direction. Sites with more than 90% sand had little fine material for holding organic matter. Sondregeasi had 93.25% sand and 1.00% clay; its organic carbon was 0.11%. This study draws on Morris *et al*. (2016) to contextualize the role of mineral and organic matter in tidal-wetland sediment volume. Botohilisalo'o differed texturally from the other sites in texture, having the lowest sand fraction (82.00%) and the highest silt fraction (13.13%). Despite the higher fine fraction, organic carbon was only 0.17%, showing that the substrate was still weakly developed. Sediment and substrate adjustments in these mangrove settings were evaluated following Krauss *et al*., (2014).

Environmental association

Water temperature was the only measured indicator with significant positive correlations at both six and twelve months. The values were r = 0.81 and r = 0.79 in the heatmap. These correlations are not evidence that temperature alone controlled live plant percentage. The warmer locations may also have experienced differences in water movement, exposure, and local residence times near the planted mangroves. For planted *Rhizophora* on coral-rubble substrate, the temperature result has to stay linked with the rooting condition. Most sites had sand above 90%, clay no higher than 5.00%, and organic carbon below 0.34%. A warm site still needs enough substrate stability for anchorage and root-zone development. Mangrove physiological responses to varying environmental conditions were evaluated following Lovelock *et al*., (2016). Sand and clay did not reach the significance threshold, but their directions followed the substrate record. Sand was negative at six and twelve months, while clay was positive. The site data support that reading: sand reached 93.25% in Sondregeasi, while clay was only 1.00% at that site. The roles of mineral and organic matter in determining tidal-wetland sediment volume are evaluated based on the principles established by Morris *et al*., (2016). Total N, available P, and available K were not significant as single site-level variables. Total N was 0.04–0.07%, available P 2.30–4.22 ppm, and available K 0.17–0.41 m.e/100 g. These values remain in lower compare to muddy mangrove ecosystem. They are not treated as direct causal drivers of live plant percentage. Pearson correlation was calculated from the eight village-level site means. Following Field (2018), the Pearson coefficients were interpreted strictly as measures of correlation. Water temperature showed a relatively strong positive correlation with the percentage of live plants at the 6th month (r = 0.805) and the 12th month (r = 0.792). Physiologically, temperature influences metabolic activities, photosynthesis, respiration and nutrient absorption which play an important role in the growth and adaptability of mangroves to environmental stress (Wang and Gu, 2021; Kang *et al.,* 2024). Caution is required when interpreting this relationship, as the small number of locations (n = 8) makes the correlation coefficient highly sensitive to site-specific differences. In addition, the range of water temperatures between locations is still within the tolerance range for tropical mangrove growth, so water temperature is probably not the main limiting factor, but rather reflects more complex habitat conditions, such as hydrology, inundation frequency, tidal dynamics, substrate stability and water circulation. According to prior studies, the success of mangrove growth and restoration is more influenced by the interaction of various environmental factors than by temperature alone (Alongi, 2018). Therefore, the relationship between water temperature and percentage of live plants in this study is more appropriately viewed as an exploratory association at the location level rather than a cause-and-effect relationship. Although these results point to water temperature as a key habitat component for restoration success, further research is required. Validating the role of all habitat factors will demand a larger sample size, complete hydro-geomorphological metrics, and stronger statistical approaches. The percentage of live plants was measured on the same plots in the 3rd, 6th, and 12th months, so conceptually the data have a repeated

measures structure. This study evaluated the relationship between habitat characteristics and live plants independently for each observation time. Therefore, the resulting correlations reflect specific time points rather than temporal dependencies between time periods. This approach was chosen because the analysis focused on evaluating habitat conditions at each monitoring stage, while the limited number of analysis units and the presence of replanting activities during the study period meant that the data did not meet the assumptions required for a more complex longitudinal analysis. As a result, these findings represent an exploratory, period-by-period analysis. Future studies should use mixed-effects models or generalized linear mixed models (GLMM) to handle repeated data and better evaluate the effects of time and interacting habitat variables.

Implication for the ecological mangrove restoration

While both sites utilized the same planting density, their twelve-month plant survival rates differed dramatically. Hiligawolo recorded an 87.86% survival rate compared to 39.60% at Botohilitano, resulting in a 48.26 percentage point difference. In coral-rubble planting land, a hectare count alone is not enough. The site name and the twelve-month record have to stay together. The substrate values also have to be checked before planting is expanded. With sand ranging between 82.00% to 93.25%, clay between 1.00% to 5.00%, and organic carbon between 0.05% to 0.34%, the textural profile denotes a coarse early-stage planting medium as opposed to highly developed mangrove mud. Lewis (2005) placed hydrology and site condition before planting technique; that order matches the Nias sites. Sifahandro and Balefadoro Tuho had different monitoring histories from the high-record sites. At three months, Sifahandro recorded 38.66% and Balefadoro Tuho 45.88% after planting with nursery seedlings. Failed planting points were later replanted with propagules. The six- and twelve-month values included both the first planting and the replacement planting. Similarly, Kodikara *et al*. (2017) evaluated restoration success based on actual field performance rather than relying on mere planting metrics. N, P, and K worked as habitat information in this study. Total N was 0.04–0.07%, available P 2.30–4.22 ppm, and available K 0.17–0.41 m.e/100 g. None of these variables was significant as a single site-level correlation with live plant percentage. These values remain lower when compared to those of natural mangrove stands established in mud-dominated ecosystems (Friess *et al.,* 2019). Alongi (2018) treated nutrient dynamics as part of mangrove habitat function. For the coral-rubble block, the field sheet should be completed before planting starts. The sheet should list substrate texture, substrate pH, organic carbon, water condition, planting material, field exposure, and expected replacement planting. The eight Nias sites were in one monitoring program, but their field records were not the same. Schmitt *et al*., (2013) used site-specific planning for mangrove coasts with local variation. Keeping Botohilitano and Hiligawolo as separate site records also keeps the restoration target tied to field evidence (Friess *et al.,* 2022). Sifahandro, Balefadoro Tuho, and Botohilitano need different follow-up notes in the site sheet. By replanting the dead individuals with new propagules, Sifahandro's live plant percentage increased from 38.66% at three months to 82.24% at six months. Balefadoro Tuho increased from 45.88% to 76.05% in the same monitoring interval. Botohilitano did not show the same response; it was 63.76% at three months, 55.65% at six months, and 39.60% at twelve months. The maintenance record was kept with each monitoring period so field counts could guide replacement planting (Ellison *et al.,* 2020). Botohilitano and Hiligawolo should be classified as independent site records within national restoration databases. Although subjected to the same planting density, their twelve-month survival rates diverged significantly; Hiligawolo recorded 87.86% survivorship, surpassing Botohilitano's 39.60% by a substantial 48.26 percentage points. A planted-area total would not

show that gap. Sasmito *et al*., (2023) discussed Indonesia's mangrove restoration targets together with field constraints, and the Nias data show why site-level records are needed on coral-rubble planting land. Planting in Nias was done on reef-flat ground exposed after the earthquake. It was not old mangrove mud. The substrate still showed that origin: sand 82.00–93.25%, clay 1.00–5.00%, and organic carbon 0.05–0.34%. With little clay and organic carbon, the plots had little material for first-year root-zone development. Lovelock *et al*., (2015) reported the role of elevation and sediment supply in Indo-Pacific mangroves. Subsequent site assessments must separate open coastlines from habitats where planted mangroves can successfully survive their first year. Hiligawolo and Botohilitano cannot be placed in the same management class after the twelve-month record. Hiligawolo reached 87.86%, while Botohilitano stayed at 39.60%. Romañach *et al*., (2018) linked mangrove restoration outcome with site condition, restoration design, and follow-up management. The mortality of mangrove seedlings at this location likely stems from a combination of diverse environmental and biological factors, rather than a single variable. In coral rubble habitats, low substrate stability can inhibit root penetration, increase the risk of plants collapsing, and reduce the ability of seedlings to obtain water and nutrients. In addition, variations in hydroperiod, inundation frequency, wave exposure, and tidal conditions can increase physiological stress, especially in the early stages of seedling growth (Lewis, 2005). Biological stressors, including crab herbivory, pest and pathogen infestations, and interspecific competition-are well-documented impediments to the early-stage success of mangrove restoration (Friess *et al.,* 2019). Because this study did not determine the direct drivers of seedling mortality or delineate the relative influence of each environmental variable, the identified association between habitat quality and plant survival must be approached with caution. Future research needs to integrate monitoring of the causes of seedling death, hydrological measurements, substrate stability, and biotic disturbances to gain a more comprehensive understanding of the factors that determine the success of mangrove restoration in coral rubble habitats. The low content of organic matter in the coral fragment substrate indicates that habitat improvement has the potential to increase the success of mangrove restoration. The addition of organic matter, compost, or sediment enrichment can increase organic carbon content, water holding capacity, nutrient availability, and support the development of the root system and the activity of soil microorganisms, thereby increasing the ability of seedlings to adapt to sediment-poor substrates. However, the efficacy of these potential interventions remains unassessed in this study. Consequently, future research must systematically evaluate diverse habitat improvement techniques within an adaptive restoration framework to enhance mangrove establishment success in tectonically uplifted coral fragment substrates (Lewis, 2005; Friess *et al.,* 2019).

Study limitation

This study focuses habitat assessment on water quality and soil fertility parameters because these two groups of parameters are environmental indicators that can be directly measured during the monitoring period and have the potential to influence the success of mangrove planting. However, this study does not include quantitative measurements of hydrological and geomorphological parameters, such as elevation relative to sea level, frequency and duration of inundation, and tidal dynamics. These factors are critical determinants of habitat physical conditions, influencing sediment distribution, substrate aeration, and the success of mangrove stand establishment, particularly in earthquake-uplifted coral fragment substrates (Lewis, 2005; Friess *et al.,* 2019). Therefore, the relationship between habitat characteristics and percentage of living plants in this study needs to be interpreted taking these limitations into account. To achieve a more comprehensive assessment of habitat suitability and the factors governing mangrove

restoration, future research must integrate hydrological and geomorphological metrics with detailed water quality and soil analyses. The relatively low nutrient concentrations in the study substrates do not necessarily indicate that mangrove growth is limited by nutrient availability. Biogeochemical profiles of mangroves in carbonate and coral-rubble environments reflect lower levels of organic matter, N, and P, which can be attributed to the restricted deposition of organic litter and fine-textured sediments characteristic of these substrate types (Feller *et al.,* 2003). For example, mangroves on carbonate islands in Belize and the Caribbean have been reported to have organic carbon contents generally <2%, total N <0.20%, and available P <10 milligrams per kilogram (mg/kg), yet they maintain growth through efficient nutrient use, nutrient recycling, and physiological adaptation to oligotrophic conditions (Feller *et al.,* 2003). Therefore, the nutrient values obtained in this study are more appropriately viewed as a natural characteristic of the coral rubble substrate rather than as evidence of nutrient limitation. Proving nutrient limitation requires robust experimental validation, such as the implementation of nutrient-enrichment tests or the use of reference sites controlled for geomorphological and hydrological similarity (Alongi, 2018). Mangrove restoration in coral fragment habitats due to tectonic uplift has the potential to provide significant ecological benefits, such as increasing coastline stability, providing habitat for coastal biota, supporting biodiversity recovery, and increasing long-term carbon storage capacity (Friess *et al.,* 2019). In contrast to restoration efforts within natural, mud-dominated mangrove habitats, interventions on coral-rubble substrates encounter significantly greater challenges. Due to the less conducive physical habitat conditions, these environments necessitate more intensive monitoring, supplementary replanting, and rigorous adaptive management strategies. This condition has the potential to increase the costs of implementing and maintaining restoration. However, this study did not evaluate economic costs or long-term cost effectiveness, so it cannot directly compare the efficiency of restoration in coral rubble habitats with conventional mangrove restoration sites. Therefore, future research needs to integrate analyzes of costs, ecological benefits, and ecosystem services to evaluate the effectiveness of restoration more comprehensively. The sustainability of mangrove restoration in coral rubble habitats due to tectonic uplift also needs to be considered in the context of climate change. Rising sea levels, changes in tidal patterns and increasing wave intensity have the potential to change the effective elevation, hydroperiod and substrate stability which are the main factors in the suitability of mangrove habitat (Lovelock *et al.,* 2015; Alongi, 2018). In coral rubble habitats, these changes can increase erosion, reduce root stability, and limit sediment accumulation necessary for long-term development of mangrove stands. Conversely, successful mangrove establishment and the subsequent accumulation of sediment and organic matter can significantly bolster coastal protection, increase adaptive capacity to sea level rise, and augment the overall resilience of coastal ecosystems to climate change (Friess *et al.,* 2019; Sasmito *et al.,* 2023). Therefore, the success of restoration in coral rubble habitats is not only determined by the initial conditions of the habitat, but also by the ability of the ecosystem to maintain its ecological function against environmental changes in the long term. To properly assess the sustainability of restoration in tectonically uplifted ecosystems, long-term monitoring of hydrological changes, sediment dynamics, and shoreline stability is essential. The frequency, duration, and depth of tidal inundation, along with wave exposure and coastal hydrodynamic conditions, are the main factors determining habitat suitability, seedling stability, and the success of mangrove restoration. Variations in hydroperiod affect oxygen availability in the root zone, salinity, sediment deposition, and nutrient supply, while exposure to high waves can increase substrate instability, inhibit root formation, and cause seedlings to be

uprooted or fall over, especially in coral rubble habitats (Lewis, 2005). Given that hydrological parameters were beyond the scope of this study, their relative contribution to the differences in live plant percentages between locations remains unquantified. Therefore, the relationship between habitat characteristics and percentage of live plants in this study needs to be interpreted carefully. Future research needs to integrate measurements of hydroperiod, elevation relative to tides, wave dynamics, and sedimentation processes to obtain a more comprehensive assessment of habitat suitability and the factors that influence the success of mangrove restoration (Friess *et al.,* 2019). Root penetration, seedling anchorage, and the accumulation of sediment and organic material—all of which are vital to mangrove development—are fundamentally influenced by the physical attributes of coral-fragment substrates, such as surface stability, fragment size, and layer thickness (Lewis, 2005). In addition, coastal uplift due to tectonic activity can change elevation and hydroperiod, thereby affecting the suitability of habitat for mangrove growth (Friess *et al.,* 2019). Since these parameters were not measured, the differences in plant survival across locations are likely explained by variations in the physical characteristics of the substrate. Therefore, future research needs to integrate analysis of substrate physical properties, elevation, and sedimentation dynamics to evaluate the success of restoration more comprehensively.

CONCLUSION

Mangrove planting on earthquake-uplifted coral-rubble land in Nias gave uneven first-year records across the eight village-level sites. The twelve-month live plant percentage differed by 48.26 percentage points between sites, with Botohilitano recording 39.60% and Hiligawolo 87.86%, despite both receiving identical planting densities. Planted area and planting density alone did not describe the condition of each site. The substrate record separated these sites from mature mangrove mud. Sand ranged from 82.00% to 93.25%, clay from 1.00% to 5.00%, and organic carbon from 0.05% to 0.34%. Substrate pH was acidic, with values from 5.23 to 5.92. Total N, available P, and available K were also low. These variables describe a coarse, low-carbon, low-fertility planting medium. Live plant percentage has to be read with the replacement record. Three-month survival rates were low at both Sifahandro (38.66%) and Balefadoro Tuho (45.88%) after initial planting. To improve site coverage, failed planting points were replaced with new propagules. The six- and twelve-month records included the first planting and the replacement planting. They are reported as live plant percentage, not original-cohort survival. The Pearson analysis used eight village-level sites, so the results are site-level associations only. A positive association was observed between water temperature and seedling survival rates at six and twelve months post-planting. The carbon-to-nitrogen ratio showed a negative association, especially at six months. Total N, available P, and available K were not significant as single variables, but they remain part of the habitat diagnosis. For uplifted coral-rubble planting land, the next planting decision should keep site records separate. Live plant percentage, replanting history, substrate texture, substrate pH, organic carbon, water condition, fertility values, field exposure, and planting material need to be checked together before expansion. For this coastal typology, site assessment should extend beyond mere consideration of the planted area or the total number of planting units. The study results show variations in the success of mangrove restoration between locations, which emphasizes the importance of specific habitat assessments before restoration activities are carried out. However, these results warrant cautious interpretation, as seedling survival percentages were confounded by supplemental replanting activities. Furthermore, the relationship between habitat characteristics and survival remains exploratory; therefore, these findings cannot yet establish definitive predictors for restoration success. Therefore, future research needs to

integrate measurements of hydrology, elevation relative to tides, hydroperiod, and geomorphological characteristics to gain a more comprehensive understanding of the factors that determine the success of mangrove restoration in coral rubble habitats due to tectonic uplift.

AUTHOR CONTRIBUTIONS

E. Tuhono, contributed to conceptualization, field investigation, data collection, data analysis, methodology, visualization, and writing the original draft. Z. Nasution, the corresponding author, contributed to supervision, methodology review, scientific interpretation, and manuscript review. D. Delvian contributed to supervision, ecological interpretation, and manuscript review. N.M. Noor contributed to scientific review, manuscript editing, and critical revision.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
°C	Degree Celcius
AAS	Atomic absorption spectrophotometry
cm	Centimeter
C/N ratio	Carbon-to-nitrogen ratio
DO	Dissolved oxygen
EMR	Ecological mangrove restoration
g	Gram
ha	Hectare
K	Potassium
KCl	Potassium chloride
kg	Kilogram
L	Liter
LP	Live plant percentage
m.e.	Milliequivalent
mg	Milligram
mg/kg	Milligram per kilogram
mg/L	Milligrams per liter
mm	Millimeter
N	Nitrogen
P	Phosphorus
pH	Potential of hydrogen
ppm	Parts per million
ppt	Parts per thousand

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ORIGINAL RESEARCH ARTICLE

Oceanic environmental variability and fishing effort reallocation in data constrain small-scale fishery

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ABSTRACT

BACKGROUND AND OBJECTIVES: Small-scale fisheries in tropical multi-gear systems are shaped by marine environmental variability and pressure on target stocks. In the Timor Sea, seasonal variation in sea surface temperature and chlorophyll-a influences the spatio-temporal distribution of fishing opportunities, while demersal snapper stocks remain vulnerable to overexploitation. This study evaluated whether oceanographic variability and demersal stock pressure were associated with fishing-effort reallocation, while distinguishing fleet-level restructuring from vessel-level gear switching.

METHODS: Vessel-level landing records from 2014 to 2020 were analyzed for vessels of 30 gross tonnage or less, comprising 3,441 records from 619 vessels. Sea surface temperature and chlorophyll-a data were obtained from satellite products, spatially averaged over the fishing domain, aggregated into monthly means, transformed into anomalies, and matched to landing records. To comprehensively evaluate gear dynamics, a multi-tiered analytical framework comprising compositional testing, multinomial logistic regression models, functional gear groupings, and vessel-level Markovian transition matrices were established. Demersal stock status for Lutjanus malabaricus, Lutjanus sebae, and Pristipomoides multidens was determined via length-based spawning potential ratio estimates.

FINDINGS: Sea surface temperature and chlorophyll-a showed strong seasonal and interannual variability but no long-term trends. Gear composition shifted significantly, with purse seine effort increasing and bottom longline use declining relative to handlines. After controlling for month, vessel size, trip intensity, and environmental anomalies, the multinomial model showed an increasing probability of purse seine use over time. Purse seine deployment was significantly associated with lagged temperature and chlorophyll-a anomalies, indicating that pelagic fishing responded to environmentally mediated opportunities rather than productivity alone. Vessel-level transition analysis revealed a high degree of operational inertia; out of 355 paired vessel-year empirical observations, only 32 instances of gear switching were detected, yielding a nominal transition rate of 9.0 percent. Spawning potential ratio values were below the 40 percent management tapercentassessed species, with *Lutjanus sebae* and *Pristipomoides multidens* below the 20 percent limit reference point.

CONCLUSION: The Timor Sea small-scale fishery is undergoing partial effort reallocation rather than complete gear migration. Purse seine expansion reflects fleet restructuring, indicating adaptation to spatio-temporal environmental variability and demersal stock depletion. Management should prioritize snapper stock rebuilding, pelagic effort monitoring, vessel-level gear tracking, and satellite-based environmental indicators.

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INTRODUCTION

Small-scale fisheries in tropical seas operate as dynamic social–ecological systems in which multispecies exploitation, diverse fishing gears, heterogeneous fleet structures, and oceanographic variability jointly shape fishing strategies. While deep demersal snapper and grouper fisheries hold substantial economic importance in Indonesia, numerous target stocks face escalating fishing pressure—a vulnerability acutely pronounced among species characterized by long life spans and slow growth rates (Wibisono *et al.,* 2022; Wibisono, 2020). At the same time, the performance of these fisheries may also be affected by marine environmental variability because temperature, productivity, and habitat conditions can influence fish distribution, catchability, and fishing-ground formation (Runcie *et al*., 2019; Khan *et al*., 2024).These challenges are intensified by the limited availability of long-term fisheries data, causing management strategies to rely heavily on biological indicators such as catch composition, fish size structure, and reproductive status. Amid the challenges of managing data-limited marine resources, the length-based spawning potential ratio (LB-SPR) methodology has emerged as a vital benchmark for evaluating stock status and verifying that reproductive output remains above critical biological thresholds (Rincón-Sandoval and López-Rocha, 2024; Kasim *et al.,* 2024). However, biological indicators alone may not fully explain changes in fishing behavior, especially when fishing opportunities are also shaped by environmental variability. Remotely sensed oceanographic data, particularly sea surface temperature (SST) and chlorophyll-a, offer a practical way to add an environmental layer to data-limited fisheries analysis because these variables can be observed consistently across space and time using satellite products (López-Martínez *et al*., 2023; Khan *et al*., 2024). Oceanographic variability directly shifts the spatial and temporal distribution of fisheries resources by modifying thermal habitat, primary productivity, prey availability, and the formation of productive fishing grounds. SST reflects thermal suitability and water-mass dynamics, while chlorophyll-a is commonly used as a proxy for primary productivity and potential pelagic foraging habitat. Such environmental variability across tropical marine ecosystems serves as a key driver of fleet adaptation, impacting baseline catch rates while shifting the comparative advantages of demersal- and pelagic-oriented fishing operations (Runcie *et al*., 2019; McInnes *et al*., 2017; Putri *et al*., 2024). In multi-gear fisheries, declining availability of target demersal resources may encourage fishers to modify their fishing strategies in response to ecological and economic pressures. Such adaptive responses can include shifting fishing grounds, increasing fishing intensity, diversifying target species, or reallocating effort toward alternative gears and more productive pelagic resources (Silas *et al.,* 2020; Wiyono *et al.,* 2006). Gear reallocation can be interpreted as a response to two interacting pressures: the declining viability of demersal fishing amid stock depletion, and the expanding opportunities for pelagic fishing driven by favorable oceanographic conditions. However, changes in fleet-level gear composition do not necessarily indicate that individual vessels are actively switching fishing gears. Fishers' decisions are often constrained by financial capital, operational experience, seasonal variability, market access, licensing arrangements, and household dependence on specific fisheries (Andrews *et al.,* 2020; Daw *et al.,* 2012). This distinction underscores the critical analytical nuance required to differentiate between macro-level fleet reconfigurations and discrete, vessel-level gear transitions. Effort displacement from demersal to pelagic fisheries may potentially reduce pressure on depleted snapper stocks, but it can also transfer fishing pressure toward other ecosystems and fishery resources (Nomura *et al.,* 2021; Yletyinen *et al.,* 2018). Previous studies have examined grouper-snapper stock status, small-

scale gear complexity, adaptive fishing behavior, and oceanographic effects on catch dynamics, but these components are often analyzed separately. Extensive empirical literature from Indonesia underscores the inherent socio-ecological complexity of grouper-snapper complexes, emphasizing that data-limited demersal fisheries require high-granularity, gear-specific monitoring alongside spatial and precautionary management frameworks (Herdiana *et al*., 2023; Nadiarti *et al*., 2021; Wibisono *et al*., 2021). However, few studies have integrated vessel-level landing records, gear-use transition analysis, demersal stock-status indicators, and remotely sensed oceanographic variables to evaluate whether fishing-effort reallocation reflects environmental opportunity, biological stock pressure, or broader fleet restructuring. Oceanographic variability, particularly SST and chlorophyll-a anomalies, contributed to changes in fishing strategy by altering the relative attractiveness of demersal- and pelagic-oriented fishing. Specifically, positive chlorophyll-a anomalies are expected to be associated with increased purse seine activity because higher surface productivity may improve pelagic fishing opportunities, while low spawning potential ratio (SPR) values for demersal snapper stocks may indicate biological pressure that reinforces partial effort reallocation away from demersal-associated gears. Consistent with broader literature, this hypothesis posits that environmental fluctuations dictate the spatial and temporal availability of marine resources, which in turn drives tactical adjustments in small-scale fishing behavior to accommodate changing catch viability (Runcie *et al*., 2019; Khan *et al*., 2024; Saldaña *et al*., 2017). This study examines small-scale snapper fisheries operating in the Timor Sea, eastern Indonesia, by integrating vessel-level landing records, remotely sensed SST and chlorophyll-a anomalies, multinomial gear-use models, vessel-level transition matrices, and LB-SPR estimates for key demersal snapper species. Through this integrated approach, the study evaluates whether increasing pelagic-oriented fishing reflects environmental opportunity, demersal stock pressure, or broader fleet-level restructuring. The findings offer valuable contributions to adaptive fisheries management by integrating oceanographic variability, fishing-effort displacement, stock recovery objectives, and vessel-level tracking within a single, cohesive framework. This study aims to evaluate whether oceanographic variability and demersal stock pressure are associated with fishing-effort reallocation in a data-limited small-scale fishery of the Timor Sea. The structural objectives of this study seek to bridge oceanographic variability with fleet dynamics through five sequential aims: first, establishing baseline temporal trends for SST and chlorophyll-a; second, mapping chronological and seasonal variations in fishing activity across years (y) and months; third, determining if localized environmental anomalies dictate the probability of targeting demersal or pelagic resources; fourth, isolating true vessel-level behavioral switching from aggregate fleet-wide trends; and finally, evaluating the implications of these dynamics for demersal snapper stock sustainability and proactive risk management. The analysis focuses on small-scale vessels landing in Kupang, eastern Indonesia, and operating in the Arafura and Timor Sea during the period of 2014–2020, while field survey conducted in 2024.

MATERIALS AND METHODS

Study area and data sources

The study was conducted in the Timor Sea, eastern Indonesia, using 2014–2020 landing records from small-scale fisheries operating through the Port of Kupang, East Nusa Tenggara Province (Fig. 1). The multi-species fishery targets a deep demersal snapper and grouper complex, alongside other reef-associated teleosts, which are harvested utilizing a diverse array of fishing gears including handlines, bottom longlines, gillnets, and purse seines. The three major snapper species caught in the Timor Sea were *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens*.

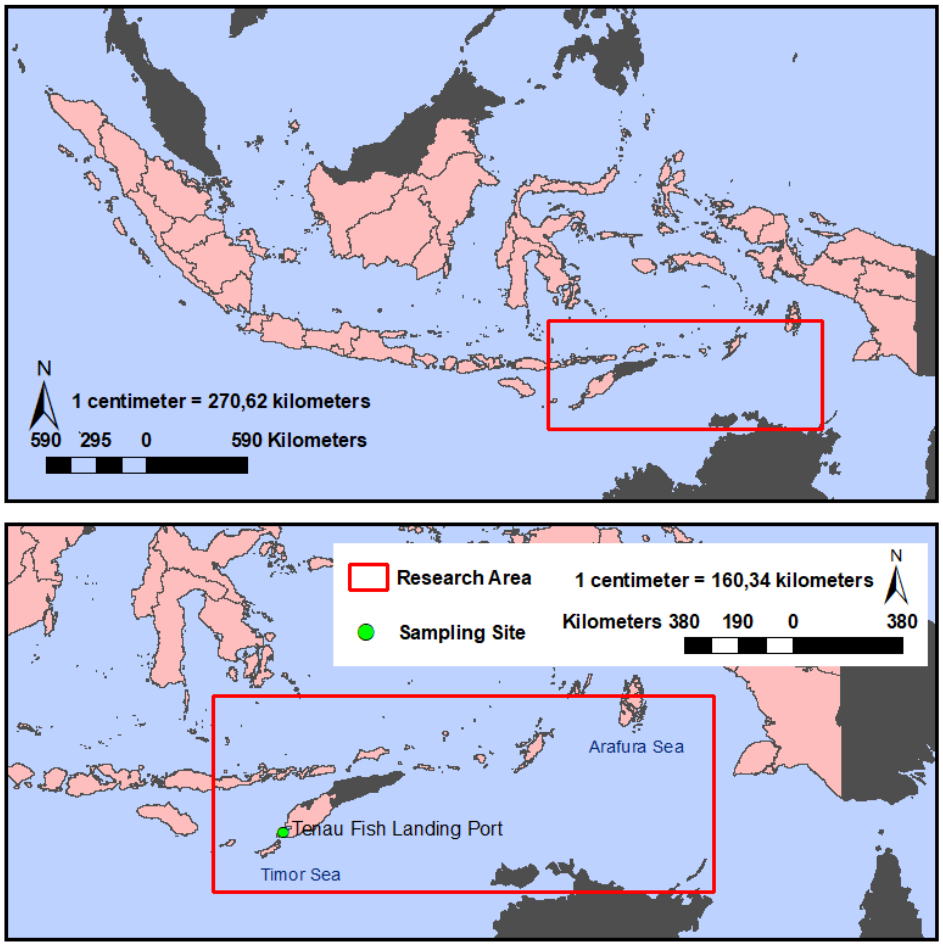

Fig. 1: Geographical location of the study area along with sampling site in the Tenau Landing Port, Kupang, Indonesia

The Timor Sea has strong seasonal and interannual variability driven by southeast and northwest monsoons, regional upwelling, and water-mass exchanges (Peña-Molino *et al.*, 2022). These processes influence SST, nutrient availability, primary productivity, and chlorophyll-a variability. This setting is suitable for examining how environmental variability affects fisheries dynamics and fishing behavior. Fishery-dependent landing records were analyzed to evaluate spatio-temporal gear-use patterns and vessel-level behavioral transitions, while concurrent biological sampling was deployed to assess the reproductive status and gonadal maturation indices of key demersal snapper stocks. Both datasets were integrated to test whether gear changes were consistent with an emerging shift from demersal-targeting gears toward pelagic-oriented gears under declining snapper stock conditions.

Oceanographic data

Oceanographic variables were used as environmental predictors of gear use. SST data were taken from the Copernicus Marine Service Global Ocean OSTIA Sea surface temperature Level 4 product, which provides daily sea surface foundation temperature at 0.05° × 0.05° resolution in NetCDF-4 format. Chlorophyll-a concentration was taken from the Copernicus-glob-color global ocean color bio-geo-chemical

Level 4 product, using the mass concentration of chlorophyll-a in seawater at 4 × 4 kilometer (km) spatial and daily temporal resolution. Both environmental variables were delineated according to the spatial extent of the Timor Sea fishing domain, column- or spatially averaged, and subjected to monthly temporal aggregation before being coupled with fishery landing records by corresponding year and month. Chlorophyll-a was log-transformed to reduce skewness. Monthly anomalies were calculated by subtracting the long-term monthly mean from each observation, and one-month lagged anomalies were used to represent delayed environmental effects on fishing activity. These environmental covariates were integrated into predictive gear-choice frameworks to quantify the specific influence of oceanographic variability on operational transitions between demersal-associated and pelagic-oriented gears.

Gear classification and functional grouping

Landing records were standardized before analysis. Vessel names, registration marks, fishing gear names, and port names were harmonized by removing redundant spaces, correcting inconsistent capitalization, and standardizing spelling variants. To ensure accurate tracking, individual vessels were defined and tracked based on a composite metric of registration mark, vessel name, and gross tonnage. Records were restricted to vessels of ≤30 gross tonnage (GT) for the main small-scale fisheries analysis. Fishing gears were grouped into six analytical categories: handline, pole-and-line, gillnet/net, purse seine, bottom longline, and others. Handline and bottom longline were treated as demersal-associated gears because they commonly target snapper and other demersal species, whereas purse seine was interpreted as a pelagic-oriented gear. This categorization scheme served to evaluate whether the fleet exhibited a systematic transition away from demersal-targeting and toward pelagic-oriented fishing strategies.

Environmental drivers of gear use

Gear composition was summarized annually and monthly using both vessel counts and trip counts. For each period t, the proportional contribution of gear *g* was calculated using Eq. 1 (Zhu and Fang, 2016):

$$P_{g.t} = \frac{N_{g,y}}{\sum_{g=1}^{G} N_{g,t}} \quad (1)$$

Where: $p_{g,t}$ is the proportion of gear g in period t, $N_{g,t}$ is either the number of vessels or number of trips using gear (g), and G is the total number of gear categories. To evaluate whether the distributional shifts in gear composition over time were statistically significant, a chi-square test of independence was executed on the temporal (year-by-gear) contingency table. The strength of association was evaluated Cramér's V using Eq. 2 (Okeke, 2009):

$$V = \sqrt{\frac{X^2}{n(k-1)}} \quad (2)$$

Where: χ^2 is the chi-square statistic, n is the total number of observations, and k is the smaller number of rows or columns in the contingency table. A multivariate analysis of gear composition was also performed using permutational multivariate analysis of variance (PERMANOVA) based on Bray–Curtis dissimilarity. Monthly gear composition was represented as a matrix of gear proportions. Bray–Curtis dissimilarity between periods i and j was calculated using Eq. 3 (Anderson, 2017):

$$BC_{i,j} = 1 - \frac{2\sum_{g=1}^{G} \min(x_{ig}, x_{jg})}{\sum_{g=1}^{G} x_{ig} + \sum_{g=1}^{G} x_{jg}} \quad (3)$$

Where: x_{ig} and x_{jg} are the proportions or counts of gear (g) in periods i and j. PERMANOVA was then used to test the effects of year and month using Eq. 4 (Anderson, 2001):

$$D_{ij} \sim Year + Month \quad (4)$$

Where: D_{ij} is the Bray–Curtis dissimilarity matrix. Year represented long-term temporal change, while month was included to account for seasonal variation. A multinomial logistic regression model was utilized to assess temporal changes in gear-choice probabilities while controlling vessel specifications, operational characteristics, and environmental influences. The response variable was fishing gear category, with handline used as the reference gear because it was the dominant gear in the dataset. The model was specified using Eq. 5 (Runcie *et al*., 2019)

$$Gear_i \sim Year_i + Month_i + GT_i + Trips_i + SST\ anomaly_i + Chl-a\ anomaly_i \quad (5)$$

or, in probability form using Eq. 6 (Hosmer *et al*., 2013):

$$\Pr(Gear_i = g) = \frac{\exp(\beta_{0g} + \beta_{1g}Year_i + \beta_{2g} + Month_i + \beta_{3g}GT_i + \beta_{4g}Trips + \beta_{5g}SST\ anomaly + \beta_{6g}Chl\text{-}a\ anomaly)}{1 + \sum_{n=1}^{G-1}\exp(\beta_{0h} + \beta_{1h}Year + \beta_{2h}Month_i + \beta_{3h}GT_i + \beta_{4h}Trips_i + \beta_{5h}SST\ anomaly + \beta_{6h}Chl\text{-}a\ anomaly)} \quad (6)$$

Where: $\Pr(Gear_i = g)$ is the probability that record i used gear g, $Year_i$ is the year of landing, $Month_i$ accounts for seasonality, GT_i is vessel size, $Trips_i$ is the number of trips, SST $anomaly_i$ and Chlorophyll-a anomaly is differences between the actual value and the normal or climatological value in the same month. Model results were interpreted using relative risk ratios, using Eq. 7 (Long and Freese, 2014)

$$RRR = e^{\beta} \quad (7)$$

A relative risk ratio greater than 1 indicates an increasing likelihood of using a given gear relative to handline, whereas a value below 1 indicates a decreasing likelihood.

Vessel-level gear transition analysis

To distinguish aggregate fleet restructuring from actual fisher- or vessel-level gear switching, a transition analysis was conducted. Annual gear dominance was operationalized at the individual vessel level based on maximum trip frequency; in instances of equal trip distribution, the gear associated with the highest aggregate record volume served as the procedural tiebreaker. Only vessels observed in two consecutive years were included in the transition analysis. The probability of transitioning from gear (g) in year (t) to gear (h) in year $t+1$ was calculated using Eq. 8 (Norris, 1997):

$$P_{gh} = \Pr(Gear_{t+1} = h \mid Gear_t = g \quad (8)$$

Where: P_{gh} is the transition probability from gear g to gear h. Diagonal elements of the transition matrix represent gear persistence, while off-diagonal elements represent gear switching. The overall migration rate was calculated using Eq. 9 (Meyer and Krumme, 2021):

$$MigrationRate = \frac{N_{switch}}{N_{paired}} \quad (9)$$

Where: N_{switch} is the number of vessel-year pairs that changed to dominant gear between consecutive years, and N_{paired} is the total number of consecutive vessel-year pairs. To evaluate whether gear-switching behaviors exhibited directional preference or adhered to a symmetric distribution, Bowker's test of symmetry was executed on the square transition matrix using Eq. 10 (Agresti, 2013):

$$X^2 = \sum_{i<j} \frac{(n_{ij} - n_{ji})^2}{n_{ij} + n_{ji}} \quad (10)$$

Where: n_{ij} is the number of vessels moving from gear i to gear j, and n_{ji} is the number moving in the opposite direction. A significant result indicates that gear switching is directional rather than random or symmetric.

Demersal stock status assessment

Length-frequency and biological data were used to estimate population parameters for *L.*

malabaricus, *L. sebae*, and *P. multidens*. Growth was described using the von Bertalanffy growth function as Eq. 11 (Hordyk *et al*., 2015):

$$L_t = L_\infty\,(1 - e^{-K(t-t_0)}) \quad (11)$$

Where: L_t is fish length at age t, L_∞ is asymptotic length, K is the growth coefficient, and t_0 is the theoretical age at zero length. Total mortality Z was estimated from length-based methods, and fishing mortality F was obtained using Eq. 12 (Hordyk *et al*., 2015):

$$Z = F + M \quad (12)$$

Where: M is natural mortality. The ratio F/M was used as an indicator of fishing pressure relative to natural mortality. Size at first maturity was estimated using a logistic maturity model as Eq. 13 (Hordyk *et al*., 2015):

$$P(L) = \frac{1}{1+ e^{-r(L-L_{50})}} \quad (13)$$

Where: $P(L)$ is the probability that an individual of length $L$is mature, $r$is the slope of the maturity curve, and L_{50} is the length at which 50 Percent (%) of individuals are mature. In the LB-SPR framework, the maturity curve can also be expressed using Eq. 14 (Hordyk *et al*., 2015):

$$P\,(L) = \frac{1}{1+ e^{-(\frac{\ln(19)(L-L_{50})}{L_{95}-L_{50}})}} \quad (14)$$

Where: $L_{95}$is the length at which 95% of individuals are mature. Length at first capture was estimated using a logistic selectivity curve Eq. 15 (Hordyk *et al*., 2015):

$$S\,(L) = \frac{1}{1+ e^{-(\frac{\ln(19)(L-SL_{50})}{SL_{95}-SL_{50}})}} \quad (15)$$

Where: $S(L)$ is the probability of capture at length L, SL_{50} is the length at 50% selectivity, and SL_{95} is the length at 95% selectivity.

Length-based spawning potential ratio

Stock status was assessed using length-based spawning potential ratio. SPR measures the remaining reproductive potential of an exploited population relative to an unfished population Eq. 16 (Hordyk *et al*., 2015):

$$SPR = \frac{SSB_{fished}}{SSB_{unfished}} \quad (16)$$

Where: SSB_{fished} is spawning biomass under fishing and $SSB_{unfished}$ is spawning biomass in the absence of fishing. In the LB-SPR model, SPR was estimated from length composition, maturity, growth, and selectivity parameters. The simplified length-based formulation was, using 17 (Hordyk *et al*., 2015):

$$SPR = \frac{\sum(1-L_x)^{[(\frac{M}{K})(\frac{F}{M})+1]}L_x^b}{\sum(1-L_x)^{[\frac{M}{K}]}L_x^b} \quad (17)$$

Where: L_x is relative length, M/K is the ratio of natural mortality to growth, F/M is the relative fishing mortality, and $b$is the length–weight exponent. SPR values were interpreted using commonly applied reference points: 20% as a limit reference point and 40% as a target reference point. Stock status benchmarks were demarcated such that values below 20% served as evidence of a highly depleted or overfished state; conversely, values spanning the 20% to 40% interval indicated a stock positioned below the target reference point yet remaining above the critical limit threshold. The fisheries, oceanographic, and stock-status datasets were interpreted within an integrated social–ecological framework. Oceanographic variability, represented by SST and chlorophyll-a, was evaluated as a potential driver of changes in fishing opportunity and gear-use patterns. Increasing use of purse seine was interpreted as evidence of a greater contribution of pelagic-oriented fishing activity, whereas changes in the relative importance of handline and bottom longline were examined in relation to both

environmental variability and broader fleet dynamics. Rather than integrating the LB-SPR stock-status indicators as direct explanatory covariates within the behavioral gear-selection models, they were utilized as an exogenous baseline to contextualize the ecological condition of key demersal snapper stocks throughout the study period. Vessel-level transition rates were incorporated to distinguish actual gear switching by individual vessels from aggregate changes in fleet composition, thereby avoiding overinterpretation of fleet-level trends as widespread fisher-level adaptation. By deploying this integrated analytical framework, the study was able to simultaneously quantify four interconnected processes: environmental variability, changes in gear-use probability, fleet restructuring, and the ecological condition of demersal stocks, providing an integrated framework for assessing environmental and fisheries management risks in the Timor Sea.

RESULTS AND DISCUSSION

Oceanographic Variability and productivity patterns

Based on monthly observations from 2014 to 2020 (Fig. 2), the study area showed pronounced seasonal oceanographic variability without significant long-term trends. SST ranged from approximately 26.1 to 31.1 degrees Celsius (°C), with warmer conditions during the Northwest Monsoon (November–April), cooler conditions during the Southeast Monsoon (June–September), and minima generally around August–September. This empirical trend aligns precisely with the monsoon-driven hydrodynamic regimes and localized seasonal upwelling characteristic of eastern Indonesian marine systems, where sustained southeast monsoon winds induce surface cooling and subsequent nutrient enrichment (Peña-Molino *et al*., 2022; Kämpf, 2015; Yu *et al*., 2024). Annual SST increased only slightly, with a slope of 0.0398 °C/y, and the trend was not statistically significant ($p = 0.6141$; $R^2 = 0.055$), indicating seasonal and interannual rather than sustained warming signals during 2014–2020. Monthly chlorophyll-a ranged from approximately 0.18 to 0.55 milligrams per cubic meter (mg/m³), with recurrent peaks of 0.45–0.55 mg/m³ and lower values of 0.18–0.25 mg/m³. Annual mean chlorophyll-a showed only a weak increasing tendency, with a slope of 0.0051 mg/m³/y, which was likewise not statistically significant ($p = 0.3746$; $R^2 = 0.160$). Consequently, surface productivity did not exhibit a sustained, long-term secular trend across the study period; instead, it was governed by oscillatory seasonal dynamics driven by shifting ambient environmental conditions.

Compared with surrounding regions, chlorophyll-a in the study area indicates relatively productive surface waters for eastern Indonesian seas. Handoko *et al*. (2024) reported average chlorophyll-a of approximately 0.09–0.45 mg/ m³ across the Banda Sea, Flores Sea, Timor Sea, and Arafura Sea, with seasonal increases during the Southeast Monsoon. Observed chlorophyll-a concentrations frequently localized between 0.45 and 0.55 mg/m³, aligning with or marginally exceeding the upper threshold of the offshore baseline; nevertheless, these values remained significantly below those recorded in highly productive zones of the Arafura Sea, where coupled shelf and upwelling mechanisms sustain concentrations of several mg/m³ (Yu *et al*., 2024). These patterns are linked to the regional monsoon system. During the Southeast Monsoon, stronger winds enhance upwelling in eastern Indonesia, including the Arafura Sea, southern Java–Timor corridor, and parts of the Lesser Sunda region. Previous studies show that Arafura Sea upwelling intensifies during this period, lowering SST and elevating chlorophyll-a (Kämpf, 2015; Yu *et al*., 2024). However, upwelling effects in the study area are unlikely to be uniform; they should be strongest in exposed coastal and shelf environments, while broader fishing grounds

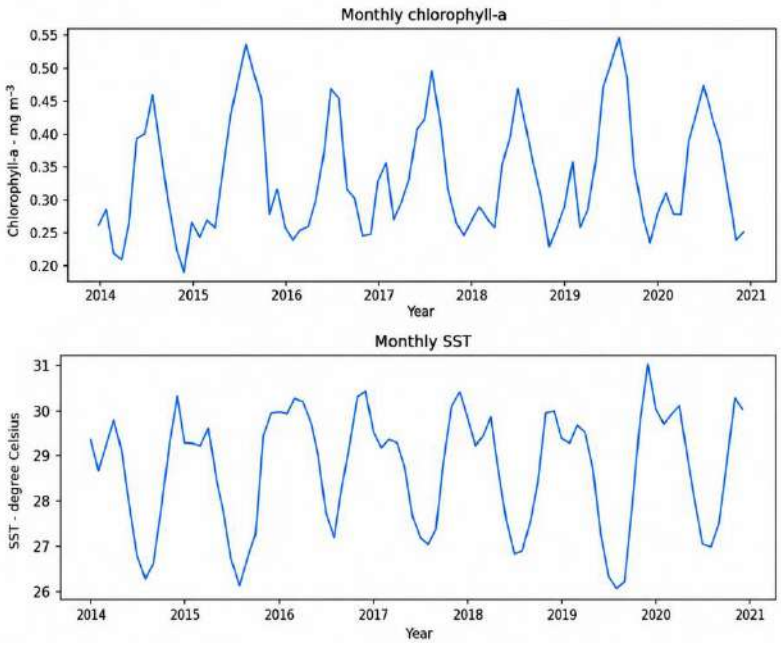

Fig. 2: Monthly mean for SST and Chlorophyill-a from 2014–2020

reflect monsoonal forcing, circulation, water-mass exchange, and interannual variability. Overall, oceanographic conditions in the Timor Sea exhibited marked variabilityat seasonal and interannual scales but lacked a statistically significant secular trajectory over the 2014–2020 study period. SST and chlorophyll-a displayed seasonal cycles, alternating anomalies, and periodic productivity increases. Thus, purse seine increases during specific periods should be interpreted not only as responses to demersal stock pressure, but also as responses to environmental opportunities created by SST and chlorophyll-a variability.

Temporal changes in fishing activity and gear composition

The landing-record dataset contained 3,575 vessel landing records from 646 unique vessels. After restriction to small-scale vessels of ≤30 GT, the analytical dataset comprised 3,441 records from 619 vessels. Six standardized gear categories were identified: handline, pole-and-line, gillnet/net, purse seine, bottom longline, and others. Handline emerged as the predominant gear type within the fishery, constituting 1,513 records. The remaining effort was distributed in descending order of frequency among pole-and-line with 617 records, gillnet/net with 480 records, purse seine with 354 records, bottom longline with miscellaneous gears accounting for the final 289 records, and others with 188 records. The temporal pattern, as indicated in Fig. 3, showed a marked restructuring of the fleet, with handline and purse seine becoming increasingly prominent in later years, while bottom longline declined in relative importance and pole-and-line lost its early dominance. The expanding footprint of purse seine operations alongside the concomitant decline in bottom longline usage points to a progressive fleet restructuring from demersal to pelagic-targeted efforts, unfolding against a baseline of marked variability in SST and chlorophyll-a concentrations. Annual landing records increased from 210 in 2014 to 641 in 2018, 1,059 in 2019, and 1,071 in 2020, indicating expansion in recorded activity, reporting intensity, or vessel participation after 2018.

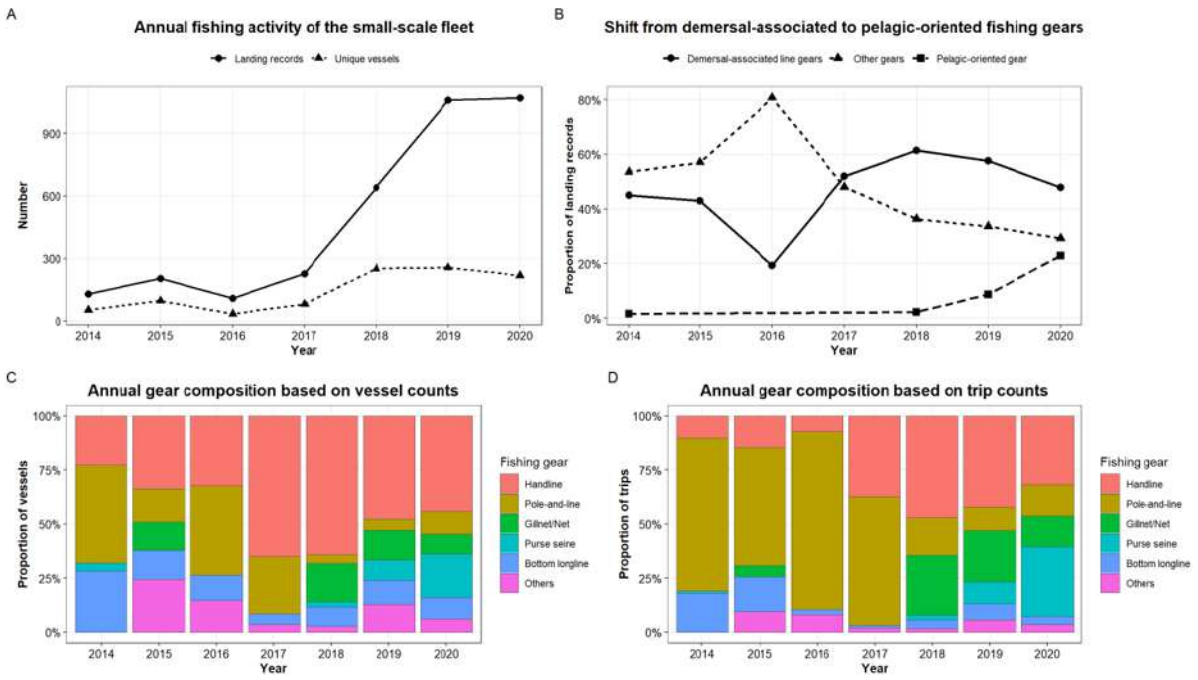

Fig. 3: Temporal dynamics of fishing activity and fishing gear composition in the small-scale fleet landing at Kupang from 2014 to 2020. Panel A shows annual landing records and unique vessels. Panel B shows the relative contribution of demersal-associated line gears, pelagic-oriented gear, and other gears. Panel C shows annual gear composition based on vessel counts, while Panel D shows gear composition based on trip counts.

This increase was uneven across gears. In 2014, the small-scale fleet was dominated by pole-and-line: 45.3% of vessels, followed by bottom longline (28.3%), handline (22.6%), and purse seine (3.8%). Based on trip counts, pole-and-line represented 70.8% of trips, bottom longline 18.1%, handline 10.2%, and purse seine less than 1%, showing strong early dominance of line-based demersal strategies. Later years showed a clearer shift. Handline records increased from 22 in 2014 to 457 in 2020, and purse seine from 2 to 246 records. Bottom longline fishing operations exhibited fluctuations without significant expansion, whereas the pole-and-line sector maintained a persistent yet diminished presence. Consequently, the small-scale fleet transitioned from an early reliance on demersal-associated line gears toward a more diversified structure characterized by increased purse seine representation. This pattern indicates potential reallocation toward pelagic-oriented opportunities under variable SST and chlorophyll-a conditions. The chi-square test confirmed a highly significant year–gear association ($\chi^2 = 1171.5$; 30 degrees of freedom; $p < 2.2 \times 10^{-16}$). Cramér's V was 0.261, indicating a moderate but meaningful association. The PERMANOVA based on Bray–Curtis dissimilarity revealed that interannual variance accounted for 55.7% of the total variation in monthly gear composition and was highly significant. Conversely, seasonal effects (month) explained a negligible 6.6% of the variance and lacked statistical significance. These findings indicate that structural changes within the fishery were primarily driven by interannual dynamics rather than seasonal fluctuations, reflecting a broader macro-level reorganization between 2014 and 2020.

Oceanographic drivers of gear use

The environmental multinomial logistic regression model elucidated the temporal

dynamics of gear utilization and its relationship to oceanographic variability. Handline was the reference category because it dominated the dataset. The full environmental model improved fit relative to the null model (Table 1), confirming that temporal, operational, and oceanographic predictors explain a significant proportion of the variation in gear choice. Relative to handline, purse seine had the strongest positive temporal trend (Table 2), with a year coefficient of 1.343 and a relative risk ratio (RRR) of 3.829. This indicates that, even after controlling season, vessel size, trip intensity, and oceanographic predictors, the relative likelihood of purse seine use increased markedly over the study period. In contrast, bottom longline showed a significant negative temporal trend relative to handline reference category (-0.387 and an RRR of 0.679), denoting a progressive decline over the study period. Gillnet/n*et al*so showed a positive temporal trend, although the increase was much weaker than that observed for purse seine. Pole-and-line and the "others" category did not show significant year effects. Overall, these results confirm a structural shift within the small-scale fleet, characterized by an increase in purse seine use and a concomitant decline in bottom longlines. This pattern reflects a strategic reallocation of effort from demersal to pelagic fisheries. The addition of oceanographic predictors revealed that gear choice was also environmentally structured. As shown in Table 3 and Fig. 4B, the likelihood of using purse seine relative to handline was significantly associated with both SST anomaly and Chlorophyll-a anomaly. For purse seine, the coefficient for SST anomaly was negative (-0.516; RRR = 0.597; p = 0.013), and the coefficient for log Chlorophyll-a anomaly was also negative (-0.474; RRR = 0.623; p = 0.024). These results indicate that the relative likelihood of purse seine use decreased under higher SST and higher Chlorophyll-a anomalies and conversely increased under relatively cooler and lower-than-average chlorophyll conditions in the previous month. Consequently, the utilization of purse seines appears independent of broad-scale productivity increments, indicating instead a strategic linkage to localized pelagic fishing opportunities that emerge under transitional or non-peak productivity conditions.

This pattern indicates that purse seine use was shaped by pelagic opportunity rather than productivity alone. Although chlorophyll-a indicates productive waters, high chlorophyll does not always coincide with maximum surface catchability of schooling pelagic fish. Pelagic species availability may increase under specific oceanographic conditions, such as the concentration of prey fields, the presence of transitional water masses, or the aggregation of schools along frontal zones following elevated productivity events. The negative association between purse seine use and chlorophyll-a anomaly suggests responses to aggregation opportunities after or around localized productivity pulses, not necessarily during peak chlorophyll. The negative SST anomaly effect also indicates greater purse seine likelihood after cooler conditions, possibly reflecting enhanced mixing, localized upwelling influence, or water-mass changes that improve pelagic habitat and aggregation. Consequently, while purse seine operations expanded over the long term, their monthly deployment patterns remained heavily conditioned by short-term thermal variability. Gear-specific responses differed: gillnet/net had negative associations with both SST and chlorophyll-a anomalies, whereas bottom longline was positively associated with chlorophyll-a anomaly but not SST. Overall, variations in gear deployment patterns mirrored both systemic long-term fleet restructuring and acute, short-term oceanographic fluctuations. Monitoring SST and chlorophyll-a may help anticipate environmentally mediated shifts in fishing behavior, especially purse seine use for pelagic opportunities, thereby supporting adaptive fisheries management and more responsive ecosystem-based resource planning.

Table 1: Model fit comparison for the multinomial logistic regression

Comparison	Likelihood ratio (LR)_statistic	df	p_value	Akaike information criterion (AIC)_null	AIC_full	Delta_AIC
Full model vs null model	3549.79	80	0	10643.09	7253.29	3389.79

Table 2: Gear-specific temporal effects from the multinomial logistic regression model

Gear comparison	Year coefficient	Standard error (SE)	Total mortality (z) value	p value	Relative risk ratio	95% CI	Interpretation
Pole-and-line vs Handline	-0.068	0.057	-1.192	0.233	0.934	0.835-1.045	No significant association
Gillnet/Net vs Handline	0.286	0.076	3.767	0.00016	1.331	1.147-1.544	Increasing relative likelihood over time after controlling for oceanographic predictors
Purse seine vs Handline	1.343	0.178	7.537	4.82E-14	3.829	2.701-5.430	Increasing relative likelihood over time after controlling for oceanographic predictors
Bottom longline vs Handline	-0.387	0.052	-7.429	1.09E-13	0.679	0.613-0.752	Decreasing relative likelihood over time after controlling for oceanographic predictors
Others vs Handline	-0.091	0.068	-1.328	0.184	0.913	0.798-1.044	No significant association

Table 3: Gear-specific oceanographic effects from the environmental multinomial logistic regression model

Gear comparison	Environmental predictor	Year coefficient	Standard error (SE)	z value	p value	Relative risk ratio	95% CI	Interpretation
Pole-and-line vs Handline	SST anomaly	0.201	0.129	1.560	0.119	1.223	0.950-1.574	No significant association with Lagged SST anomaly
Pole-and-line vs Handline	Chlorophyll-a anomaly	0.354	0.134	2.643	0.008	1.425	1.096-1.853	Increasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Gillnet/Net vs Handline	SST anomaly	-0.717	0.128	-5.593	2.23E-08	0.489	0.380-0.628	Decreasing relative likelihood with higher Lagged SST anomaly
Gillnet/Net vs Handline	Chlorophyll-a anomaly	-0.661	0.133	-4.980	6.35E-07	0.517	0.398-0.670	Decreasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Purse seine vs Handline	SST anomaly	-0.516	0.207	-2.488	0.013	0.597	0.398-0.896	Decreasing relative likelihood with higher Lagged SST anomaly
Purse seine vs Handline	Chlorophyll-a anomaly	-0.474	0.210	-2.254	0.024	0.623	0.412-0.940	Decreasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Bottom longline vs Handline	SST anomaly	0.059	0.106	0.558	0.577	1.061	0.862-1.306	No significant association with Lagged SST anomaly
Bottom longline vs Handline	Chlorophyll-a anomaly	0.447	0.114	3.925	8.69E-05	1.563	1.251-1.954	Increasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Others vs Handline	SST anomaly	0.125	0.135	0.929	0.353	1.133	0.870-1.476	No significant association with Lagged SST anomaly
Others vs Handline	Chlorophyll-a anomaly	0.069	0.143	0.487	0.626	1.072	0.811-1.418	No significant association with Lagged log Chlorophyll-a anomaly

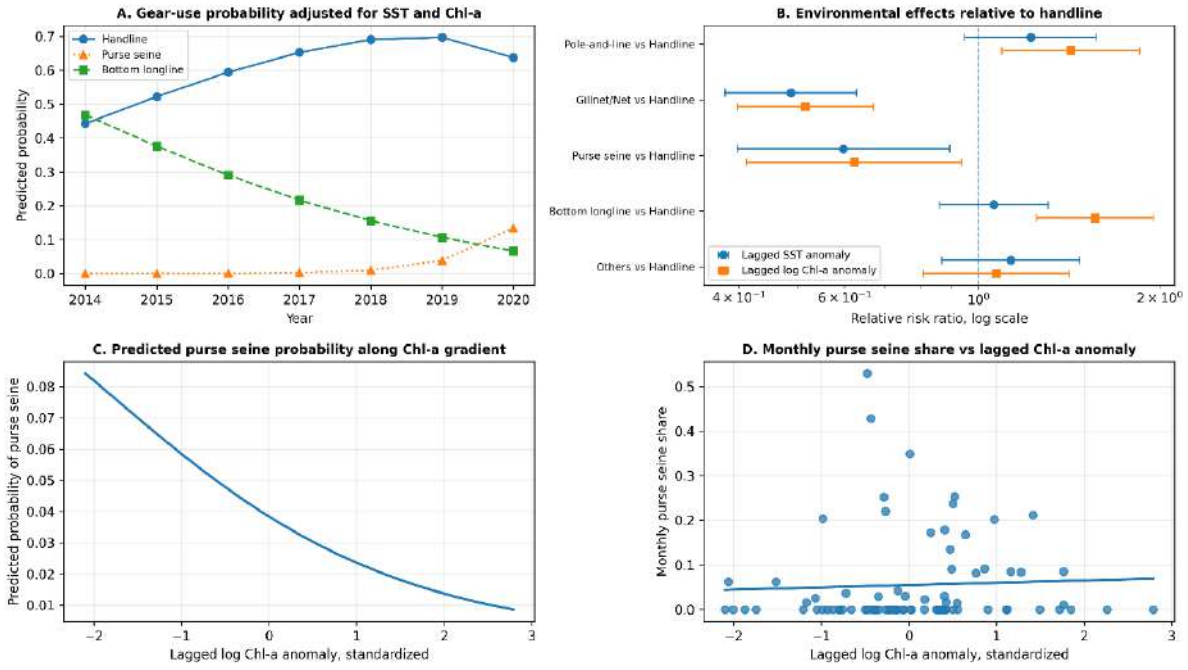

Fig. 4: Gear-specific trends and oceanographic predictors of purse seine expansion in the small-scale fleet

Vessel-level gear transitions and fleet restructuring

Aggregate and model-based analyses showed strong gear-composition changes (Fig. 5), but vessel-level transition analysis showed limited individual gear switching. Among 355 paired vessel-year transitions identified in consecutive observation periods, only 32 involved a shift in dominant gear, indicating a relatively low gear migration rate of 9.0%. Thus, aggregate restructuring should not be interpreted as widespread vessel-level switching. No gear changes occurred in 2014–2015 or 2015–2016. Migration appeared after 2016, with rates of 5.9% in 2016–2017 and 6.1% in 2017–2018. The highest rate occurred in 2018–2019, with 17 of 118 transitions switching gear, or 14.4%, then decreased to 8.2% in 2019–2020. Consequently, the detection of gear-switching behavior became more pronounced during the latter stages of the study period, coinciding with the rapid expansion of both fleet composition and recorded fishing effort. Although aggregate gear composition changed strongly, vessel-level switching was limited and concentrated in directional pathways, especially gillnet/net to purse seine. The transition matrix showed high persistence: pole-and-line had complete persistence, bottom longline 97.3%, purse seine 93.8%, handline 91.5%, gillnet/net 77.1%, and "others" 71.4%. These elevated diagonal values demonstrate that majority of vessels retained their dominant gear type between consecutive years, indicating high operational fidelity. Off-diagonal transitions were structured. The main pathway was gillnet/net to purse seine, with 11 transitions, equal to 22.9% of gillnet/net paired transitions. Other pathways included handline to others, others to handline, handline to bottom longline, bottom longline to handline, and purse seine to gillnet/net. Bowker's test of symmetry was significant (test statistic = 13.6; 4 degrees of freedom; p = 0.0087), showing that switching was directional rather than random or symmetric. Consequently, purse seine growth extends beyond a simple cohort of existing vessels switching gears; rather, it indicates selective

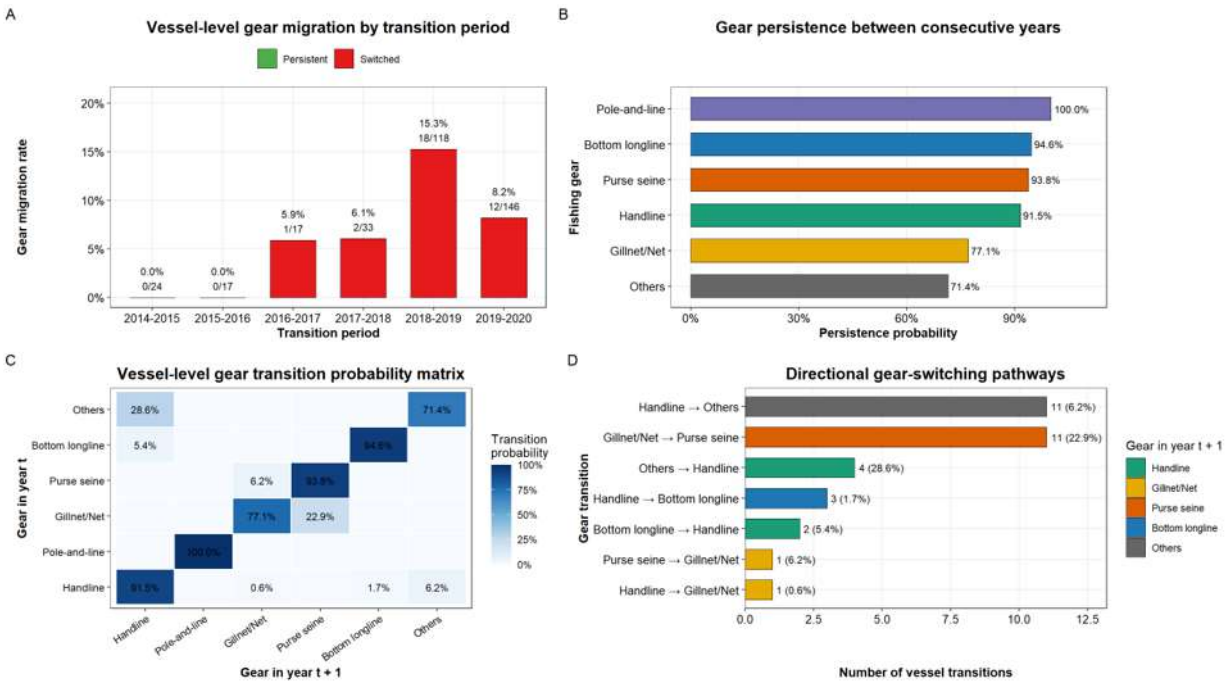

Fig. 5: Vessel-level gear transitions and the scale of gear switching in the small-scale fleet

pelagic-oriented vessels, and systemic shifts in fleet structure. The observed change is best described as fleet-level restructuring with selective vessel-level adaptation rather than mass gear transition.

Functional gear reorientation under environmental variability

The functional gear analysis grouped handline, bottom longline, and gillnet/net as demersal-associated gears, purse seine as a pelagic-oriented gear, and pole-and-line and others as other gears, as described in Fig. 6. This categorization establishes a functional framework for interpreting the oceanographic gear-use model, explicitly demonstrating whether the growing predominance of purse seine operations corresponded to a broader systemic shift in fishing orientation. Across the analytical dataset, demersal-associated gears remained the dominant functional group, accounting for 2,283 landing records, followed by other gears with 804 records and purse seine with 354 records. Annual composition, however, showed substantial variation. The demersal pressure proxy index did not decline steadily across the study period, but instead fluctuated strongly, with higher values in 2018–2019 followed by a decline in 2020. These findings indicate that the fleet maintained a robust reliance on demersal-associated fisheries, despite a concurrent expansion in the relative importance of pelagic-oriented operations during the latter stages of the study period. The clearest functional change was the expansion of purse seine. Its share of landing records increased from 1.6% in 2014 to 8.7% in 2019 and 23.0% in 2020, while its share of trips increased from 0.9% in 2014 to 10.2% in 2019 and 32.3% in 2020. Furthermore, this trend is supported by the multinomial model, wherein a significant temporal increase in purse seine operations relative to handlines was observed after accounting for oceanographic predictors. Notably, the proliferation of purse seine operations did not signify a total displacement of demersal-associated gears. Rather, it reflects a recent, partial and recent functional reorientation,

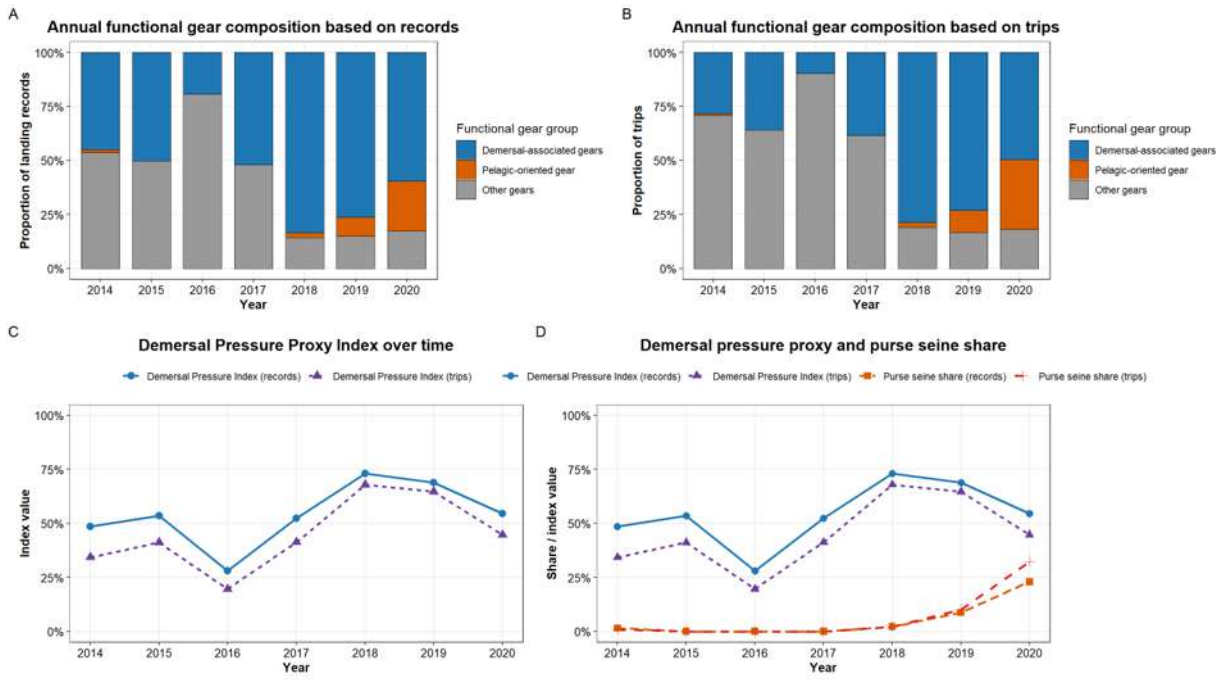

Fig. 6: Functional gear reorientation and demersal pressure context in the small-scale fleet

in which pelagic-oriented fishing expanded concurrently with a sustained reliance on demersal strategies. In the revised environmental framing, this pattern is interpreted as evidence of fishing-effort reallocation under multiple influences. Mechanistically, short-term oceanographic variability creates transient opportunities for pelagic exploitation, while chronic pressure on demersal stocks establishes the broader ecological imperative for fishers to increasingly use alternative gear strategies. Therefore, the Demersal Pressure Index does not indicate a simple transition away from demersal fishing, but it supports a more nuanced interpretation: the fleet remained demersal-linked, yet became increasingly capable of exploiting pelagic opportunities, particularly during 2019–2020. This functional reorientation serves as a critical bridge to the stock-status analysis, given that the persistent reliance on demersal-associated gears coincided with consistently depressed SPR values for key demersal snapper species.

Demersal stock status as ecological context

The biological stock indicators provide ecological context for interpreting gear-use reallocation in the Timor Sea small-scale fleet. While the preceding analyses demonstrate that gear selection co-varied with temporal and oceanographic factors, the corresponding SPR metrics reveal that primary demersal snapper stocks were already experiencing severe exploitation pressure. The three main species assessed were *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens*. These species differed in biological characteristics, maturity size, selectivity, and stock status, but all had SPR values below the commonly used 40% management target. For *Lutjanus malabaricus* (Fig. 7), the estimated length at first maturity was 44.5 centimeters (cm), while length at 50% capture was approximately 51 cm. The estimated SPR was 23%, which is slightly above the 20% limit reference point but well below the 40% management target. This indicates that the stock has not yet breached its minimum biological

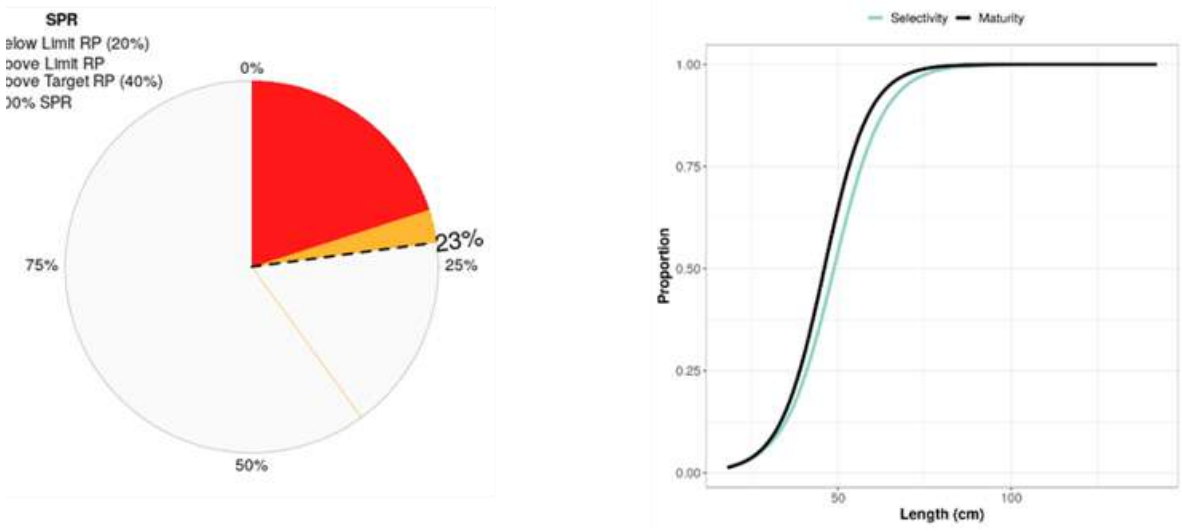

Fig. 7: SPR value, mean length at capture, and length at first maturity of Lutjanus malabaricus

threshold, its overall reproductive potential has been substantially compromised. The estimated fishing mortality to natural mortality ratio (F/M) of 1.81 suggests that fishing mortality exceeds natural mortality, indicating considerable fishing pressure on the stock. Thus, *L. malabaricus* can be interpreted as a stock under stress but not yet in the most critical category. For *Lutjanus sebae* (Fig. 8), the estimated length at first maturity was 46.8 cm and length at 50% capture was approximately 50.5 cm. The estimated SPR was 15%, which is below the 20% limit reference point, confirming a depleted status and a high probability of ongoing overfishing. The F/M ratio was estimated at 2.01, suggesting that fishing pressure is more than twice the level of natural mortality. Given that *L. sebae* is a long-lived and relatively slow-growing species, this low SPR is concerning because recovery may be slow even if management measures are implemented. The most critical condition was observed for *Pristipomoides multidens* (Fig. 9). This species had an estimated length at first maturity of 46.7 cm and length at 50% capture of 47.17 cm, were highly convergent, indicating that individuals were being harvested almost immediately upon reaching reproductive maturity. It is estimated SPR was only 6%, far below the 20% limit reference point and far below the 40% management target. The F/M ratio was 4.88, the highest among the three assessed species, indicating extremely high fishing pressure relative to natural mortality. This result suggests that *P. multidens* is in severely depleted condition and requires urgent management attention. These SPR results show that demersal snapper resources in the Timor Sea were subject to severe biological pressure, a condition that unfolded in parallel with structural modifications to the fleet's gear configurations. Although oceanographic variability may help explain short-term differences in gear-use probability, the low SPR values indicate that demersal fishing occurred against a background of reduced reproductive capacity, particularly for *L. sebae* and *P. multidens*. Thus, these stock-status results do not imply a direct causal link to purse seine growth but instead offer critical ecological context explaining why effort reallocation occurs alongside chronic demersal resource pressure. In this framing, SPR provides the biological backdrop, while SST and chlorophyll-a variability help explain environmentally mediated fishing opportunities and gear-use responses across seasons and changing oceanographic conditions over time.

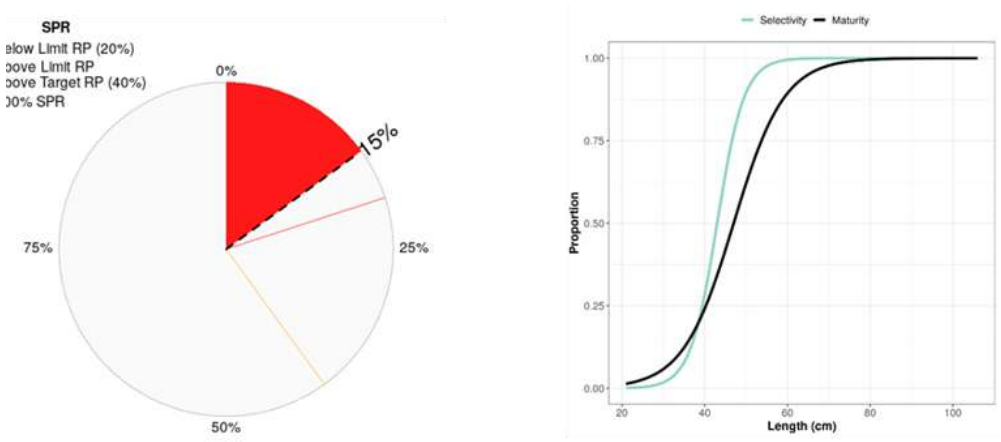

Fig. 8: SPR value, mean length at capture, and length at first maturity of Lutjanus sebae

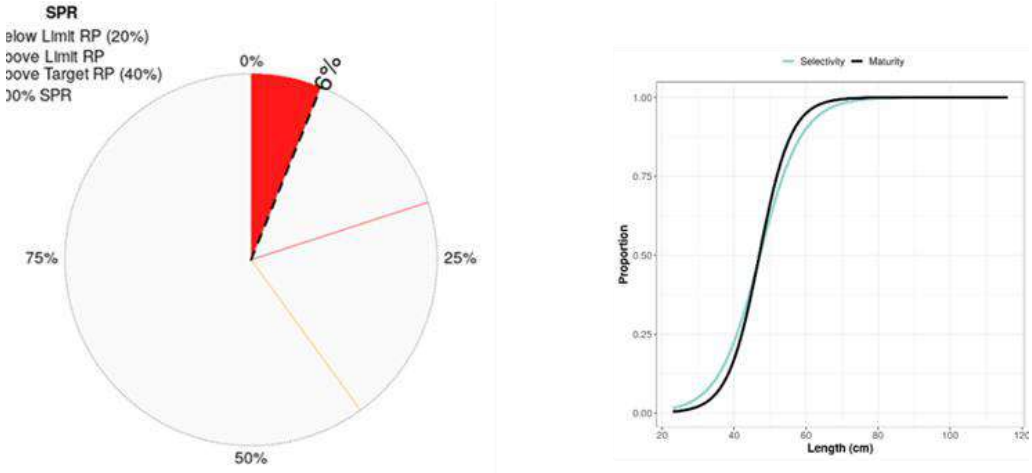

Fig. 9: SPR value, mean length at capture, and length at first maturity of Pristipomoides multidens

Environmental variability, stock pressure, and fishing-effort reallocation

The stock pressure–gear response matrix, detailed in Table 4, integrates three analytical dimensions: oceanographic variability, demersal stock condition, and observed gear-use reallocation. The SPR results showed that the three assessed demersal snapper species exhibited compromised reproductive potential, with empirical SPR values consistently falling below the 40% management target threshold. Two species, Lutjanus sebae and Pristipomoides multidens, were already below the 20% limit reference point, indicating severe biological pressure. These species are mainly associated with handline, bottom longline, and gillnet/net fisheries, which were classified as demersal-associated gears. This biological pressure coincided with a period of pronounced structural shifts in fleet gear composition and Controlling for operational and oceanographic variables, the multinomial regression framework revealed a pronounced temporal trajectory toward purse seine deployment, while bottom

Table 4: Integrated stock pressure and gear response matrix linking demersal snapper stock status with observed fishing gear dynamics in the Timor Sea small-scale fleet

Stock group	Main target gears	SPR evidence	Stock pressure status	Observed gear response	Policy relevance
Lutjanus malabaricus demersal stock	Handline, bottom longline, gillnet/net	SPR = 23%	Below target; moderate–high pressure	Bottom longline declined; handline remained dominant; purse seine increased	Prevent further decline through size limits, stock monitoring, and effort control
Lutjanus sebae demersal stock	Handline, bottom longline, gillnet/net	SPR = 15%	Below limit; overfished risk	Increasing evidence of fleet reorientation toward purse seine	Recovery measures, spawning protection, and monitoring of displaced effort
Pristipomoides multidens demersal stock	Handline, bottom longline, gillnet/net	SPR = 6%	Critically depleted	Selective but directional gear switching; increasing purse seine representation	Priority recovery stock; strict harvest control and possible temporary restrictions
Pelagic resources	Purse seine	Not assessed	Unknown	Strong increase in purse seine uses over time	Pelagic monitoring needed to prevent unmanaged effort displacement
Mixed resources	Pole-and-line, others	Not assessed	Unknown	No consistent temporal trend	Improve species-level reporting and gear-target classification

longline operations significantly contracted relative to the handline baseline. Simultaneously, SST and chlorophyll-a anomalies were significantly correlated with the relative probability of gear choice, demonstrating that short-term environmental fluctuations directly modulate fishing opportunities and operational strategies, consistent with previous findings on the influence of upper-ocean variability on marine ecosystems and fisheries (Jaishree and Ravichandran, 2024). The increase in purse seine fishing should therefore not be interpreted as a direct or fleet-wide replacement for demersal fishing. Vessel-level transition analysis showed that most vessels retained their dominant gear, and only 9.0% of consecutive-year vessel pairs changed gear. This indicates that the observed pattern represents selective adaptation and fleet restructuring rather than widespread individual gear migration. Contextually, the proliferation of purse seine fishing underscores a localized reallocation of harvesting capacity toward pelagic-oriented dynamics; however, this shift did not diminish the continued importance of demersal-associated fisheries. Similar interactions between environmental conditions, fishing activities, and fisheries management have also been recognized within broader socio-environmental and territorial contexts of artisanal fisheries (Díaz-Ponce *et al.,* 2026). This interpretation has important management implications. Rebuilding demersal snapper stocks should be combined with monitoring of displacement and pelagic fishing expansion. Implementing demersal recovery protocols without concurrent tracking of gear utilization risks a hidden reallocation of fishing effort toward alternative, poorly assessed pelagic resources. The matrix therefore supports an adaptive management approach that integrates snapper recovery measures, environmental monitoring, vessel-level gear tracking, and cross-resource fishing pressure assessment.

Implications for environmental and fisheries management

This study indicates that the small-scale fishery operating through the Timor Sea is undergoing partial fishing-effort reallocation within a variable marine environment. The declining relative importance of bottom longline and increasing use of purse seine suggest that fishing activity became more diversified across demersal- and pelagic-oriented strategies. This trend does not imply a total abandonment of demersal fishing, as demersal-associated gears persisted throughout the study period and the Demersal Pressure Index failed to show a continuous monotonic decline. Instead, the results point to selective effort diversification and fleet restructuring, particularly after 2018–2019. The oceanographic results offer

critical contextual frameworks for interpreting the observed structural reconfigurations within the fishery. SST and chlorophyll-a did not show significant long-term trends during 2014–2020, but both variables showed strong seasonal and interannual variability. Such variability can influence fish distribution, habitat suitability, catchability, and fishing-ground formation, thereby affecting the relative attractiveness of different fishing strategies (Runcie *et al*., 2019; McInnes *et al*., 2017). Purse seine expansion reflects not only responses to demersal stock pressure but also favorable environmental conditions. The significant shift in annual gear composition confirms fleet restructuring rather than random variation. Purse seine use increased over time after controlling for month, vessel size, and trip intensity, indicating a genuine change in fleet strategy. However, vessel-level transitions were limited, with only 9.0% of paired vessel-year observations changing dominant gear. This means that aggregate fleet restructuring was not driven by widespread gear switching by individual vessels, but likely by a combination of selective switching, vessel entry, differential activity levels, and changes in reporting intensity. Parallel empirical research in data-limited, small-scale fisheries indicates that fishers frequently adapt by adjusting fishing duration, spatial grounds, depth strata, target species, or operational expenditures, rather than executing complete gear substitutions (Saldaña *et al*., 2017; Frawley *et al*., 2021). Stock-status indicators provide ecological context for these gear-use patterns. The estimated SPR values for *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens* were all below the 40% management target, while *L. sebae* and *P. multidens* were below the 20% limit reference point. These results indicate reduced reproductive capacity in key demersal snapper stocks, especially *P. multidens*, which had an SPR of only 6%. Nonetheless, this close temporal alignment—characterized by suppressed SPR thresholds, a contraction in bottom longline operations, and a simultaneous surge in purse seine deployment—warrants a nuanced and cautious interpretation. The evidence indicates that demersal stock pressure, environmental variability, and fleet restructuring are associated, but stock depletion alone did not drive purse seine expansion. Although effort shifted from depleted demersal stocks may reduce snapper fishing pressure, it may increase pressure on pelagic resources, particularly under favorable oceanographic conditions. Without comparable monitoring of pelagic fisheries, emerging sustainability risks may remain undetected until catch rates decline. Ecosystem-based approaches are therefore needed because gear changes can affect target species, bycatch, trophic structure, fishing power, and competition among fishing groups (Herrón *et al*., 2019; Sun *et al*., 2023). For management, policies should operate at two connected levels. First, demersal snapper recovery remains urgent, especially for *L. sebae* and *P. multidens*, through species-specific size limits, protection of spawning areas, seasonal restrictions, and control of fishing mortality. Second, cross-fishery effort displacement toward pelagic frameworks and purse seine deployment warrants systematic monitoring to safeguard against the inadvertent reallocation of ecological risk between resource complexes. These actions should be supported by environmental indicators such as SST and chlorophyll-a anomalies, which may provide early-warning information on changing fishing opportunities and potential shifts in fleet behavior. Adaptive and climate-ready management frameworks emphasize the need for flexible policies that respond to shifting resource availability, environmental variability, and changing fleet behavior (Bell *et al*., 2020; Bastardie *et al*., 2022). The rise of purse seine also has implications for fishing power. Purse seine operations can be more efficient than passive gears, particularly when supported by larger vessels, improved engines, lights, navigation, or fish-finding technology. Consequently, omitting these efficiency gains from effort standardization frameworks may cause nominal effort data to substantially underestimate the true magnitude of contemporary fishing pressure. Management should therefore move beyond gear names alone and consider vessel size, propulsion, gear type,

fishing grounds, species composition, and environmental conditions. Such classifications can better represent fishing power and ecological impact in tropical multi-gear fisheries (Munga *et al*., 2014; Eigaard *et al*., 2014). Additionally, this study highlights the urgent need to improve taxonomic resolution in commercial catch reporting. Purse seine was classified as pelagic-oriented based on gear characteristics, but direct species-composition data from purse seine landings would strengthen interpretation. Participatory or application-based monitoring frameworks possess the capacity to enhance the resolution of catch and effort data while simultaneously fostering direct stakeholder engagement in fisheries management (Porriños *et al*., 2025). For the Timor Sea, such monitoring would be most useful if combined with monthly SST and chlorophyll-a information, allowing managers to evaluate whether changes in catch composition or gear use coincide with environmental anomalies. These outcomes should be interpreted considering several structural limitations. The landing datasets are potentially confounded by shifting reporting fidelity, most notably from 2018 onward. Additionally, the dominant-gear attribution method lacks the granularity to capture high-frequency intra-annual shifts among multi-gear vessels. The biological assessment was restricted exclusively to three demersal snapper species; consequently, the ecological implications for pelagic frameworks subject to escalating purse seine pressure warrant further independent evaluation. In addition, SST and chlorophyll-a are broad environmental indicators and do not capture subsurface temperature, currents, fronts, dissolved oxygen, prey fields, or fine-scale fishing-ground selection. These limitations are common in data-limited fisheries, where incomplete monitoring can obscure true effort, catch composition, stock condition, and fisher response to environmental variability (Gill *et al*., 2017; Dunbar *et al*., 2023). While acknowledging these structural constraints, the synergy of this integrated methodology establishes a more resilient framework for adaptive resource management than traditional, single indicator approaches such as standalone stock or gear analysis. By combining oceanographic indicators, LB-SPR estimates, multinomial gear-use models, and vessel-level transition matrices, this study distinguishes environmental variability, demersal stock condition, aggregate fleet restructuring, and actual vessel-level switching. Overall, the Timor Sea small-scale snapper fishery appears to be undergoing adaptive reorganization rather than a complete transition away from demersal fishing. Consequently, effective management frameworks must synthesize demersal snapper stock rebuilding, pelagic effort monitoring, gear-transition tracking, participatory catch reporting, and satellite-based environmental monitoring to mitigate the risk of serial resource depletion while safeguarding the operational flexibility required by small-scale fishing communities.

CONCLUSION

This study demonstrates that fishing-effort reallocation in the Timor Sea small-scale fishery was shaped by the interaction of oceanographic variability, changing gear-use patterns, fleet restructuring, and persistent demersal stock pressure. SST and chlorophyll-a showed strong seasonal and interannual variability during 2014–2020, providing an important environmental context for interpreting changes in fishing strategies. Paradoxically, despite the absence of significant long-term trend in either variable, their transient anomalies retained a significant association with gear-use probability. This divergence underscores the role of short-term oceanographic variability in modulating contemporary fishing opportunities across distinct gear cohorts. The small-scale fleet showed clear temporal restructuring. Purse seine increased markedly over the study period, while bottom longline declined relative to handline. The environmental multinomial logit model confirmed that the probability of purse seine deployment increased significantly, even after controlling for temporal factors (months), vessel dimensions, trip intensity, and anomalies in both SST and chlorophyll-a. This indicates that the rise of purse

seine reflected a genuine change in gear-use probability rather than only seasonal or operational differences. However, the direction of the environmental effects suggests that purse seine use was not simply driven by higher productivity alone but may have been linked to more specific pelagic fishing opportunities associated with cooler and transitional environmental conditions. Vessel-level transition analysis revealed that macro-level fleet restructuring does not reflect widespread gear substitution by individual fishers. Only 32 of 355 consecutive vessel-year pairs changed to dominant gear, corresponding to a migration rate of 9.0%. Therefore, the observed shift is best described as selective vessel-level adaptation and fleet-level restructuring rather than a complete migration away from demersal fishing. The SPR estimates provide ecological context for interpreting the observed reallocation. All assessed demersal snapper species were below the 40% management target, while *Lutjanus sebae* and *Pristipomoides multidens* were below the 20% limit reference point. Although the data underscores a state of pronounced biological duress among demersal resources, this pressure must not be construed as the sole catalyst underlying regional purse seine proliferation. Overall, the evidence suggests partial fishing-effort reallocation toward pelagic-oriented opportunities under variable oceanographic conditions and continued demersal stock pressure. Management should therefore combine demersal snapper rebuilding, pelagic effort monitoring, vessel-level gear tracking, improved species-level reporting, and satellite-based environmental monitoring to prevent unmanaged displacement of fishing pressure.

AUTHOR CONTRIBUTIONS

K. Kasim contributed to the conceptualization of the study, prepared the initial draft of the manuscript, and conducted the literature review. M.R. Putri supervised the manuscript writing process. S. Nurdjaman provided overall study supervision and contributed to the conceptual development of the draft, while I.A. Fikri offered critical revisions to enhance the quality of the manuscript. T.A. Saputra supported data collection and supervision, and H. Selia contributed to data analysis and interpretation. S. Triharyuni strengthened the references, citations, and analytical components, while B.R.D. Nugraha compiled the field data. All authors reviewed and approved the final manuscript for publication.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
°	Degree
°C	Degrees Celsius
°C/y	Degrees Celsius per years
≤	Less than or equal to
×	Multiplication sign
χ^2 / $\chi 2$	Chi-square statistic
AIC	Akaike information criterion
BC	Bray–Curtis dissimilarity
CC BY	Creative Commons Attribution License
CI	Confidence Interval
cm	Centimeter
D_{ij}	Bray–Curtis dissimilarity matrix
Eq	Equation
F	Fishing mortality
F/M	Fishing mortality to natural mortality ratio
g	Gear
G	Total number of gears
GT	Gross tonnage
K	Growth coefficient
km	Kilometer
L	Fish length
L∞	Asymptotic length
L50	Length at 50% maturity
L95	Length at 95% maturity
LB-SPR	Length-Based Spawning Potential Ratio
LR	Likelihood ratio
M	Natural mortality
MMAF	Ministry of Marine Affairs and Fisheries
M/K	Natural mortality to growth coefficient ratio
mg/m³	Milligrams per cubic meter
$N_{g,t}$	Number of vessels or number of trips
N_{paired}	The total number of consecutive vessel-year pairs
N_{switch}	number of vessel-year pairs that changed to dominant gear between consecutive years
ORCID	Open Researcher and Contributor ID
PERMANOVA	Permutational multivariate analysis of variance
P_{gh}	Transition probability from gear g to gear h
Pr	Probability
RRR	Relative risk ratio
SE	Standard error
SL50	Length at 50% selectivity
SL95	Length at 95% selectivity
SPR	Spawning potential ratio
SSB	Spawning stock biomass
SST	Sea surface temperature
WWF	Worldwide Fund for Nature
x_{ig}	The proportions or counts of gear (g) in periods i
x_{jg}	The proportions or counts of gear (g) in periods j
y	Years
Z	Total mortality

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ORIGINAL RESEARCH ARTICLE

The effects of environmental regulations on corporate social responsibility and the brand equity paradox

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ABSTRACT

BACKGROUND AND OBJECTIVES: With environmental regulations in China becoming increasingly stringent, whether corporate social responsibility enhances or undermines brand equity remains an open question. The study objectives were 1) to test the direct effect of corporate social responsibility on brand equity, 2) to examine the mediating roles of financing constraints and technological innovation inputs, and 3) to assess the heterogeneous moderating effects of different environmental regulations, while also accounting for spatial interdependence among firms.

METHODS: To analyze the data, this study applies a spatial autoregressive model with fixed effects to a panel of Chinese A-share listed manufacturing firms observed between 2015 and 2020. Robustness checks include alternative variable measures, the inclusion of omitted variables, model replacement, and endogeneity treatments. Mediation, moderation, and heterogeneity effects were assessed through a series of stepwise regression models incorporating relevant interaction terms.

FINDINGS: Corporate social responsibility practices are found to significantly reduce brand equity, with a coefficient of -74.520 at the 1 percent significance level, and brand equity exhibits a strong positive spatial correlation among firms in the same industry, with a spatial autoregressive coefficient of 0.350 at the 1 percent level. At the 1 percent significance level, financing constraints exert a suppression effect, partially offsetting the direct negative impact, leading to an increase of 643.193 in brand equity per unit of constraint intensity. Technological innovation inputs act as a partial mediator, with a positive effect of 97.592 on brand equity at the 1 percent level. Heterogeneity tests indicate that the negative relationship is more pronounced for firms in regions with stringent environmental regulations, low innovation capacity, or low economic development, as well as for larger firms. In terms of moderating effects, self-disclosure and market-incentive regulations intensify the negative impact; conversely, command-and-control and public-participation regulations exhibit a weakening effect.

CONCLUSION: Overall, this study elucidates the corporate social responsibility-brand equity paradox by identifying dual mediating pathways and heterogeneous moderating effects of various environmental regulations. It also contributes a replicable firm-level nested spatial weight matrix, advancing the use of spatial econometrics in brand research. Furthermore, the diversity of environmental regulations enables local governments to implement targeted policies mixes that discourage symbolic corporate social responsibility behaviors and encourage authentic green transformation.

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INTRODUCTION

One dominant perspective, grounded in stakeholder theory, suggests that corporate social responsibility (CSR) is integral to promoting corporate sustainability. It acts as a key catalyst for the ecological transformation of industrial structures, thereby fostering high-quality development. Extensive empirical studies have examined how CSR practices influence various organizational performance dimensions, encompassing financial results, innovation capabilities, environmental stewardship, and social impact (Halkos and Skouloudis, 2018; Saeed *et al*., 2023; Zhou *et al*., 2023a). From a supply chain standpoint, CSR initiatives have been found to positively influence green supply chain management (Novitasari *et al*., 2022) and expedite carbon emission reductions in manufacturing sectors (Zhou *et al*., 2023b). Furthermore, while socially responsible firms often necessitate consistent financial commitment; proactive engagement in CSR can bolster investor confidence and loyalty, thereby mitigating systemic, credit, and liquidity related risks (Zhao *et al*., 2021; Nirino *et al*., 2022; Bannier *et al*., 2022). These diminished risk profiles enable firms to reduce precautionary cash holdings (Cheung, 2016), thereby lowering capital costs, alleviating financing constraints, and improving the overall efficiency of both investment and innovation activities (Yao *et al*., 2022; Guo *et al*., 2023). Furthermore, CSR adoption may provide a strategic advantage as a first mover, allowing firms to differentiate themselves and establish a robust reputation that reinforces their sustainable competitive edge (Marakova *et al*., 2021; Lee *et al*., 2022). Furthermore, as posited by upper echelon theory, managerial discretion plays a decisive role in the adoption and execution of CSR strategies. In contexts characterized by weak internal governance and opportunistic tendencies, executives may prioritize personal gains such as through insider trading over corporate integrity, thereby jeopardizing the firm's reputation and financial stability (Barnea and Rubin, 2010). Applying the perspective of value theory, a brand functions as a critical intangible asset that signals product quality and reliability, enabling firms to establish a first-mover advantage in competitive markets. Extant research on brand equity largely emphasizes its economic implications, alongside an exploration of the various factors that influence its formation. Brand differentiation contributes significantly to enhancing enterprise value by generating a premium effect, which reinforces long-term competitive advantages (Gupta *et al*., 2020). Moreover, by leveraging distinctive brand attributes, companies can increase operating revenues (Narteh, 2018) while mitigating operational risks, thus enabling them to lower excess cash holdings and improve capital allocation efficiency (Bharadwaj *et al*., 2020). Widely recognized as a foundational driver of brand equity, innovation plays a pivotal role in shaping long-term brand development. Successfully translating innovation efforts into brand-related outcomes can significantly elevate a firm's innovation performance (Zameer *et al*., 2019). In addition, factors such as marketing competence, research and development intensity, and the quality of sustainability reporting all have a substantial impact on brand valuation (Loh and Tan, 2020; Lin *et al*., 2021). However, in the context of emerging markets—where financial systems are often less mature—persistent issues like corruption continue to undermine corporate credibility, thereby constraining the growth of brand equity (Lin and Chuang, 2016). While CSR is extensively recognized as a key driver of brand equity, the precise nature of this relationship remains a subject of ongoing academic debate. According to signaling theory, proactive participation in CSR initiatives captures consumer attention and positively influences brand perception, thereby supporting brand development and enhancing brand equity (Tosun and Tavşan, 2023). Conversely, information asymmetry theory suggests a disconnect between

consumers' interpretations of CSR efforts and the actual extent of corporate investments in such activities. Consequently, if CSR actions are not clearly perceived or understood by consumers, their contribution to brand equity may be limited (Nickerson *et al*., 2021). This implies that only CSR efforts perceived as authentic and credible can generate meaningful reputational benefits for firms. Furthermore, in environments characterized by resource scarcity, the financial commitment required to fulfill social responsibilities may impose an opportunity cost, thereby reducing the resources accessible for strengthening brand equity. In the absence of standardized evaluation systems or institutionalized CSR metrics, firms frequently rely on charitable donations as a public symbol of social responsibility. However, these visible acts can be strategically employed to divert attention from more serious internal issues such as environmental misconduct, labor rights violations, excessive financial leverage, or deteriorating creditworthiness (Chen *et al*., 2023). Building upon the aforementioned theoretical framework, this study posits that stakeholder and signaling theories suggest CSR initiatives bolster brand equity by projecting reliability and cultivating stakeholder engagement. In contrast, resource-based, information asymmetry, labor value, and upper echelons theories anticipate deleterious effects. These divergent predictions do not represent mutually exclusive explanations but rather illustrate the confluence of conflicting forces operating within a shared institutional landscape. Whether CSR ultimately enhances or undermines brand equity depends on the relative strength of these competing mechanisms, which is in turn shaped by contextual factors such as consumers' perceived credibility, capital market efficiency, and the intensity of regulatory enforcement. Notwithstanding the considerable body of research addressing the microeconomic consequences of CSR, this study identifies three substantial gaps in the extant literature, underscoring the imperative for further empirical and theoretical scrutiny 1) Empirical studies offer limited insight into the underlying mechanisms by which CSR activities influence the formation of brand equity. 2) The heterogeneous moderating effects of various environmental regulatory frameworks on this relationship are insufficiently addressed. 3) Spatial analytical approaches addressing inter-firm dependencies within industry clusters remain largely underdeveloped in the current literature. Addressing these multidimensional aspects is crucial for informing environmental policymaking and optimizing corporate strategy, particularly within the context of emerging markets. This study addresses these identified lacunae through significant theoretical and methodological advancements. By integrating stakeholder theories and labor value theory, this study utilizes panel data from Chinese listed manufacturing firms (2015–2020) and employs a spatial econometric framework to generate novel insights. This study advances the extant literature through three primary contributions. 1) At the theoretical level, it delineates "paradox" inherent in the CSR and brand equity relationship by deploying a dual-channel mediation framework. 2) At the methodological level, this study constructs an industry-region nested spatial weight matrix tailored to micro-level firm analysis, thereby pioneering an innovative application of spatial econometrics within the domain of brand equity research. 3) From a policy-oriented perspective, this study categorizes environmental regulations into four distinct typologies: self-disclosure environmental regulation (SDER), market-incentive environmental regulation (MIER), command-and-control environmental regulation (CCER), and public-participation environmental regulation (PPER), and reveals their differentiated moderating effects. Adopting a systematic research design encompassing literature synthesis, hypothesis formulation, empirical validation, and implications, this study constructs a technical roadmap (Fig. 1) to illustrate the effects of environmental regulations on CSR and brand equity paradox. This study empirically

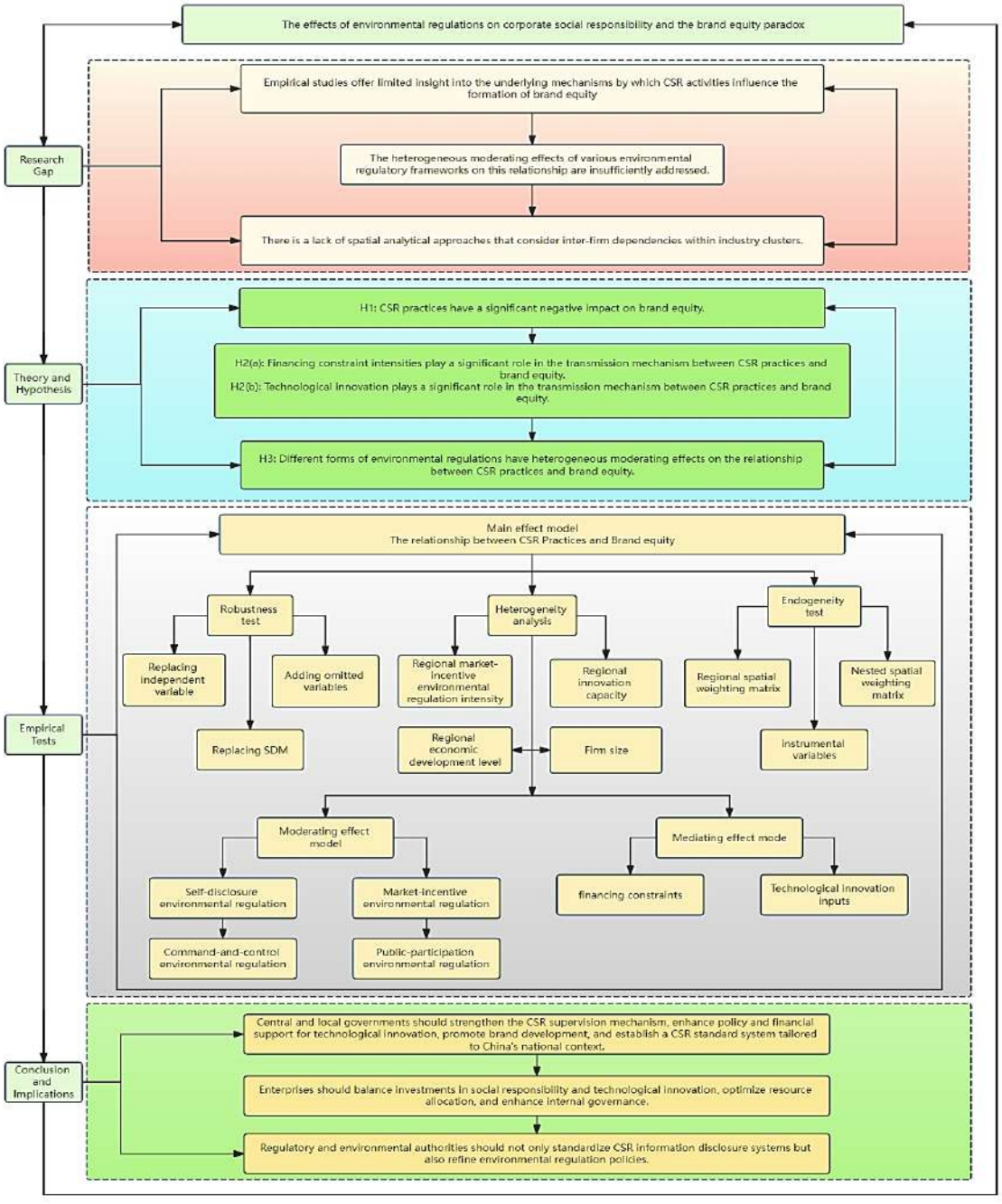

Fig. 1: A technical roadmap of CSR practices and brand equity paradox

investigates the direct impact of CSR on brand equity, while elucidating the mediating roles of financing constraints and technological innovation. Furthermore, it assesses the heterogeneous moderating effects of four distinct environmental regulation frameworks across different institutional contexts.This study has been conducted in the School of Management, Sichuan University of Science and Engineering, Zigong, China, during the year 2025.

Theoretical foundations and hypothesis development

The relationship between CSR practices and brand equity

As primary stakeholders, consumers increasingly demand transparency and accountability from brands. Consequently, it is imperative that firms establish credible brand commitments and demonstrate consistent adherence to these pledges to cultivate consumer trust and enduring brand loyalty (Abid *et al*., 2019). In cases where these commitments fall short, CSR can play corrective, compensatory, and goodwill-enhancing roles. From an accountability perspective, Nickerson *et al*. (2021) contend that proactive CSR initiatives can alleviate adverse environmental or social outcomes, thereby strengthening brand performance. Nevertheless, CSR efforts focused solely on generating goodwill may, paradoxically, undermine brand equity. Furthermore, the effectiveness of different CSR dimensions on brand equity is not uniform. Lin and Chung (2018) and Singh *et al*. (2023) empirically demonstrate that consumer behavior—and consequently brand equity—is primarily driven by the environmental and social components of CSR initiatives. Consumers' perceptions of brands, a fundamental component of brand equity, exert a direct influence on their overall level. Drawing on social identity theory, studies have shown that when consumers view a firm as socially responsible, their emotional connection to the brand strengthens, leading to greater brand loyalty (Gilal *et al*., 2020; Godefroit-Winkel *et al*., 2021; Tosun and Tavşan, 2023). Furthermore, ethical business practices play a critical role in fostering long-term consumer loyalty (Quezado *et al*., 2022). Based on the institutional realities of China's transition economy, the context in which CSR is implemented differs markedly from that of developed capital markets. To begin with, at the firm level, the widespread prevalence of "CSR decoupling" and "greenwashing" indicate that many companies treat social responsibility primarily as an instrument of impression management rather than as a substantive commitment to stakeholders (Chen *et al*., 2023). From a resource-based perspective, such symbolic expenditures deplete financial resources that could otherwise be allocated to substantive brand-building initiatives, while simultaneously failing to yield the reputational returns posited by signaling theory. Furthermore, should these practices be exposed, they risk adverse consequences, potentially compromising corporate credibility. Furthermore, from a consumer perspective, the increasing saturation of material needs among Chinese consumers has catalyzed a transition toward healthier and more sustainable consumption patterns, Furthermore, from a consumer perspective, the increasing saturation of material needs among Chinese consumers has catalyzed a transition CSR initiative. When CSR initiatives are revealed to be mere performative acts, they directly provoke consumer skepticism and distrust, thereby eroding perceived brand authenticity and trustworthiness. Furthermore, with respect to the institutional environment, weak investor protection, underdeveloped credit rating systems, and top-down government mandates for CSR among state-owned enterprises (SOEs) collectively create institutional voids, thereby limiting effective resource allocation and reducing the credibility of corporate sustainability commitments. Consequently, these conditions suggest that CSR initiatives are frequently adopted as a reactive obligation rather than a strategic, voluntary choice, a dynamic that further attenuates their signaling effectiveness. Taken together, the interplay of these contextual factors leads to a net negative effect of CSR on brand equity for manufacturing firms in China, a finding that stands in sharp contrast to the predominantly positive evidence reported in developed economies. Based on the above analysis, this study proposes the following hypothesis.

H1: CSR practices have a significant negative impact on brand equity.

Transmission mechanisms of CSR practices and brand equity

According to signaling theory, CSR initiatives communicate a positive and trustworthy corporate image to a wide range of stakeholders, including investors, suppliers, regulatory authorities, customers, and employees (Ding *et al*., 2022). High-quality CSR performance augments corporate transparency and bolsters visibility among potential investors and the broader public. By narrowing the information gap between firms and investors, CSR engagement can effectively ease financing constraints. Empirical evidence presented by Farooq and Noor (2023), and Chen (2023), indicates a significant inverse relationship between CSR engagement and financing constraints, an effect that is particularly pronounced when assessed through the dimension of environmental performance. These outcomes lend support to the shareholder value hypothesis, suggesting that CSR engagement facilitates progress toward carbon neutrality by reducing financial barriers. In addition, CSR practices play a pivotal role in shaping business credit. Within the supply chain, proactive CSR engagement functions as a risk-mitigation strategy; it enhances confidence between stakeholders—namely, suppliers and distributors—and promotes mutually beneficial, collaborative partnerships. Bannier *et al*. (2022) further demonstrated that companies exhibiting robust CSR behaviors tend to experience lower credit risk. Moreover, reputation effects theory argues that sustained CSR engagement strengthens a company's public image, thereby enhancing its perceived reliability. Policy initiatives such as green credit frameworks and environmental taxation provide socially responsible firms with expanded access to capital, a development that substantively improves corporate credit profiles while effectively reducing borrowing thresholds. Conversely, the managerial self-interest hypothesis contends that CSR activities are often employed to advance the private interests of corporate executives, where management reaps the economic gains while shareholders bear the risks. In China's shifting investor protection landscape, proactive CSR initiatives may inadvertently intensify agency conflicts, thereby undermining investor trust and constraining the development of brand equity (Jiang and Lan, 2022). In summary, whether the analysis is grounded in the managerial self-interest perspective or the shareholder value framework, financing constraints emerge as a critical factor shaping the linkage between CSR implementation and brand equity formation. Accordingly, this study proposes the following hypothesis.

H2(a): Financing constraint intensities play a significant role in the transmission mechanism between CSR practices and brand equity.

Guided by the principles of stakeholder theory, corporations are prioritizing technological and methodological modernization to foster environmental sustainability, a strategic realignment that effectively satisfies the increasingly rigorous demands of both the investment community and the consumer base. Empirical studies by Zhou *et al*. (2019) and Huang *et al*. (2021) corroborate that CSR engagement encourages firms to allocate more resources toward technological innovation. Moreover, proactive CSR practices foster a favorable ethical image, which can bolster investor confidence in a firm's R&D activities (Ho *et al*., 2016). These innovation-driven efforts are vital to the development of brand equity. As Zameer *et al*. (2019) highlight, technological innovation augments brand equity by bolstering consumer preference and optimizing brand perception. The gradual adoption of advanced technologies mitigates production expenditures, enabling firms to redirect resources toward more robust branding efforts. Ultimately, sustained innovation contributes to competitive differentiation, raises brand visibility and reputation, and significantly boosts brand equity. Nevertheless, an alternative

perspective highlights the inherent challenges associated with technological innovation, which is often characterized by high risk, substantial costs, and extended development cycles. When market conversion potential is constrained and regulatory compliance costs exceed anticipated strategic benefits, such innovations may exert a deleterious impact on brand equity (Kim, 2016). From a resource-based perspective, under conditions of constrained financial and managerial resources, CSR investments may crowd out funding that could otherwise support technological advancement and brand enhancement. For instance, a reduction in advertising expenditures—driven by increased CSR allocations—could diminish consumer brand awareness, adversely affecting sales performance and overall brand equity. Additionally, recent global disruptions—such as the United States (U.S.)–China trade tensions, the COVID-19 pandemic, and the Russia–Ukraine conflict—have heightened economic policy uncertainty. Under such conditions, CSR can act as a reputational "insurance mechanism", preserving corporate image and buffering against external shocks. However, Hua *et al*. (2020) caution that this protective mechanism may inadvertently incentivize firms to accumulate excess cash reserves, thereby diminishing their propensity for long-term investments. Severo *et al*. (2018) further argue that reliance on the reputational goodwill derived from CSR may weaken firms' incentives to pursue innovation, especially when such efforts are seen as sufficient to secure consumer loyalty. In sum, resource limitations and agency conflicts may compel managers to favor CSR activities that bolster reputation, effectively crowding out investment in long-term, high-risk innovation projects with ambiguous outcomes. Therefore, this study proposes the following hypothesis.

H2(b): Technological innovation plays a significant role in the transmission mechanism between CSR practices and brand equity.

Moderating effects of heterogeneous environmental regulations

Porter's hypothesis suggests that regulatory pressures can act as a catalyst, motivating firms to pursue green technological innovations and reduce emissions through environmentally responsible behavior (Mbanyele and Wang, 2021). Empirical findings by Jiménez-Parra *et al*. (2018) further support this view, indicating that CSR activities contribute meaningfully to reductions in air pollution, with environmental regulations functioning as amplifying moderators. Moreover, regulatory pressures encourage firms to align their development models with sustainable consumption trends, a shift that substantively enhances both brand appeal and perceived value (Lin *et al*., 2021). The moderating impact of environmental regulations on the relationship between CSR practices and brand equity is contingent upon the specific regulatory instruments imposed on firms. Applying a signaling theory lens, this study posits that MIER fosters competitive advantage—specifically through cost efficiency and product differentiation—by accelerating the corporate adoption of green development strategies. These initiatives may enable firms to secure a first-mover advantage in competitive markets, thereby enhancing profitability. Conversely, the "pollution haven" hypothesis posits that CCER may impose substantial compliance costs that could offset the benefits derived from CSR engagement. This financial burden may precipitate a "crowding-out" effect, diverting resources from other strategic investments, or alternatively, incentivizing firms to relocate operations to jurisdictions with more lenient environmental regulations—a trajectory that ultimately erodes brand equity (Zhu and Wang, 2018). Moreover, voluntary disclosure of environmental performance can enhance corporate transparency, contributing to a favorable green image. The attainment of public recognition as an environmentally responsible firm catalyzes consumer trust, which subsequently bolsters brand credibility and market influence.

Based on these theoretical insights, this study proposes the following hypothesis.

H3: Different forms of environmental regulations have heterogeneous moderating effects on the relationship between CSR practices and brand equity.

Based on the above theoretical foundations and the proposed hypotheses, this study constructs a conceptual framework for the effects of environmental regulations on CSR practices and brand equity paradox (Fig. 2).

MATERIAL AND METHODS

Data sources

This study examines the mechanism through which CSR practices affect brand equity under varying types of environmental regulation. The empirical analysis utilizes a panel dataset comprising of Chinese A-share listed manufacturing firms spanning the period from 2015 to 2020. Several considerations underpin the choice of the 2015 to 2020 period as the research window. 1) This timeframe coincides with China's 13th Five-Year Plan (2016 to 2020), a pivotal policy episode during which the revised Environmental Protection Law (Zhang *et al.*, 2015) was fully implemented, and CSR disclosure mandates were progressively tightened, enabling a systematic assessment of regulatory impacts on firm behavior. 2) This study intentionally excludes the period coinciding with the COVID-19 pandemic (beginning in 2020), as the resulting exogenous shock introduced extraordinary volatility in corporate strategies, financing conditions, and consumer brand perceptions, which would have confounded the empirical analysis. 3) Data availability imposes strict matching and verification requirements for all variables, including World Brand Lab rankings, Hexun CSR scores, and China stock market and accounting research (CSMAR) financial indicators; at the time of data collection, 2020 was the most recent year for which complete and validated data were available. After excluding companies with incomplete data or abnormal financial conditions—such as those classified under "special treatment" (ST)—the final sample includes 264 valid firm-year observations from 44 companies. Data pertaining to brand equity are drawn from the World Brand Laboratory, whereas CSR performance scores are sourced from Ding *et al*. (2025a). Information on financial constraints and R&D investments is retrieved from the CSMAR database. Environmental regulation data were compiled from the National Bureau of Statistics (NBS), CSMAR, the Peking University Law Information Network (PKULAW), and Baidu Index. Control variables were obtained from CSMAR, and all data processing and econometric analyses were performed using Stata 17.

Variable identification

Dependent variables

This study adopts the methodology of Ke *et al*. (2023) and utilizes data on China's top 500 most valuable brands, as provided by the World Brand Lab, with brand equity serving as the dependent variable.

Independent variables

Following Wang *et al*. (2022a) and Ding *et al*. (2022), this study uses CSR ratings from the Hexun.com database as the measure for the independent variable. CSR is assessed across five dimensions: shareholders, employees, suppliers and customers, the environment, and social responsibility, which include 13 secondary and 37 tertiary indicators. Based on the total score, the ratings are classified into four levels: A, B, C, and D, corresponding to scores of 4, 3, 2, and 1, respectively. Furthermore, the aggregate CSR score is used as a proxy variable for robustness testing.

Mediating variables

To quantify the intensity of corporate financing constraints, this analysis employs the absolute value of the SA index, calibrated such that an

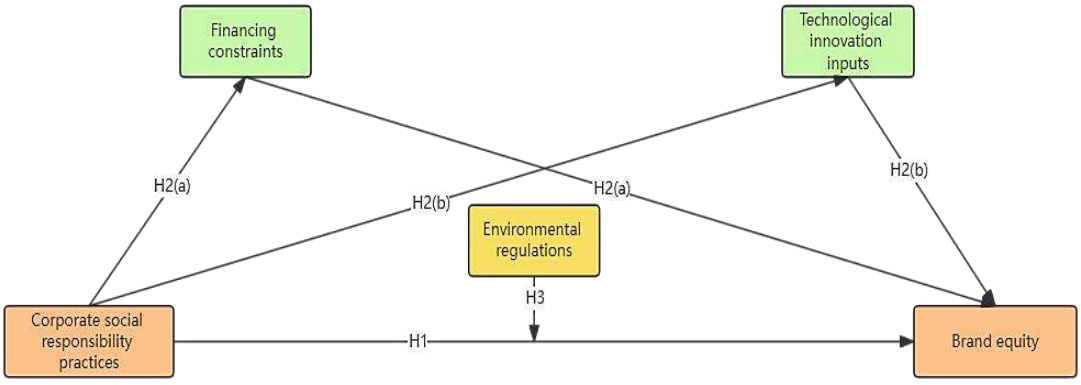

Fig. 2: A conceptual framework for the effects of environmental regulations on CSR practices and brand equity paradox

increase in this value corresponds to heightened constraint levels. In accordance with standard empirical practices, the natural logarithm of technological innovation inputs serves as a robust indicator of corporate innovation intensity.

Moderating variables

Consistent with the study conducted by Chen and Leng (2023), this study classifies heterogeneous environmental regulations into four categories: SDER, CCER, MIER, and PPER. In accordance with the framework established by Ding *et al*. (2022), SDER is measured along three dimensions via textual analysis. Furthermore, building upon the framework established by Wang *et al*. (2022b), this study quantifies CCER by the frequency of penalties recorded in regional environmental protection cases. MIER is operationalized as the ratio of completed investments in industrial pollution control relative to the total assets of large-scale industrial firms; while PPER is measured by the annual Baidu search index for the term "environmental pollution".

Control variables

Following Kumar and Zattoni (2015) and Bao and Xue (2023), this study incorporates the return on assets, net operating profit margin, CEO duality, percentage of independent directors, and supervisory board size as control variables. These variables are incorporated to encapsulate the primary determinants of internal governance mechanisms, corporate profitability, and leadership configuration. Detailed definitions of each variable are presented in Table 1.

Research method

Spatial weight matrix construction

This study constructs a 44×44 industry-specific spatial weight matrix based on the 2012 industry classification standard of the China Securities Regulatory Commission (CSRC). Companies within the same industry are assigned a value of 1, while those in different industries are assigned a value of 0. To mitigate endogeneity, multiple spatial weight matrices was employed to ensure the robustness of the empirical estimations. The first approach involves constructing a regional spatial weight matrix, where a value of 1 is assigned to firms located within the same province, and a value of 0 is assigned otherwise. A nested spatial weight matrix is subsequently developed by summing the regional and industry spatial matrices. In this configuration, firm pairs receive a weight of 2 if they share both geographical and industrial commonalities, a weight of 1 if they share only one attribute, and 0 otherwise. Finally, an alternative nested matrix is constructed by applying the pointwise multiplication method to the elements of the industry and regional spatial matrices.

Table 1: Variable definitions and descriptive analysis

Variable Category	Specific Indicator	Sign	Variable Description	Data Source	Mean	Min	Max
Dependent variable	brand equity	BE	brand equity of listed companies	World Brand Lab.com	419.5	32.68	3656
Independent variable	Corporate social responsibility	CSR	Corporate social responsibility rating	Hexun Database	1.182	1	4
Mediating variables	Financing constraint intensities	SA	SA index	CSMAR Database	3.679	2.188	4.269
	Technological innovation inputs	TII	Natural logarithm of technological innovation inputs		18.649	14.473	23.855
Moderating variables	Self-disclosure environmental regulation	SDER	Environmental information disclosure score calculated by textual analysis method	CSMAR Database	9.318	5	16
	Market incentive environmental regulation	MIER	Ratio of completed investment in industrial pollution control to total assets of industrial enterprises above scale	NBS Database	1.84E-04	6.63E-05	4.24E-04
	Command and control environmental regulation	CCER	Number of penalties for regional environmental protection cases	PKULAW Database	3656	99	18753
	Public participation environmental regulation	PPER	Annual search index with environmental pollution as keyword	Baidu Index	156.6	87.78	215.4
Control variables	Return on assets	ROA	Ratio of net profit to total assets	CSMAR Database	0.0591	-0.493	0.209
	Net operating profit margin	OPM	Ratio of net profit to operating income		0.105	-1.06	0.628
	CEO duality	CEO	General manager and chairman are the same as 1. otherwise 0		0.201	0.000	1.000
	Percentage of independent directors	PID	Ratio of number of independent directors to total number of board members		0.374	0.250	0.625
	Supervisory board size	SSB	Total number of supervisory boards		4.042	2.000	9.000

Here, only firms that simultaneously belong to the same industry and are situated in the same province are assigned a value of 1, while all other firm pairs receive a value of 0. This is a more stringent condition that can isolate the "pure" peer effect. These approaches are incorporated to ensure the robustness of the analysis and to address potential endogeneity. Should the main coefficients remain stable in both sign and significance across the two matrices, the robustness and reliability of the baseline regression findings will be substantially strengthened. The operations on the nested spatial weight matrices were conducted using the NumPy library in Python 3.8, with PyCharm 2021.2.2 as the integrated development environment (IDE). Furthermore, all spatial weight matrices constructed in this study were row normalized.

Model construction

To examine the relationship between CSR practices and brand equity, this study develops a fixed effects model that excludes the spatial weight matrix, using Eq. 1 (Kim and Lee, 2019):

$$BE_{it}=\alpha_0+a_1CSR_{it}+\alpha_2Controls_{it}+FixedEffect+\varepsilon_{it} \quad (1)$$

The study also develops a spatial autoregressive (SAR) model with fixed effects, again integrating the spatial weight matrix, based on the framework presented in Eq. 1, as detailed in the following equation specification, using Eq. 2 (Wuri *et al.*, 2024):

$$BE_{it}=\beta_0+\rho_0 WBE_{it}+\beta_1 CSR_{it}+\beta_2 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (2)$$

For the heterogeneity analysis, interaction terms between dummy variables and the primary independent variable were utilized to explore how the relationship between CSR practices and brand equity varies across two dimensions: the external environment and internal firm characteristics. Observations in all regression models were stratified based on the median value. Accordingly, this study introduces a series of dummy variables corresponding to regional market-incentive environmental regulation intensity, regional innovation capacity, regional economic development level, and firm size, each accompanied by its interaction term with the independent variable. To elucidate the underlying mechanisms, this analysis integrates financing constraint intensity and technological innovation input as mediating variables. To examine the mediating role of these variables in the relationship between CSR practices and brand equity, we utilize the causal stepwise regression approach. To assess the mediating role of financing constraint intensity, this study first develops a SAR model with fixed effects, where CSR practices serve as the independent variable and financing constraint intensity as the dependent variable. The spatial weight matrix is integrated, as described in Eq. 3 (Cao *et al*., 2022):

$$SA_{it}=\gamma_0+\rho_1 WSA_{it}+\gamma_1 CSR_{it}+\gamma_2 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (3)$$

Subsequently, financing constraint intensity is added to investigate its influence on brand equity, using Eq. 4 (Jiang *et al*., 2024):

$$BE_{it}=\delta_0+\rho_2 WBE_{it}+\delta_1 CSR_{it}+\delta_2 SA_{it}+\delta_3 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (4)$$

Similarly, to test the mediating effect of technological innovation input, this study first constructed the SAR model with fixed effects. In this specification, CSR practices serve as the independent variable and technological innovation input as the dependent variable, again incorporating the spatial weight matrix, using Eq. 5 (Cao *et al*., 2022):

$$TII_{it}=\zeta_0+\rho_3 WTII_{it}+\zeta_1 CSR_{it}+\zeta_2 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (5)$$

In the next step, technological innovation input is added to Eq. 2 to examine its effect on brand equity, using Eq. 6 (Wuri *et al*., 2024):

$$BE_{it}=\lambda_0+\rho_4 WBE_{it}+\lambda_1 CSR_{it}+\lambda_2 TII_{it}+\lambda_3 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (6)$$

To examine the moderate effects of heterogeneous environmental regulations, this study introduces SDER, MIER, CCER, and PPER, along with their respective interaction terms with the independent variable. Consequently, Eqs. 7 to 10 are used sequentially to assess the moderating effects of SDER, MIER, CCER, and PPER (Ding *et al*., 2025b):

$$BE_{it}=\mu_0+\rho_5 WBE_{it}+\mu_1 CSR_{it}+\mu_2 SDER_{it}+\mu_3 CSR_{it}*SDER+\mu_4 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (7)$$

$$BE_{it}=\tau_0+\rho_6 WBE_{it}+\tau_1 CSR_{it}+\tau_2 MIER_{it}+\tau_3 CSR_{it}*MIER_{it}+\tau_4 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (8)$$

$$BE_{it}=\phi_0+\rho_7 WBE_{it}+\phi_1 CSR_{it}+\phi_2 CCER_{it}+\phi_3 CSR_{it}*CCER_{it}+\phi_4 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (9)$$

$$BE_{it}=\omega_0+\rho_8 WBE_{it}+\omega_1 CSR_{it}+\omega_2 PPER_{it}+\omega_3 CSR_{it}*PPER_{it}+\omega_4 Controls_{it}+FixedEffect+\varepsilon_{it} \quad (10)$$

where, i represents firms; t represents years; $\alpha_0, \beta_0, \gamma_0, \delta_0, \zeta_0, \lambda_0, \mu_0, \tau_0, \varphi_0$ and ω_0 are constant terms; W represents the spatial weight matrix normalized by rows; ρ_0-$\rho_8$are spatial autoregressive coefficient; α_1-α_2, β_1-β_2, γ_1-γ_2, δ_1-δ_3, ζ_1-ζ_2, λ_1-λ_3, μ_1-μ_4, τ_1-τ_4, φ_1-φ_4 and ω_1-ω_4 are variable coefficients; Controls represents control variables set; FixedEffect represents fixed effect and ε_{it} is a random disturbance term.

Spatial autocorrelation test

This study employs Moran's index to examine the spatial autocorrelation of corporate brand equity. As shown in Table 2, the Moran's indices for the brand equity of 44 listed companies from 2015 to 2020 range between 0.422 and 0.560, with statistical significance at the 1 percent (%) level. Additionally, the overall Moran's index across the six-year period is 0.213, also significant at the 1% level. These empirical results provide evidence of significant positive spatial autocorrelation in brand equity among industry-peer firms.

Pearson correlation coefficient and multicollinearity test

To examine potential multicollinearity among the variables, this study employs both Pearson correlation coefficients and variance inflation factors (VIF). Consistent with the results presents in Table 3, brand equity is significantly and positively correlated with the size of the supervisory board and the ratio of independent directors at the 1% significance level, while exhibiting a significant inverse relationship with CEO duality at the 5% level. Despite the presence of some significant intercorrelations among the independent variables, the VIF estimates for all predictors remain substantially below 5, averaging 1.580. Collectively, these diagnostics indicate the absence of serious multicollinearity issue, confirming that the selected variables are appropriate for inclusion in the subsequent regression analysis.

RESULTS AND DISCUSSION

Baseline regression result

To examine the relationship between CSR practices and brand equity, a stepwise regression approach is utilized. This methodological approach is executed in two stages: initially, without the inclusion of control variables, and subsequently, with their full integration. The corresponding results are detailed in Table 4. Models 1 and 2 report the estimation outcomes of the general panel model with fixed effects, excluding the spatial weight matrix. The findings consistently reveal a significant negative association between CSR practices and brand equity at the 1% level. Models 3 and 4 provide the results of the SAR model with random effects, incorporating an industry-specific spatial weight matrix. Consistent with the primary analysis, these findings indicate that CSR practices are significantly and negatively associated with brand equity, also at the 1% level. Models 5 and 6 present the estimation outcomes of the SAR model with fixed effects, with the industry spatial weight matrix included. These findings further support the conclusion that CSR practices have a significant and negative influence on brand equity at the 1% level. Consequently, *H1* is fully supported. When accounting for both control variables and industry-specific spatial spillover effects, the empirical findings demonstrate that each unit increase in CSR performance leads to an average decline of 74.520 units in brand equity. Given that the sample mean of brand equity is 419.53 as shown in Table 1, this decline is equivalent to 17.8% of the mean, indicating that the negative effect of CSR on brand equity is economically significant as well. Furthermore, Models 3 through 6 demonstrate that the spatial autoregressive coefficients are significantly positive at the 1% level. This evidence of positive spatial autocorrelation in brand equity across firms in the same industry reinforces the robustness and appropriateness of the spatial econometric approach adopted in this study. This implies that firms within the same industry face similar consumer groups, supply chain networks, and regulatory environments, and that strong brand performance by competitors enhances brand awareness and reputation across the entire industry. Moreover, the tendency of firms to imitate or benchmark the CSR and branding strategies of industry leaders often precipitates strategic convergence, reducing differentiation and intensifying competitive pressures across increasingly homogeneous market environments.

Table 2: The results of the Global Moran's Index value test for brand equity

Year	Moran's Index	Expected value of Moran's Index	Standard deviation of Moran's Index	Z-score	P-value
2015	0.560	-0.023	0.172	3.390	0.001***
2016	0.506	-0.023	0.171	3.089	0.002***
2017	0.526	-0.023	0.165	3.322	0.001***
2018	0.511	-0.023	0.165	3.246	0.001***
2019	0.454	-0.023	0.162	2.937	0.003***
2020	0.422	-0.023	0.161	2.764	0.006***
2015-2020	0.213	-0.004	0.062	3.497	0.000***

Note: 2-tail test; *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively.

Table 3: Pearson correlation coefficient and multicollinearity test

Variables	BE	CSR	OPM	PID	CEO	SSB	ROA	VIF
BE	1.000							
CSR	-0.034	1.000						1.020
OPM	-0.025	0.040	1.000					2.600
PID	0.217***	0.091	-0.069	1.000				1.100
CEO	-0.119*	0.022	-0.146**	0.057	1.000			1.090
SSB	0.608***	-0.033	-0.097	0.137**	-0.205***	1.000		1.090
ROA	-0.038	-0.011	0.768***	-0.186***	-0.025	-0.125**	1.000	2.610

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively.

Table 4: The regression results of CSR and brand equity

Dependent variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	General panel model		SAR			
	BE					
CSR	-103.334*** (-4.26)	-94.728*** (-3.96)	-78.304*** (-3.60)	-78.534*** (-3.69)	-80.967*** (-4.05)	-74.520*** (-3.83)
OPM		-64.338 (-0.24)		14.630 (0.06)		11.989 (0.06)
PID		1847.855*** (4.14)		1658.040*** (4.40)		1661.659*** (4.61)
CEO		-7.961 (-0.12)		21.742 (0.38)		43.953 (0.81)
SSB		-24.665 (-0.66)		57.962** (2.11)		-13.756 (-0.46)
ROA		405.745 (0.67)		133.392 (0.26)		181.685 (0.37)
Intercept	541.593*** (17.38)	-74.811 (-0.33)	389.391*** (5.36)	-474.180** (-2.54)		
Fixed effect	Yes	Yes	No	No	Yes	Yes
Spatial autoregressive coefficient			0.355*** (7.32)	0.344*** (7.16)	0.352*** (7.27)	0.350*** (7.29)
No. Observations	264	264	264	264	264	264
R-Squared	0.077	0.147	0.025	0.339	0.001	0.029

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

Robustness test

To validate the stability of our empirical results, this study implements a rigorous robustness testing framework—comprising the substitution of the independent variable, the addition of omitted control variables, and the estimation of alternative spatial econometric models—the findings of which are presented in Table 5. In Model 1, CSR scores are used as a proxy variable, and the results indicate that CSR practices have significant negative effect on brand equity at the 1% level. Model 2 incorporates additional control variables to capture dimensions of executive diversity, corporate governance, and firm size. Specifically, these include management's average

Table 5: The results of robustness tests

Dependent variables	Model 1 Replacing independent variable	Model 2 Adding omitted variables	Model 3 Replacing SDM
		BE	
CSR	-3.190*** (-3.62)	-60.151*** (-3.24)	-60.463*** (-3.08)
Control variables	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes
Spatial interaction items	No	No	Yes
Spatial autoregressive coefficient	0.353*** (7.37)	0.288*** (6.03)	0.329*** (6.20)
No. Observations	264	264	264
R-Squared	0.019	0.001	0.064

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

age, the number of executives, the top ten shareholders' ownership ratio, and the natural logarithms of total assets and total employees. The results continue to demonstrate a significant negative effect of CSR practices on brand equity at the 1% level. Model 3 employs SDM to further explore the relationship between CSR practices and brand equity. The results confirm a significant negative impact of CSR practices on brand equity at the 1% level.

Endogeneity test

To mitigate potential endogeneity, this analysis utilizes regional and nested spatial weight matrices in conjunction with instrumental variables. The empirical findings are presented in Table 6. Model 1 presents the estimation outcomes with the introduction of a regional spatial weight matrix, which also indicates a significant negative effect of CSR practices on brand equity at the 1% significance level. Model 2 utilizes a nested spatial weight matrix with the pointwise addition method, demonstrating that CSR practices have a significant negative effect on brand equity at the 1% level. Finally, applying a nested spatial weight matrix using the pointwise multiplication, Model 3 similarly indicates that CSR practices exert a significant negative effect on brand equity at the 1% level. Since the CSR mean of other firms in the same industry (CSR-mean) reflects aggregate macroeconomic or sectoral trajectories, it is exogenous to a specific firm's brand equity, ensuring compliance with the exclusion restriction. Accordingly, this study uses the industry-average CSR of other firms as the instrumental variable to test for endogeneity. Models 4 to 5 present the first stage and second-stage regression results, respectively. Notably, incorporating the industry-average CSR score of competing firms introduces missing values, resulting in an unbalanced panel that precludes the execution of spatial regressions. Therefore, this study employs a two-dimensional panel data model for regression analysis. Model 4 reveals a significant positive correlation between the industry-average instrumental variable and the endogenous variable at the 1% level, while Model 5 demonstrates that CSR exerts a significant negative effect on brand equity at the 1% level. In addition, an under-identification test is conducted; the LM statistic yields a P-value of 0.000, strongly rejecting the null hypothesis of under-identification. Furthermore, the weak identification test reports a Cragg-Donald Wald F statistic of 12.385, which exceeds the critical value of 10, indicating that weak instrument bias is not a serious concern. In conclusion, the baseline regression outcomes herein exhibit consistency, confirming their robustness and credibility.

Heterogeneity analysis

Heterogeneity analyses are conducted by incorporating interaction terms between dummy variables and independent variables. The specifications reported in Table 7 categorize observations based on the median values of the

Table 6: The results of the endogeneity test

Dependent variables	Model 1	Model 2	Model 3	Model 4	Model 5
	Regional spatial weighting matrix	Nested spatial weighting matrix		2SLS	
		Pointwise addition method	Pointwise multiplication method	First stage	Second stage
CSR	BE -65.297*** (-3.38)	-57.224*** (-3.02)	-84.800*** (-4.20)	CSR	BE -313.238 (-2.37)
CSR_mean				0.343*** (3.52)	
Control variables	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes
Spatial interaction items	No	No	No	No	No
Spatial autoregressive coefficient	0.405*** (7.81)	0.509*** (9.01)	0.312*** (5.66)	No	No
Underidentification test (P_value)					0.000
Weak identification test (Cragg-Donald Wald F statistic)					12.385
Overidentification test of all instruments					Exactly identified
No. Observations	264	264	264	170	170
R-Squared	0.008	0.014	0.152	0.338	

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

Table 7: The results of the heterogeneity test

Dependent variables	Regional market-incentive environmental regulation intensity	Regional innovation capacity	Regional economic development level	Firm size
	Model 1	Model 2	Model 3	Model 4
	BE			
CSR	-31.750 (-1.35)	-34.409 (-1.19)	-27.521 (-1.11)	-6.373 (-0.20)
RMIER	-187.445*** (-3.47)			
CSR*RMIER	-82.921** (-2.34)			
ICI		165.874* (1.92)		
CSR*ICI		-73.330* (-1.90)		
GDP			-112.760 (-1.64)	
CSR*GDP			-66.426* (-1.71)	
SIZE				208.625*** (3.14)
CSR*SIZE				-101.725*** (-2.58)
Control variables	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes
Spatial autoregressive coefficient	0.264*** (5.39)	0.351*** (7.37)	0.340*** (7.18)	0.344*** (7.22)
No. Observations	264	264	264	264
R-Squared	0.014	0.031	0.031	0.147

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

dummy variable. From the external environment perspective, subgroup regression models are constructed along three dimensions: Regional market-incentive environmental regulation intensity (RMIER), regional innovation capacity (ICI), regional economic development level (GDP) and firm size. In Model 1, incorporates a dummy variable that takes a value of 1 for regions exhibiting high environmental regulation intensity and 0 otherwise. The results indicate that the coefficient of the interaction term is significantly negative at the 5% level. This suggests that the negative effect of CSR practices on brand equity is more pronounced for firms in regions with high environmental regulation intensity compared to those in regions with lower regulation intensity. This outcome implies that heightened regulatory stringency across regions escalates corporate compliance costs, which consequently drives firms toward greater reliance on "greenwashing" practices. In Model 2, regions with low innovation capacity are assigned a value of 1, while other regions are assigned a value of 0. The results reveal that the coefficient of the interaction term is significantly negative at the 10% significance level. This implies that the detrimental effect of CSR on brand equity is amplified for enterprises located in regions characterized by lower innovation capacity, relative to their counterparts in high-innovation settings. This finding implies that firms in regions with low innovation capacity are constrained by a scarcity of technological resources. They tend to treat CSR as a short-term goodwill-generation device rather than a long-term strategic commitment, making it difficult to effectively convert CSR into brand value. Moreover, consumers in these areas are more discerning of such symbolic actions, which further exacerbates the negative effect of CSR on brand equity. In Model 3, regions with low economic development levels are assigned a value of 1, while other regions are assigned a value of 0. The results show that the coefficient of the interaction term is significantly negative at the 10% significance level. This suggests that the negative effect of CSR practices on brand equity is more pronounced among firms economically less-developed regions than among those in more-developed areas. Furthermore, this result suggests that heightened fiscal constraints in lagging regions exert a crowding-out effect on brand-building and R&D outlays. Coupled with the feeble consumer perception and response to CSR in these localities, firms are unable to capture brand premiums from social responsibility, thereby aggravating the negative CSR–brand equity relationship. To account for internal organizational traits, subgroup regressions are performed by partitioning the sample according to firm size. In Model 4, large-scale firms are assigned a value of 1, while small-scale firms are assigned a value of 0. The results indicate that the coefficient of the interaction term is significantly negative at the 1% significance level. This suggests that the negative effect of CSR practices on brand equity is more pronounced for large-scale firms than for small-scale firms. This indicates that heavy public scrutiny leads stakeholders to view the CSR activities of large firms as symbolic gestures compelled by administrative mandates, thus hindering authentic consumer endorsement. Notably, the insignificant main effects of CSR across all four models indicate that the negative CSR-brand equity relationship is primarily driven by firms in the high-intensity subgroups, with no significant effect observed in the low-intensity counterparts. In summary, the analyses demonstrate that the effect of CSR practices on brand equity exhibits heterogeneity across different subgroups, including environmental regulation, innovation capacity, economic development level, and firm size.

Expanded analysis

Mediating effect of financing constraints and technological innovation inputs

To investigate the internal transmission mechanism between CSR practices and brand equity, this study employs a causal stepwise regression method to examine the mediating

effects of financing constraints and technological innovation inputs. The regression results are presented in Table 8. The mediating effect of financing constraints is examined using Models 1 and 2. Model 1 shows that CSR engagement significantly increases financing constraints at the 5% level. Model 2 indicates that CSR practices negatively affect brand equity at the 1% level, whereas financing constraints positively influence brand equity at the 1% level. These results suggest that financing constraints exert a suppression effect, partially offsetting the direct negative impact of CSR on brand equity. As CSR intensifies financing constraints, firms strengthen brand equity to improve access to limited financial resources, activating a defensive branding mechanism that mitigates the adverse effect of CSR on brand equity. This finding highlights the importance of institutional support and policy environments in shaping firms' strategic responses to financial constraints (Nithiananthan *et al.,* 2026), thereby supporting *H2(a)*. Models 3 and 4 examine the mediating effect of technological innovation inputs. Model 3 indicates that CSR practices are significantly and negatively associated with technological innovation inputs at the 10% level. Model 4 shows that technological innovation inputs positively affect brand equity at the 1% level, while CSR practices continue to exert a significant negative effect at the 1% level. These findings indicate that technological innovation inputs partially mediate the relationship between CSR practices and brand equity, supporting *H2(b)*, and suggest that sustained innovation investment alongside CSR initiatives helps firms preserve brand value under evolving environmental and institutional expectations (Almunawwaroh *et al.,* 2026).

Moderating effects of heterogeneous environmental regulations

Following the examination of the internal mediating mechanisms, this study investigates whether heterogeneous environmental regulations moderate the relationship between CSR practices and brand equity by incorporating interaction terms between the independent and moderating variables. The regression results, presented in Table 9, indicate that the interaction term between SDER and CSR practices is significantly negative at the 1% level (Model 1), while that between MIER and CSR practices is significantly negative at the 10% level (Model 2), suggesting that both regulations amplify the adverse impact of CSR practices on brand equity. In contrast, the interaction term between CCER and CSR practices is significantly positive at the 10% level (Model 3), indicating that CCER mitigates this adverse effect. These findings highlight that the effectiveness of CSR strategies depends not only on internal organizational capabilities but also on policy implementation and environmental governance frameworks (Almunawwaroh *et al.,* 2026; Nithiananthan *et al.,* 2026). Similarly, Model 4 indicates that the coefficient for the interaction term between PPER and CSR practices is statistically significant and positive at the 5% level, indicating that PPER mitigates the adverse impact of CSR practices on brand equity. In conclusion, SDER and MIER intensify the negative impact of CSR practices on brand equity, while CCER and PPER alleviate it. *H3* is fully supported. This study employs a spatial econometric framework to analyze Chinese micro-firm data, finding that CSR practices exert a significant negative effect on brand equity, whereas brand equity displays a prominent positive spatial correlation among intra-industry peers. Heterogeneity tests further explore the moderating roles of different environmental regulations. Based on these results, several key findings merit attention. 1) The negative effect of CSR on brand equity is more pronounced in regions with lower innovation capacity and economic development levels. Constrained by restricted technological and financial resources, enterprises in these regions tend to deploy corporate CSR initiatives primarily as instruments

Table 8: The mediating effect results of financing constraints and technological innovation inputs

Dependent variables	Model 1	Model 2	Model 3	Model 4
	SA	BE	TII	BE
CSR	0.013** (1.98)	-81.452*** (-4.25)	-0.158* (-1.85)	-60.414*** (-3.39)
SA		643.193*** (3.98)		
TII				97.592*** (7.58)
Control variables	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes
Spatial autoregressive coefficient	0.389*** (7.21)	0.294*** (5.80)	0.113** (2.03)	0.296*** (6.28)
No. Observations R-Squared	264 0.011	264 0.022	264 0.112	264 0.144

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

Table 9: The moderating effect results of heterogeneous environmental regulations

Dependent variables	Model 1	Model 2	Model 3	Model 4
	BE			
CSR	-57.780*** (-2.86)	-49.963*** (-2.78)	-33.364 (-1.36)	-96.995*** (-4.42)
SDER	-5.605 (-0.98)			
CSR*SDER	-26.429*** (-2.86)			
MIER		-4.18e+06*** (-8.83)		
CSR*MIER		-3.72e+05* (-1.67)		
CCER			0.010*** (2.91)	
CSR*CCER			0.015* (1.96)	
PPER				-4.246*** (-5.17)
CSR*PPER				1.394** (1.98)
Control variables	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes
Spatial autoregressive coefficient	0.351*** (7.38)	0.216*** (4.34)	0.329*** (6.71)	0.283*** (5.68)
No. Observations R-Squared	264 0.056	264 0.001	264 0.028	264 0.057

Note: *, **, *** Significant at 10%, 5% and 1% confidence levels, respectively, with t-stats in parentheses.

for short-term goodwill rather than as enduring strategic commitment (Mbanyele and Wang, 2021; Fernandes *et al*., 2023), leading to a gap between consumer perceptions and actual corporate investment. 2) The negative effect is stronger in regions with stringent environmental regulations and among large firms. Strict regulations raise compliance costs, prompting some firms to resort to "greenwashing". Meanwhile, large enterprises—frequently SOEs—encounter heightened public scrutiny, leading stakeholders to interpret their CSR activities as symbolic compliance driven by administrative mandates rather than authentic initiatives (Ding *et al*., 2023), thereby impeding genuine consumer recognition. 3) Different types of environmental regulations exhibit heterogeneous moderating effects. SDER and MIER amplify the negative impact of CSR on brand equity. SDER, while improving information transparency, may

increase corporate pressure and damage green image (Ding *et al*., 2022). Due to the limitations of underdeveloped capital markets, MIER fails to convey environmental signals efficiently (Pan, 2021); in contrast, CCER and PPER serve to attenuate the adverse impact. CCER strengthens corporate compliance through administrative measures, and strong CSR performance can offset compliance costs (Zhu and Wang, 2018). PPER, as an informal regulation, effectively complements formal regulations by enhancing public environmental awareness and supervisory capacity (Ge *et al*., 2021). It must be emphasized that, against the specific backdrop of China's manufacturing transformation, CSR activities are often perceived by consumers and investors as symbolic, instrumental, or superficial gestures rather than substantive commitments. The apparent contradiction between CSR practices and brand equity documented herein stems from the following underlying mechanisms: CSR initiatives are largely driven by the intention to generate goodwill rather than by a genuine commitment to addressing consumer rights; practices such as "greenwashing" and "impression management" are prevalent among Chinese firms; consumers have become more capable of identifying inauthentic brands, intensifying their skepticism toward CSR authenticity; and, under resource constraints, CSR investments crowd out resources allocated to brand building. As a result, CSR initiatives fail to generate effective brand value, instead eroding brand equity due to heightened consumer skepticism and distrust.

Limitations and future research directions

1) Sample selection and external validity. Due to the strict matching requirements necessary to establish a balanced panel dataset, the resulting sample size is considerably reduced and proves insufficient. The sample of 44 firms is drawn exclusively from the "China's 500 Most Valuable Brands" list, meaning that it captures large, mature, and consistently successful manufacturing firms with significant brand influence. While the dataset is highly appropriate for spatial autocorrelation analysis, its scope is limited by the exclusion of small and medium-sized enterprises, non-publicly traded firms, and service-industry enterprises. Future research will extend the time span and include unlisted firms, small and medium-sized enterprises, as well as companies from a broader range of industries, to test the robustness and generalizability of conclusions. Matched sample or quasi-experimental designs might also be considered to further alleviate sample selection bias. 2) Lack of dynamic modelling. In adopting a static spatial panel framework, this research abstracts from the dynamic or lagged impacts of CSR engagement on brand equity. The economic consequences of CSR initiatives are often long-term and cumulative: a firm's social responsibility spending each year may only gradually influence brand awareness, consumer trust, or financial performance in subsequent periods. In addition, because brand equity displays considerable persistence, its relationship with historical CSR actions tends to outweigh the impact of contemporaneous ones. Spatial spillovers in brand equity are also unlikely to materialize instantaneously; the brand strategies of peer competitors within the same industry may affect a firm's brand value only after some time lag. Therefore, future work will introduce dynamic spatial panel models that incorporate lagged terms for both the dependent variable and the main independent variable, thereby tracing the evolutionary dynamics of CSR effects and contrasting short-run shocks with long-run equilibrium outcomes.3) Single composite CSR indicator. We rely on the overall CSR rating from the Hexun database as our core independent variable. While the index captures diverse dimensions, collapsing them into a unidimensional overall score restricts our ability to isolate the specific impact of each underlying component. Empirically, CSR initiatives implemented in varying domains can impact brand value via distinct underlying pathways. Future studies will

disaggregate CSR into finer sub-dimensions, such as environmental, social, and governance components, and then test their respective direct impacts, mediating pathways, and heterogeneous moderation by environmental regulations (Fatima and Elbanna, 2022). 4) Unexplored nonlinear relationships. This research estimates a linear relationship between CSR and brand equity, but the association may not be strictly linear. Moderate levels of CSR engagement can establish a brand premium via product differentiation; conversely, overinvestment may preempt essential operational resources and ultimately impair brand equity. At the same time, the marginal returns of CSR may diminish as the level of engagement rises. The moderating effect of environmental regulations also exhibits nonlinear patterns depending on the CSR level. TTo bridge this gap, future studies will introduce the squared term of CSR or apply threshold regression models to test potential optimal levels or tipping points and further investigate the boundary conditions governing these relationships. 5) The mediation effect testing method is insufficient. The SAR model, together with the spatial weight matrix, introduces spatial dependence across cross-sectional units, which renders the conventional bootstrap procedure unsuitable in the present context, since spatial correlation undermines the randomness required in resampling and leads to biased standard error estimates. To overcome this methodological shortcoming, subsequent studies will employ structural equation modeling (SEM) alongside the incorporation of a spatial weight matrix, thereby formulating a spatial structural equation model (SSEM). Such an extension would enable a spatially explicit test of mediation effects and provide a depiction of the pathway mechanisms underlying spatial spillover effects across regions, industries, and institutional settings over time, while improving causal inference, model robustness, and identifying heterogeneous spatial interactions under varying socioeconomic and environmental conditions.

CONCLUSION

This study integrates stakeholder theory and labor value theory to systematically investigate how CSR practices impact brand equity within Chinese A-share listed manufacturing firms from 2015 to 2020, revealing a significant direct negative relationship that challenges conventional optimistic predictions derived from signaling and reputation-focused frameworks. Against the backdrop of China's manufacturing transition, stakeholders—including consumers and investors—tend to view CSR engagement as mere cosmetic compliance rather than a genuine pledge, which prevents these socially responsible practices from generating tangible brand equity. Nevertheless, this baseline negative effect operates via two distinct pathways: first, a financing constraint suppression mechanism, where financial pressures stemming from heightened agency costs compel firms to protect their brand equity to signal credibility and access external capital; and second, an innovation crowding-out channel, in which heavy CSR investments encroach upon constrained R&D resources and weaken long-term differentiation capabilities. Furthermore, spatial autocorrelation analysis uncovers a positive intra-industry spillover effect, indicating that a firm's brand equity is lifted by the strong brand performance of peer competitors. This entire mechanism is heavily moderated by external environmental conditions and internal firm characteristics; specifically, CCER and PPER help mitigate the negative CSR-brand equity impact by establishing clear compliance baselines that curb symbolic behavior, whereas SDER and MIER amplify the negative effect due to underdeveloped capital markets failing to transmit information effectively. These insights offer valuable implications for government policy, particularly in refining environmental regulations, as well as for enterprises pursuing high-quality development. 1) Governments should strengthen CSR supervision, expand policy and financial support for technological innovation, foster brand

development, and establish a CSR standardization framework tailored to China's institutional context. A robust monitoring mechanism and legislative institutionalization are needed, alongside market mechanisms to internalize supervision costs. Since technological advancement drives brand equity, public policy should prioritize supporting R&D infrastructure via fiscal subsidies and tax credits; furthermore, policymakers ought to harness the influence of industry leaders to jointly promote innovation and social responsibility, thereby realizing synergistic outcomes. 2) Enterprises should balance CSR and technological innovation investments, optimize resource allocation, and improve internal governance. Industry associations should monitor product and service quality to ensure fair competition and uphold industry reputation. To prevent the displacement of innovation, firms must carefully evaluate the relative allocation of resources between innovative activities and CSR initiatives. Managers should foster a strong corporate culture, enhance top management ethics, improve executive liability insurance, and strengthen internal governance. Beyond charitable donations, firms should reduce negative externalities and enhance social welfare, cut emissions, improve employee welfare, and raise business credit–to safeguard stakeholder rights. Increasing CSR transparency and expanding its scope can build consumer trust and brand value. 3) Policymakers and environmental agencies ought to standardize CSR reporting systems and optimize environmental regulatory mechanisms, alongside fostering citizen environmental literacy and public engagement. Environmental departments should shift from command-and-control to market-based incentives, and tailor regulations to local conditions–stricter enforcement in developed regions, more lenient approaches in less developed ones. Improving environmental disclosure by listed companies can lower investor information costs and ease financing pressures. Implementing a collective constraint mechanism serves to increase punitive and regulatory costs for non-compliant firms. Lowering the threshold for citizen participation in environmental protection can significantly boost environmental awareness and action.

AUTHOR CONTRIBUTIONS

X. Ding, the corresponding author, has contributed to formal analysis, data curation, visualization, conceptualization, methodology, and the preparation and revision of the manuscript. Y. Liu has contributed to the conceptualization, methodology, supervision, project administration, and the preparation and revision of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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
CCER	Command-and-control environmental regulation
CSMAR	China stock market and accounting research
CSR	Corporate social responsibility
CSRC	China securities regulatory commission
IDE	Integrated development environment
MIER	Market-incentive environmental regulation
NBS	National Bureau of Statistics
PPER	Public-participation environmental regulation
PKULAW	Peking University Law Information Network
R&D	Research and development
RMIER	Regional market-incentive environmental regulation
SAR	Spatial autoregressive
SEM	Structural equation modeling
SDER	Self-disclosure environmental regulation
SDM	Spatial Durbin model
SOEs	State-owned enterprises
SSEM	Spatial structural equation model
ST	Special treatment
VIF	Variance inflation factors

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CASE STUDY

Sustaining mangrove-based silvofishery to support coastal landscape resilience and explore ecotourism potential

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ABSTRACT

BACKGROUND AND OBJECTIVES: The ecological integrity and socio-economic resilience of coastal areas in Indonesia are increasingly threatened by fisheries development, which has led to the degradation of mangrove forests. Mangrove-based silvofishery is increasingly recognized as a viable strategy to reconcile ecosystem conservation with aquaculture production while simultaneously boosting ecotourism potential. The study objectives were to evaluate the multidimensional sustainability level of mangrove-based silvofishery systems in the Sungai Lumpur Protected Forest, identifying prioritized management approaches via a combined rapid appraisal for fisheries and analytic hierarchy process methodology.

METHODS: A rapid appraisal for fisheries -based multidimensional scaling approach integrated with the analytic hierarchy process was used to examine the sustainability of silvofishery systems in the Sungai Lumpur Protected Forest, Ogan Komering Ilir, Indonesia. The dataset comprises information collected from 165 participants through a combination of semi-structured interviews, structured surveys, and field observations. The multidimensional scaling analysis produced a stress value of 0.14, indicating an acceptable model fit.

FINDINGS: The findings indicate that the overall system has a moderate level of sustainability. The economic dimension achieved the highest score (75), followed by the social (73.9) and environmental (68) dimensions. The technological (32.53) and institutional (40.66) dimensions were classified as less sustainable. These findings indicate that silvofishery functions as a transitional socio-economic-ecological system that sustains livelihoods and essential ecosystem services, yet lacks long-term resiliency. The favourable ecological conditions and strong social cohesion also indicate considerable potential for community-based mangrove ecotourism, provided that technological limitations and governance challenges are effectively addressed. Key management priorities involve the optimization of institutional structures, the reinforcement of land tenure security, and the adoption of adaptive and eco-friendly aquaculture innovations.

CONCLUSION: Mangrove-based silvofishery in the Sungai Lumpur Protected Forest demonstrated moderate sustainability, characterized by strong economic performance with comparatively consistent social and environmental parameters. However, the primary limitations to long-term resilience are poor institutional capacity and weak technological progress. Achieving sustainable management requires extending beyond favorable environmental and economic outcomes to incorporate robust institutional frameworks, supportive policies, and technological innovation.

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INTRODUCTION

Degradation of coastal protected forests, particularly mangrove ecosystems, has intensified across the tropics, including Indonesia. Primarily propelled by the extensive conversion of mangrove ecosystems into intensive aquaculture operations, this shift has resulted in diminished vegetative cover, degraded environmental quality, and impaired ecological integrity (Eddy *et al.,* 2022; Utomo and Septinar, 2022; Utomo *et al.,* 2025). Beyond land cover change, mangrove degradation undermines essential ecosystem services including coastal protection, carbon sequestration, and biodiversity support. As globally recognized blue carbon ecosystems, mangrove play a crucial role in controlling the climate, strengthening coastal resilience, and supporting fisheries output (Lee *et al.,* 2011; Alongi, 2023). Nonetheless, institutional constraints and ongoing human-induced pressures result in the continuous loss of mangrove forests, even within designated conservation zones (Turschwell *et al.,* 2020; Heck *et al.,* 2024). Mangrove supports aquaculture and fisheries, while also offering great potential for nature-based tourism, including birdwatching, educational trails, and carbon offset projects. This potential remains mostly unexplored across many protected areas in Indonesia, including the Sungai Lumpur Protected Forest, due to poor institutional cooperation and inadequate community capacity. Consequently, the inclusion of mangrove silvofishery within comprehensive coastal tourism plans represents a vital mechanism for economic diversification and the enhancement of conservation stewardship. From a socio-ecological systems perspective, these dynamics show a trade-off between short-term financial advantages and long-term environmental sustainability. Coastal system resilience is not only influenced by biophysical factors but also the quality of governance, institutional frameworks, and community customs (Ostrom, 2009; Cumming *et al.,* 2022). Sustainable mangrove-based silvofishery can be conceptualized as a coupled socio-ecological system in which ecological integrity, economic production, governance, and community participation are mutually interconnected. This problem has drawn increasing legislative attention in Indonesia, especially with Government Regulation of the Republic of Indonesia No. 27 of 2025 concerning Environmental Protection and Management, which aims for integrated mangrove landscape management. This framework highlights the requirement for localized, evidence-based interventions that reconcile conservation targets with socioeconomic conditions, emphasizing cross-sectoral cooperation. In this context, mangrove-based silvofishery systems have become a viable nature-based solution combining aquaculture output with environmental preservation. Silvofishery allows for resource use while preserving important ecological activities by combining fisheries operations with mangrove vegetation within the same spatial unit (Fitzgerald, 2002; Hardi *et al.,* 2025; Utomo *et al.,* 2025). Empirical findings demonstrate that by improving water quality, supporting habitat provision, and driving nutrient cycling, mangrove systems successfully enhance productivity without compromising ecological balance (Rahman and Mahmud, 2018; Basyuni *et al.,* 2019; Alam *et al.,* 2021; Mamidala *et al.,* 2023). These biological processes generate synergies with the resilience of the coastline and create opportunities for low-impact ecotourism in multi-functional mangrove settings. Despite these advantages, the long-term viability of silvofishery systems varies and is extremely context-dependent. Existing studies have largely emphasized environmental or financial advantages, often failing to address critical technological barriers, institutional bottlenecks, and policy effectiveness. Moreover, sustainability assessments are often conducted independently across individual dimensions, limiting the ability to provide comprehensive management recommendations. This constraint is

particularly consequential, as the long-term resilience of the system is fundamentally determined by the integration of ecological functions, institutional governance, and adaptive technologies (McSherry *et al.,* 2023; Ofori *et al.,* 2023). To address these challenges, multidimensional analytical techniques have increasingly been used in coastal and fisheries studies. Multidimensional scaling (MDS) and rapid appraisal for fisheries (RAPFISH) methodically assess the sustainability of fisheries across many dimensions, including environmental, economic, and social (Pitcher *et al.,* 2013; Lloyd *et al.,* 2022; Aziz *et al.,* 2024). Nevertheless, current applications are predominantly confined to conventional fisheries, as empirical research applying these methodologies to integrated socio-ecological systems such as mangrove silvofishery in protected forest settings—remains sparse. Many applications have not incorporated decision-support systems for prioritizing management actions or identifying leverage attributes that most strongly influence sustainability outcomes. Recent studies further emphasize the need for participatory governance, community-based resource management, as well as the merging of technology and policy changes to attain sustainable results (Lin, 2019; Cumming *et al.*, 2022). Accordingly, the analytic hierarchy process (AHP) serves as an effective methodological architecture to organize multifaceted decision-making and identify prioritized strategies based on diverse criteria (Saaty, 1980; Trialfhianty *et al.,* 2022). Although RAPFISH and AHP have previously been combined in sustainability studies, existing applications primarily focused on conventional fisheries, aquaculture planning, or resource management. Limited attention has been given to mangrove-based silvofishery systems located within protected forest landscapes, where ecological conservation, livelihood sustainability, and governance constraints interact simultaneously. Moreover, previous studies have rarely translated RAPFISH leverage attributes directly into AHP decision criteria to develop context-specific management priorities that also consider ecotourism development. Bridging these literature gaps, this study combines the RAPFISH and AHP methodologies to evaluate the comprehensive sustainability of mangrove-based silvofishery systems and establish prioritized management interventions. Specifically, leverage qualities were assessed across five crucial dimensions, including ecological, economic, social, technical, and institutional, to provide more insight into system dynamics and limitations. A"glocal" approach was used to connect local socio-ecological conditions with global sustainability frameworks, while placing silvofishery within larger coastal landscape resilience and ecotourism development. Although previous studies have evaluated mangrove-based silvofisheries primarily through isolated ecological or economic lenses, a comprehensive integration that incorporates institutional and technological dimensions remains significantly scarce. Furthermore, existing studies have predominantly targeted production-oriented coastal sectors, leaving a critical gap regarding legally protected forest landscapes—areas characterized by intricate governance structures, tenure conflicts, and competing conservation goals that generate unique sustainability hurdles. Existing studies also rarely transform multidimensional sustainability assessment into prioritized management strategies. The results have methodological implications by advancing the integration of sustainability assessment and decision-support tools. Providing empirical insights for coastal resource governance and policy formulation in Indonesia, this study assesses the multidimensional sustainability of mangrove silvofishery in the Sungai Lumpur Protected Forest. Furthermore, it develops prioritized management interventions through the application of a combined RAPFISH–AHP methodology. The study were carried out at the Sungai Lumpur Protected Forest, Ogan Komering Ilir Regency, South Sumatra, Indonesia in 2026.

MATERIALS AND METHODS

Study area

This study was conducted in Sungai Lumpur Protected Forest, Ogan Komering Ilir Regency, South Sumatra, Indonesia. The area represents a protected coastal mangrove forest that is increasingly threatened by the expansion of aquaculture activities despite its designated conservation status. As an integral component of the eastern coast of South Sumatra, the region experiences substantial estuarine and tidal forcing, which dictates prevailing aquaculture methodologies and ecological dynamics. Geographically, the location is situated between 2°30'–3°30' south (S) and 104°30'–105°30' east (E). Covering about 480 hectares, the silvofishery system creates a mosaic of aquaculture ponds interspersed with mangrove flora, thereby mirroring a coupled production ecosystem landscape. The area has a flat coastal morphology characterized by mostly alluvial soils, along with a strong tidal exchange that controls the hydrodynamics of the ponds. Mangrove species including Rhizophora spp. and *Avicennia* spp. are prevalent and play a role in shoreline stability, nutrient cycling, and habitat provision. Local populations are significantly reliant on aquaculture-based livelihoods, especially shrimp and milkfish farming, in terms of socio-economics. Reflecting a complex socio-ecological arrangement, the governance structure entails intersecting institutional mandates across multiple stakeholders, notably forest management units (FMU), watershed management agencies (WMA), and local agrarian groups. Ogan Komering Ilir Regency is among the major coastal production areas in South Sumatra, with fisheries and aquaculture making a significant contribution to the regional economic output, according to data from the Indonesian Central Bureau of Statistics (CBS). The criteria for selecting the study area include 1) the existence of active mangrove-based silvofishery systems, 2) classification as a protected forest, 3) relevance to national mangrove management policies, and 4) proximity to Berbak–Sembilang National Park, emphasizing the potential for the growth of nature-based tourism. Geographical positioning is detailed in Fig. 1, while Fig. 2 presents contrasting field conditions across the aquaculture systems, emphasizing the underlying structural and ecological differences between conventional ponds lacking mangrove cover and mangrove-integrated silvofishery ponds.

Study design and analytical framework

This study used a quantitative–descriptive approach enhanced by qualitative analysis. While quantitative methods were utilized to evaluate the multidisciplinary sustainability status of silvofishery systems, qualitative data provided deeper interpretive insights to guide the development of tailored management policies (Creswell, 2014). The analytical framework combined two different methods, namely the RAPFISH and the AHP. Using a multidimensional scaling technique, RAPFISH evaluated the sustainability level across institutional, technological, social, financial, and ecological aspects, offering a methodical and quantitative analysis of system performance (Pitcher *et al.,* 2013). By evaluating management approaches according to leverage attributes, AHP effectively strengthens the diagnostic capacity of the assessment. By using pairwise comparisons and consistency testing, this approach allows for organized decision-making, thereby guaranteeing strong prioritization of intervention techniques (Saaty, 1980; Trialfhianty *et al.,* 2022). RAPFISH and AHP integration creates a diagnostic-prescriptive analytical route in which AHP translates the exhaustive sustainability analysis produced by RAPFISH into prioritized and implementable management plans. By bridging system assessment and policy formulation, this integrated framework enhances governance decision-making, specifically in complex socio-ecological contexts like mangrove silvofishery.

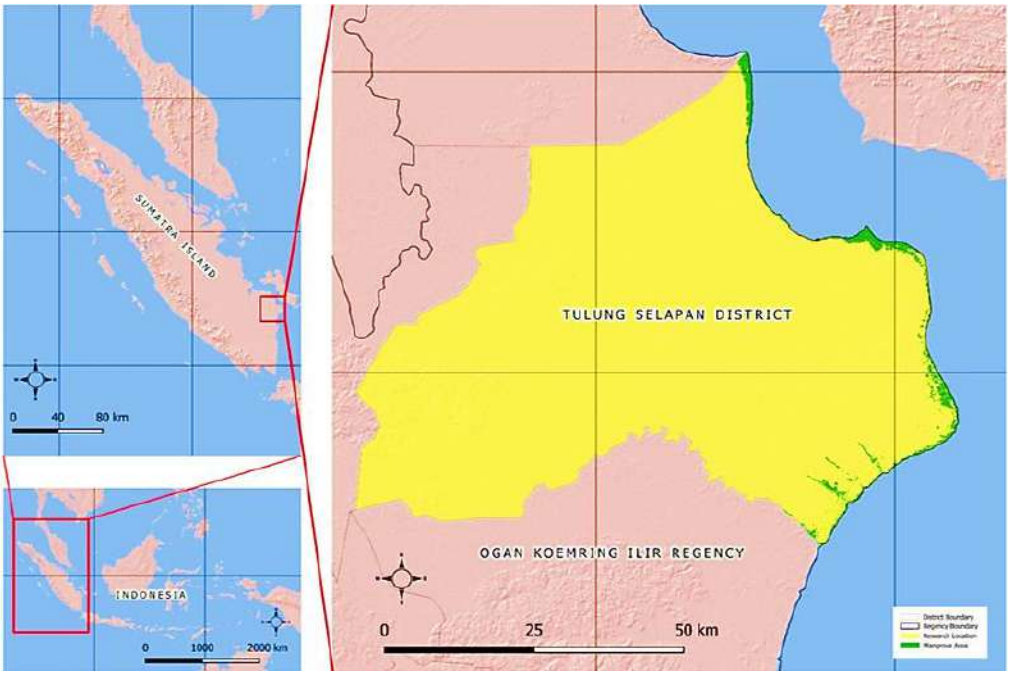

Fig. 1: Geographical location of the study area in Sungai Lumpur Protected Forest, Ogan Komering Ilir Regency, South Sumatra, Indonesia



Fig. 2: Field conditions of aquaculture systems in the study area
(a) Silvofishery pond integrating mangrove vegetation; (b) Conventional pond without mangrove cover

Data collection and sampling

The population included 656 silvofishery farmers working within the Sungai Lumpur Protected Forest. To recruit participants best suited for the research goals, a purposive sampling approach was adopted. Sample size determination was

conducted via Slovin's formula assuming a 6% error rate, resulting in a total sample size of 165 individuals (Creswell, 2014). The sampling criteria were established to guarantee the inclusion of experienced and pertinent responders, namely i) farmers who have practiced silvofishery for at least two years, ii) individuals actively engaged in aquaculture operations, and iii) key stakeholders representing institutional and governance structures connected with silvofishery development. Therefore, the final sample composition consisted of silvofishery farmers as the main actors together with institutional stakeholders including representatives from the forest management unit (FMU), the Watershed and Protected Forest Management Agency (WPMA), and program facilitators. The inclusion of these actors facilitated a more thorough system evaluation through the integration of on-the-ground production practices with institutional and policy frameworks. Moreover, the sampling approach is consistent with sustainability studies on sophisticated socio-ecological systems, where institutional and user-level viewpoints must be taken into account to guarantee analytical validity and contextual relevance.

Data collection and measurement

Primary data were collected through semi-structured interviews, structured questionnaires, and field observations to obtain both quantitative measurements and contextual insights regarding silvofishery practices. Specifically, semi-structured interviews provided in-depth qualitative perspectives on management strategies and institutional dynamics, while structured questionnaires enabled the systematic evaluation of predetermined parameters. To confirm on-site circumstances and enhance self-reported data, field observations were made. Using Microsoft Excel as a database platform, all collected data were collated and arranged before being examined with the Statistical Package for the Social Sciences (SPSS) version 31 for descriptive statistical analysis and initial data validation. To ensure the integrity of the subsequent RAPFISH analysis, this approach guaranteed data coherence, completeness, and availability**.** A source triangulation technique was used to enhance data validity and dependability (Creswell, 2014). This entailed cross-verifying data collected from several important respondents, including local facilitators, silvofishery project implementers from BPDAS-HL, and farmer group leaders. In socio-ecological studies, this triangulation is critical for mitigating bias, enhancing data validity, and ensuring the comprehensive representation of both operational and institutional perspectives. Furthermore, answers to the structured questionnaire were evaluated using a modified four-point Likert scale (1 = not important, 2 = less important, 3 = important, 4 = very important) to lower central tendency bias and raise response discrimination (Creswell, 2014). To guarantee the robustness of the MDS technique, data were examined for completeness and consistency before analysis. Table 1 outlines the measurement scale and data collection methods utilized to enhance transparency and clarity.

Analytical unit and sustainability dimensions

The RAPFISH Analysis, an acronym for Rapid appraisal for fisheries, is a set of indicators that can be used to assess the sustainability of fishery systems according to multiple dimensions. The sustainability attributes are structured along an analytical framework comprising five core dimensions, namely ecological, economic, social, technological, and institutional. These dimensions represent fundamental elements of socio-ecological systems and are frequently used in sustainability assessments. The scores were graded using a four-point ordinal scale (1–4), with higher numbers indicating better sustainability performance. Table 2 shows each defining dimension and its description. A total of 31 indicators were selected from an initial pool of 51 attributes. The selection process was based on i) field relevance to silvofishery practices, ii) data availability and measurability, and iii) expert

Table 1: Summary of data collection techniques and measurement scale

Method	Purpose	Data type	Instrument	Output
Semi-structured interview	Explore perceptions, governance, practices	Qualitative	Interview guide	Contextual insights
Structured questionnaire	Measure sustainability indicators	Quantitative	Likert-scale survey	Scored indicator dataset
Field observation	Validate field conditions	Qualitative	Observation checklist	Verification data
Triangulation	Ensure validity and reliability	Mixed	Multi-source validation	Cross-validated dataset
Measurement scale	Standardize responses	Quantitative	4-point Likert scale	Ordinal scoring (1–4)

Table 2: RAPFISH dimensions for silvofishery sustainability assessment

No.	Dimension	Score range	Description
1	Ecological	1–4	Mangrove condition, environmental quality
2	Economic	1–4	Income stability, production efficiency
3	Social	1–4	Participation, local knowledge
4	Technological	1–4	Technology adoption and innovation
5	Institutional	1–4	Governance, policy support

validation through stakeholder consultation. By implementing this filtering process, the analysis effectively captured context-specific sustainability dynamics without compromising analytical rigor**.** The indicator selection procedure and the subsequent expert validation are summarized in Table 3.

MDS

The sustainability status of the silvofishery system was evaluated using a MDS approach within the RAPFISH framework. MDS converts multidimensional attribute scores into a two-dimensional ordination for sustainability assessment. Model goodness-of-fit was evaluated using the stress function, defined using Eq. 1 (Pitcher *et al.,* 2013):

$$S = \sqrt{\frac{\sum_{i<j}(d_{ij}-d_{ij})^2}{\sum_{i<j} d_{ij}^2}} \quad (1)$$

Where: d_{ij} represents the observed distance between objects, and d_{ij} denotes the fitted distance in the ordination space. A stress value of less than 0.25 indicates a reliable and acceptable ordination.

Sustainability index classification

This index yields a quantifiable measure of sustainability performance across multiple dimensions; the specific classification criteria are outlined in Table 4.

Validation of sustainability indices

To evaluate the robustness of the RAPFISH ordination, additional validation procedures were conducted. First, the goodness-of-fit of the MDS configuration was assessed using the stress value and the coefficient of determination (R^2). Following RAPFISH guidelines (Pitcher *et al.,* 2013), stress values below 0.25 indicate an acceptable ordination, while higher R^2 values indicate stronger explanatory power. Second, a Monte Carlo simulation comprising 25 random iterations was executed at the 95% confidence level. To assess the stability of sustainability indices, this procedure applies random perturbations to attribute scores and evaluates the divergence between the resulting ordination and the baseline RAPFISH estimates. Small differences between RAPFISH and Monte Carlo results indicate that the sustainability assessment is robust and minimally affected by scoring uncertainty or random error. Finally, the consistency of sustainability rankings across dimensions was examined by comparing the original and simulated sustainability indices. Consistent ranking outcomes demonstrate that the proposed framework provides robust support for management prioritization.

Table 3: The indicator selection procedure and expert validation process

Stage	Number
Initial literature review	51
Duplicate removal	45
Expert validation	38
Field relevance	34
Data availability	31

Table 4: AHP priority weights for sustainability dimensions

Sustainability dimension	Normalized weight	Priority rank
Institutional	0.341	1
Technological	0.276	2
Economic	0.159	3
Social	0.128	4
Ecological	0.096	5

Leverage (Sensitivity) analysis

To identify key attributes influencing sustainability performance, a leverage (sensitivity) analysis was conducted using the root mean square (RMS) approach. To quantify the relative importance of each attribute, this analysis examines their respective contributions to fluctuations in the composite sustainability index. The RMS value was calculated using Eq. 2 (Salomon *et al.,* 2024):

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (2)$$

Where: n is the total number of attributes, x_i is the score of the ith attribute, $\bar{x}$ is the mean value of all attributes, $(x_i - \bar{x})$ is the deviation of each attribute from the mean, and Σ denotes the summation over all attributes.

The RMS value represents the mean deviation of each attribute from the overall mean and provides a measure of the relative influence of individual attributes on the sustainability index. Attributes exhibiting higher RMS values exert greater variability in sustainability status, designating them as critical leverage variables. These attributes provide the key information needed to parameterize AHP-based prioritization, establishing that strategy development is based on sensitivities identified from empirical data. The RAPFISH analysis was performed using MDS implemented in RAPFISH software. The ALSCAL algorithm with Euclidean distance was used to generate the ordination. Furthermore, ordination quality was evaluated using stress values (<0.25) and the coefficient of determination (R^2). To assess the stability of the sustainability indices and mitigate scoring uncertainty, Monte Carlo simulations were executed with 25 iterations.

AHP-based strategy formulation

This study applied the AHP with priority-based approaches for complementary management strategies arising from the diagnostic assessment provided by RAPFISH. As a structured multi-criteria decision-making framework, AHP facilitates the prioritization of complex problems via systematic hierarchical decomposition, pairwise comparisons, and rigorous consistency verification (Saaty 1980; Trialfhianty *et al.,* 2022). It is especially useful for socio-ecological systems that involve trade-offs between multiple and usually conflicting objectives.

Hierarchical structure

In this study, the AHP model was built upon three levels organized hierarchically to enhance analytical clarity and relevance in decision-making. The first level indicates the long-term goal, which is sustainable management of silvofishery mangrove systems. The second level

contains the five sustainability dimensions, including ecological, economic, social, technological, and institutional, which serve as the principal decision criteria. The third tier consists of decision sub-criteria formulated by synthesizing RAPFISH leverage attributes that capture critical determinants of system performance. This hierarchy allows for complex sustainability issues to be transformed into a structured decision framework, enabling logical prioritization of management strategies using multiple related dimensions. Fig. 3 conceptually delineates the hierarchical structure of the AHP model.

Pairwise comparison

Pairwise comparisons were conducted using Saaty's (1980) fundamental scale to determine the relative weights of the evaluation criteria and sub-criteria. Each element was compared systematically with others related to the general purpose of sustainability. The pairwise comparison matrix is mathematically expressed using Eq. 3 (Salomon *et al.,* 2024):

$$a_{ij} = \frac{\omega_i}{\omega_j} \quad (3)$$

Where: ω_i is the weight of element *i*, ω_j is the weight of element *j*, and a_{ij} is the relative importance of element *i* compared with element *j*.

Obtained from the normalized principal eigenvector, the priority vector reflects the hierarchical weight and relative significance of each criterion in sustainable mangrove-based silvofishery management. Overall, a prioritization matrix was generated to obtain the priority vector that determines the relative importance of each criterion.

Consistency evaluation

To ensure the reliability of expert judgments, consistency testing was conducted using the Consistency Index (CI) and Consistency Ratio (CR). The Consistency Index was calculated using Eq. 4 (Salomon *et al.,* 2024):

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (4)$$

The consistency ratio was then computed using Eq. 5 (Salomon *et al.,* 2024):

$$CR = \frac{CI}{RI} \quad (5)$$

Where: λ_{max} is the maximum eigenvalue of the comparison matrix, n is the number of criteria, and RI is the Random Index corresponding to the comparison matrix size.

A consistency ratio (CR) ≤ 0.1 indicates that the judgments are sufficiently consistent and acceptable for decision-making (Saaty, 1980). To maintain analytical rigor and ensure consistency of the derived priority weights, pairwise comparisons were iteratively adjusted whenever the CR threshold was breached**.** Pairwise comparisons were completed by nine experts comprising three mangrove scientists, two aquaculture specialists, two government officers responsible for coastal management, and two community leaders. Individual comparison matrices were aggregated using the geometric mean. CR ranged from 0.041 to 0.086, indicating acceptable consistency.

Integration with RAPFISH outputs

The connection between RAPFISH and AHP was operationalized by adding the leverage (sensitive) attributes highlighted through RAPFISH as elements within the hierarchical structure of AHP. By aligning management strategy prioritization with empirically derived sustainability constraints and system vulnerabilities, this approach established a robust and evidence-based framework. Therefore, the analytical workflow was created based on a diagnostic–prescriptive flow. First, the RAPFISH methodology was applied to examine the sustainability status of the system

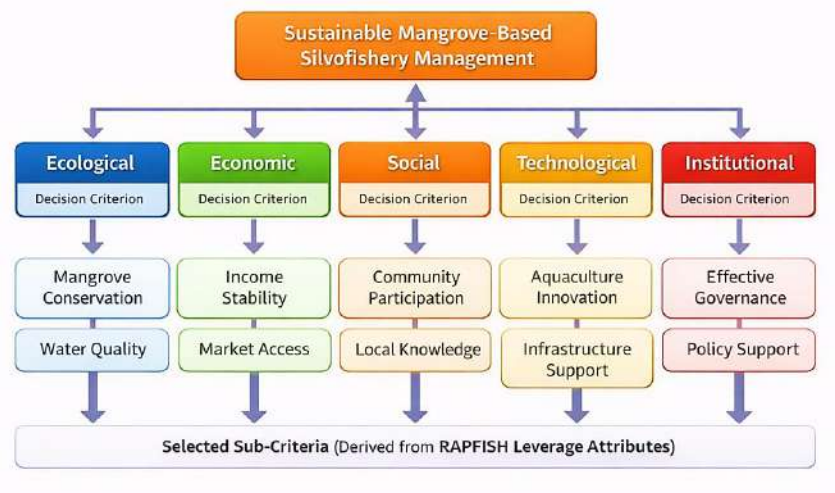

Fig. 3: Hierarchical structure of AHP for silvofishery sustainability strategy

and which leverage attributes affect sustainability performance most sensitively. Subsequently, AHP was employed to rank strategic interventions for comparative analysis of major leverage attributes determined through the RAPFISH. The integration of RAPFISH and AHP reinforces the link between sustainability assessment and operational decision-making, effectively converting diagnostic results into actionable management strategies. It allows the prediction of specific, science-based management scenarios for mangrove-based silvofishery systems across dynamic social-ecological contexts.

Integration of RAPFISH and AHP

The combination of RAPFISH and AHP provides a cohesive analytical framework that connects sustainability assessment and strategy development. In addition, this synthesis addresses a critical methodological bottleneck in sustainability studies by bridging the gap between diagnostic assessments and actionable decision-making (Cumming *et al.,* 2022; McSherry *et al.,* 2023). The framework follows a diagnostic–prescriptive pathway that connects multidimensional sustainability assessment with the prioritization of management strategies, as illustrated in Fig. 4. In this structural setup, RAPFISH functions as the diagnostic module by deploying MDS to evaluate the sustainability performance of the mangrove-based silvofishery system across diverse dimensions. In addition to generating sustainability indices, RAPFISH identifies leverage (sensitive) attributes that exert the greatest influence on overall system performance (Pitcher *et al.,* 2013). These identified leverage attributes serve as the methodological basis for the subsequent strategic analysis. AHP further adds a structured approach that incorporates the prioritized management strategies through hierarchical decomposition, pairwise comparison, and consistency-based evaluation of the relevant leverage attributes (Saaty, 1980; Trialfhianty *et al.,* 2022). The analytical procedure followed a structured, stepwise workflow designed to maintain a continuous and systematic progression of operations. It started with extensive data collection through field observations, interviews, questionnaires, and secondary data sets. MDS ordination was then used in RAPFISH analysis to assess the overall sustainability scores across different dimensions. Subsequently, the sustainability index was calculated to provide a quantitative measure of sustainability performance based on the ordination results. Subsequently, a series of leverage attributes were used to identify the most influential factors on sustainability outcomes. AHP was employed to prioritize these main characteristics and to

determine the sequential scale of strategies. The results from the prioritization formed the basis for developing sustainable management strategies and end-of-policy recommendations. This progressive integration ensures a methodical transition from diagnostic evaluations to operational strategy formulation. The framework anchors methodological rigor and policy relevance, explicitly connecting analytical outputs with decision-support mechanisms, especially evident in complex socio-ecological systems such as mangrove-based silvofishery (Ostrom, 2009; Cumming *et al.,* 2022). This integration enables progress towards hybrid sustainability assessment frameworks that connect multi-dimensional diagnostics with more structured decision-support systems, an undersxplored area in coastal socio-ecological enquiry.

Data processing and analytical tools

To safeguard analytical reliability, consistency, and replicability, data processing and analysis were systematically conducted using a combination of specialized software tools. Data entry, coding, and database management were primarily performed with Microsoft Excel, while descriptive statistical analysis and preliminary data validation were carried out using IBM SPSS. MDS and sustainability indices were calculated using the RAPFISH module (Pitcher *et al.* 2013). To guarantee appropriate MDS ordination and robust interpretation, all datasets underwent preliminary screening for completeness, consistency, and outlier identification. More specifically in quantitative studies, data screening and validation are important steps to improve reliability and reduce analytical bias (Creswell, 2014). This framework promotes multi-software reproducibility capabilities and enhances the robustness of multidimensional sustainability assessment. To enhance methodological transparency, a synthesized workflow chart summarizing the sequential analytical procedures applied in this study is provided at the end of this section (Fig. 4) to facilitate methodological understanding and reproducibility.

RESULTS AND DISCUSSION

Socio-demographic characteristics of respondents

Characteristics of respondents are described to provide the socio-economic context for silvofishery practices. These characteristics are required for interpretation of sustainability performance, adaptive capacity, and governance dynamics. Univariate analysis was conducted to describe the socio-demographic profile of silvofishery practitioners in the Sungai Lumpur Protected Forest, Ogan Komering Ilir Regency, Indonesia (N = 165) (Table 5). Most respondents were of productive working age, with 61% between 31 and 50 years old, indicating a workforce that combines substantial practical experience with adequate physical capacity for silvofishery activities. Although educational attainment was comparatively high, dominated by secondary-level completion (54%), this trend implies constrained uptake regarding technological innovation and sustainability. In terms of livelihood, silvofishery was the main occupation for 76% of respondents. The concentration of respondents in the upper income category (62%) underscores the significant contribution of silvofishery to local socioeconomic well-being. Moreover, the predominance of mid-sized families (93%) and high social homogeneity (96% Muslim) indicate a strong social structure. These conditions provide the foundation for collective action or a community-based resource governance, which represent essential pillars in the sustainability of socio-ecological systems.

Sustainability status of silvofishery systems

Following the characterization of respondents, the sustainability performance of silvofishery systems was evaluated using the RAPFISH approach across five dimensions. The results are visually represented using a kite diagram in Fig. 5. Once respondent profiles were established, five distinct dimensions were analyzed via the RAPFISH framework to quantify the sustainability performance of the silvofishery systems. Fig. 5 shows a kite diagram used to visually represent the results. The overall status of the silvofishery

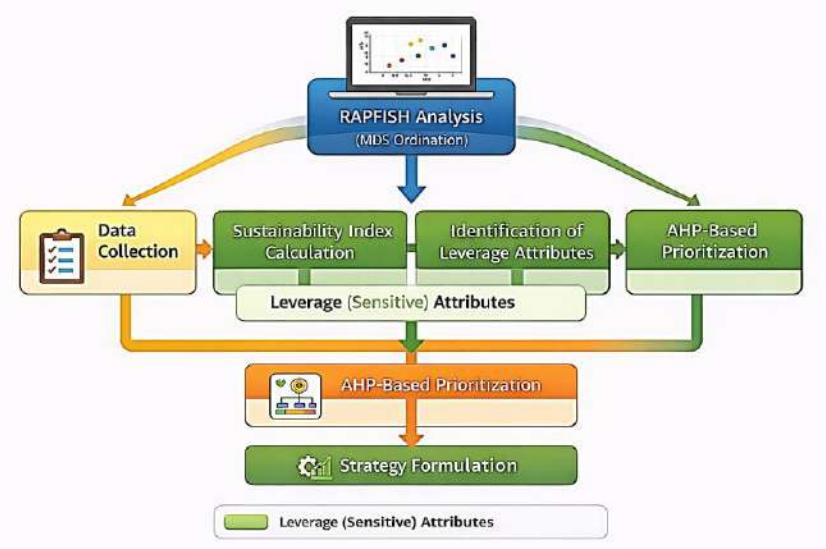

Fig. 4: Synthesized workflow of RAPFISH–AHP integration for multidimensional sustainability assessment of mangrove-based silvofishery

Table 5: Socio-demographic characteristics of silvofishery farmers

Characteristics	Category	Frequency	Percentage (%)
Age	15–30 years	45	27
	31–50 years	100	61
	51–65 years	20	12
Education	No formal education	0	0
	Primary school	41	25
	Secondary school	89	54
	Higher education	35	21
Occupation	Main occupation	125	76
	Secondary occupation	40	24
Income	< USD 2.15/day	63	38
	≥ USD 2.15/day	102	62
Household size	Small (2 persons)	7	4
	Medium (3–5 persons)	153	93
	Large (>5 persons)	5	3
Religion	Islam	159	96
	Christianity	5	3
	Hinduism	1	1

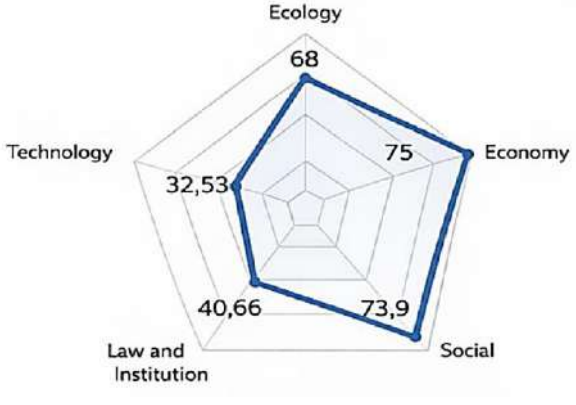

Fig. 5: Kite diagram of multidimensional sustainability status of silvofishery systems

system falls within the moderately sustainable category (sustainability index of 51–75). Nevertheless, statistically significant differences emerged among the evaluated sustainability dimensions. The lowest score (75) was given to the economic dimension, which is considered a highly sustainable state, supported by principally stable livelihood and income-generation activities. The social dimension also performed well, with a sustainability score of 73.90, reflecting strong community participation, social cohesion, and local adaptive capacity. Conversely, the ecological dimension achieved a score of 68, highlighting that sustained interventions remain necessary to reinforce ecosystem resilience and ecological functions. Meanwhile, the institutional and technological dimensions were found to be even more critical, with scores of 40.66 and 32.53, respectively (both being less sustainable). These results indicate that although the silvofishery system performs relatively well from economic and social perspectives, its long-term sustainability remains constrained by weak governance structures, limited institutional capacity, and inadequate technological development. Notwithstanding these challenges, favorable environmental and social conditions underpin the potential for community-based mangrove ecotourism, bolstered by extant ecological integrity and cohesive local social structures. Although the institutional score is low, it suggests that formal governance mechanisms for tourism management are still underdeveloped. Strengthening institutional capacity should precede the large-scale development of ecotourism through the establishment of an effective community-based management system.

Economic dimension

Exhibiting the highest sustainability score among all evaluated dimensions, the economic aspect highlights the critical role of silvofishery systems in securing local livelihoods. This performance is underpinned by fairly consistent market access, higher income levels, and positive household economy contributions. The results further substantiate the silvofishery function as a commercially feasible production system.

Ecological dimension

The ecological dimension has moderate performance (68), which reflects the importance of mangrove integration on environmental quality. Mangrove ecosystems support vital ecological functions—including habitat provision and nutrient cycling—while serving to improve water quality and attenuate land degradation risks. This indicates that silvofishery systems can comparatively function as a nature-based solution.

Social dimension

Performance in the social dimension (73.9) was supported by adequate levels of education and access to extension services and opportunities for community participation. Such factors amplify environmental accountability and facilitate the practical integration of sustainable behaviors.

Institutional and technological dimensions

The institutional and technological dimensions were identified as key vulnerabilities. Institutional constraints are primarily associated with uncertain land tenure arising from the protected forest designation, which reduces tenure security and discourages long-term investment in sustainable management. Moreover, technological constraints inherent in conventional production paradigms contribute to suboptimal water management, ineffective waste treatment, and deficient post-harvest handling. These results show that silvofishery systems are economically and socially viable but have limited long-term sustainability due to governance and innovation deficits.

Validation of RAPFISH results

The reliability of the RAPFISH ordination was evaluated using stress statistics, the coefficient of determination (R^2), and Monte Carlo simulations. The multidimensional scaling analysis produced a stress value of 0.14, indicating an acceptable

ordination according to RAPFISH criteria (<0.25). The coefficient of determination (R^2 = 0.95) demonstrated that the ordination explained most of the variability in the sustainability dataset. Validation via Monte Carlo simulations confirmed minimal divergencefrom the original RAPFISH estimates, with absolute deviations remaining below 2 index points across all every evaluated sustainability dimensions. This result indicates that the sustainability scores were stable and minimally affected by uncertainty associated with attribute scoring or respondent variability. Overall, these validation outcomes substantiate the reliability of the reported sustainability indices, thereby affirming the robustness of the subsequent ensuing leverage analysis and AHP prioritization.

Leverage (Sensitivity) analysis

Leverage (sensitivity) analysis was conducted using RMS to identify the sustainability attributes that exert the greatest influence on the overall sustainability performance of the mangrove-based silvofishery system, and the results are shown in Fig. 6. Because attributes exhibiting higher RMS values exert a greater influence on the sustainability index, they are designated as leverage factors and prioritized for further evaluation through AHP. This analysis indicated that the sensitive attributes were found mainly within the institutional and technological dimensions of sustainability. Regarding the institutional dimension, land tenure legitimacy and governance efficacy emerged as the most influential leverage attributes. These attributes address regulatory compliance, stakeholder coordination, and stability over long-term management. In contrast, evaluation of the technological dimension revealed that water management, waste treatment systems, and production technologies constituted the most critical attributes. The factors are closely associated with improvements in resource-use efficiency, environmental controls, and operational practices (eco-efficiency reviews). Higher RMS values for these attributes imply a more significant effect on sustainability performance. Therefore, interventions focused on the attributes would lead to the most important progress. These findings corroborate the multidimensional imbalance revealed through the RAPFISH framework, thereby establishing a solid empirical foundation for assessing alternative management strategies.

Strategic prioritization based on RAPFISH–AHP integration

To translate diagnostic results into actionable strategies, RAPFISH outputs were integrated with AHP to prioritize interventions. The priority weights are presented in Table 6. The AHP results indicate that the Institutional dimension is the top priority while the Technological dimension is the second. This is fully consistent with RAPFISH results, confirming the robustness of the integrated analytical framework.

Strategic implications

Priority 1: Institutional strengthening

Improved institutional strengthening was identified as the key strategic priority for achieving sustainable coastal and aquaculture management. By leveraging social forestry initiatives to formalize customary land claims and secure legal tenure for local communities, this approach aims to mitigate resource-based conflicts. It is also necessary to strengthen local governance capacity to make better decisions, institutions, and coordination. Adaptive regulatory frameworks are needed to ensure responsiveness of policies to changing circumstances, particularly in coastal areas as well as with respect to socio-economic dynamics and sustainability challenges.

Priority 2: Technological innovation

Technological innovation represents the second strategic priority aimed at improving environmental management efficiency and aquaculture productivity. This strategy incorporates the deployment of advanced water

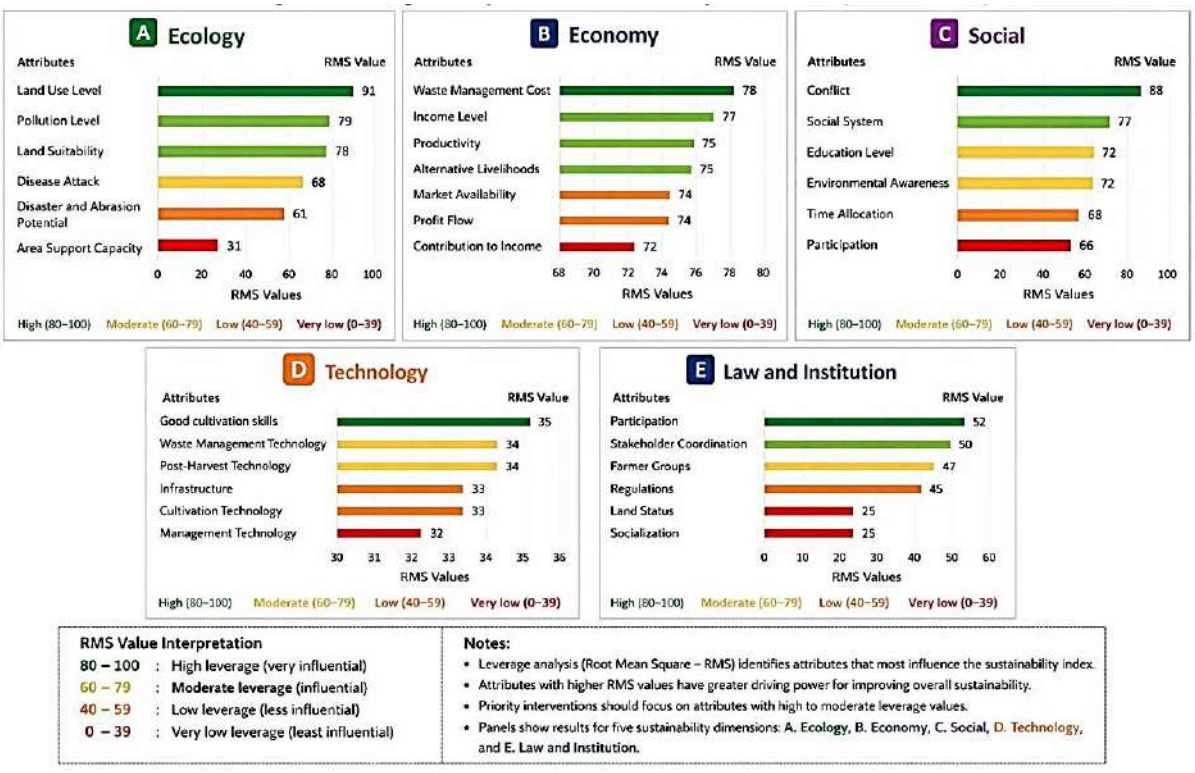

Fig. 6: Leverage analysis of sustainability attributes (RMS values)

Table 6: Priority weights of sustainability dimensions (AHP results)

Dimension	Weight	Priority rank
Institutional	Highest	1
Technological	High	2
Economic	Moderate	3
Social	Moderate	4
Ecological	Moderate	5

quality management frameworks designed to sustain ecological integrity and foster sustainable production. The adoption of environmentally friendly aquaculture technologies will minimize ecological impacts while increasing production efficiency. Furthermore, optimizing waste treatment protocols and post-harvest procedures is vital for curtailing environmental pollution, maximizing product quality, and augmenting the economic returns of aquaculture products.

Supporting dimensions: Reinforcement strategies

Although the economic, social, and environmental dimensions demonstrated relatively favorable sustainability performance, continuous improvement remains necessary to maintain and strengthen long-term sustainability outcomes. Economically, strategic efforts must center on bolstering market access, stabilizing prices, and diversifying local product offerings to fortify the resilience of community incomes. Socially, strategies should focus on capacity building, continued training programs, and knowledge transfer to strengthen community participation and adaptivity. At the same time, ecological reinforcement must prioritize community-oriented mangrove conservation initiatives and ecosystem restoration projects that help maintain biodiversity while enhancing coastal protection functions and securing the

sustainability of natural resources. Functioning as critical blue carbon sinks, mangroves deliver essential ecosystem services; nonetheless, they constitute among the most vulnerable coastal ecosystems globally, heavily compromised by governance deficiencies and anthropogenic pressures (Alongi, 2023; Sasmito *et al.,* 2025; Friess *et al.,* 2024). The results demonstrate that the combination of mangrove-dominated systems in Sungai Lumpur Protected Forest is sustainable, although substantial disparities exist among the assessed sustainability dimensions. The economic dimension represents the most significant strength, followed by social and ecological sustainability, while institutional and technological dimensions remain considerably underdeveloped. This configuration is analytically significant because it challenges the simplistic characterization of silvofishery as either a conservation success or a conservation failure. Rather, mangrove-based silvofishery functions as a transitional socio-ecological system that yields dual socioeconomic and environmental co-benefits, albeit constrained by structural limitations that impede long-term resilience. The perspective is consistent with contemporary conceptualizations of silvofishery as an integrated production–restoration strategy that simultaneously supports aquaculture production, mangrove conservation, and blue carbon functions (Alongi, 2023). These findings advance the existing literature by providing empirical evidence that integration depends on specific conditions rather than occurring automatically. Sustainability outcomes depend on the compatibility between ecological processes, livelihood incentives, and governance arrangements. Therefore, silvofishery is not the end point but a path-dependent trajectory determined by institutional and contextual technology.

Economic dominance and livelihood rationality

The strong performance of the economic dimension indicates that mangrove-based silvofishery is a viable livelihood system, substantially contributing to household income, market access, and local economic welfare. Aligning with prior studies, this outcome demonstrates that maintaining ecological integrity underpins both the enhanced productivity and long-term economic viability of mangrove aquaculture (Rahman and Mahmud, 2018; Ofori *et al.,* 2023). Ecologically, mangrove litter contributes natural nutrients to aquaculture ponds and interacts synergistically with supplementary feed, thereby improving shrimp growth, survival rates, and feed conversion efficiency while reducing production costs (Mamidala *et al.,* 2023). These ecological–economic interactions help explain the superior economic performance observed. Mangrove-derived ecosystem services simultaneously enhance environmental quality and production efficiency, yielding economic benefits that transcend individual production units. Although previous investigations have mainly documented localized productivity gains, this study confirms that the benefits are absorbed at the system (or aggregate) level and impact multidimensional sustainability outcomes (Hardi *et al.,* 2025). This provides empirical evidence for policy narratives that uphold silvofishery as a more profitable option to complete mangrove conversion.

Ecological–social integration: Functional but not equivalent

The relatively high sustainability scores for the environmental and social dimensions indicate that mangrove ecosystems and aquaculture activities are functionally integrated within the study area. Functioning as both nutrient sources and critical habitats for top predators, mangroves support ecological processes where calcium- and nitrogen-rich organic matter is processed by aquatic invertebrates, bridging terrestrial energy flows with human subsistence consumption. At the social level, education, knowledge of local environmental conditions, and access to extension services strengthen adaptive capacity and encourage environmentally responsible management practices. Prior studies confirm that

while mangrove leaf litter decomposition promotes shrimp growth and survival, final product quality is governed primarily by adjacent land-use practices rather than litter composition (Alam *et al.,* 2021; Alam *et al.,* 2022; Mamidala *et al.,* 2023). These results suggest that mangrove–aquaculture systems do not spatially co-occur, but are biophysically linked (Gao *et al.,* 2022). However, the results also challenge over-optimistic assumptions. While silvofishery combines aquaculture practices with mangrove conservation, it fails to fully capture the ecological complexity of pristine mangrove forests, especially in terms of biodiversity, habitat configuration, and ecosystem service delivery (McSherry *et al*., 2023; Friess *et al*., 2024). Consequently, these systems constitute an intermediate ecological state situated between conventional aquaculture and natural mangrove habitats. This distinction is important because it prevents the overgeneralization of the conservation benefits associated with silvofishery system.

Institutional and technological constraints as systemic bottlenecks

Suboptimal performance within the institutional and technological dimensions severely limited overall sustainability. Consequently, governance efficacy and technological capability have emerged as the chief impediments to sustainability, eclipsing limitations tied to social acceptance or economic viability. Institutional constraints are mainly manifested as uncertainties over land use agreements in protected forestlands, which frequently result in competing claims over access and control of the resources. In addition, weak articulation of formal regulations with community-based practices leads to a lack of spatial and temporal coherence in which policies are implemented locally, thereby increasing the potential gaps in compliance. Deficiencies in institutional backing and stakeholder engagement constrain effective governance, monitoring, and collaborative management, thereby hindering the realization of sustainable resource stewardship goals. Previous studies from the wider socio-ecological system literature have shown that governance effectiveness and stakeholder alignment are vital for sustainability (Sukuryadi *et al.,* 2021; Cumming *et al.,* 2022). Technological limitations also represent a major barrier to sustainable mangrove crab aquaculture. Production systems remain heavily dependent on conventional and labour-intensive farming practices, resulting in low production efficiency. Moreover, constrained technological advancements in water and waste management compromise environmental oversight, thereby escalating vulnerability to pathogen proliferation and pollution. Other challenges in the sector growth are unorganized postharvest handling systems, including poor storage, processing, and distribution facilities, which reduce product quality and market competitiveness, impacting overall economic value of the sector. Nonetheless, persistent technological limitations in aquaculture represent formidable impediments to transitioning toward sustainable production, notably within small-scale and traditional frameworks (Turlybek *et al.,* 2025). This pattern reflects broader global patterns demonstrating that governance quality strongly mediates sustainability outcomes in coastal socio-ecological systems. The extent to which environmental pressures and management interventions translate into positive ecological outcomes depends largely on the effectiveness of governance institutions. Consequently, statutory regulatory safeguards are inherently inadequate in the absence of robust governance systems equipped to drive implementation, cross-sectoral, coordination, and adaptive management (Turschwell *et al.,* 2020; Cumming *et al.,* 2022). Similarly, continued mangrove degradation within protected areas has been linked to governance systems that fail to accommodate local socio-economic conditions, while adaptive and community-based management approaches generally produce more favourable conservation outcomes (Heck *et al.,* 2024). In the case of Sungai Lumpur, the principal problem extends beyond

regulatory absence to include institutional mismatch between land tenure and access rights as well as sustainable systems for production. Consequently, this misalignment erodes incentives for long-term capital investment, restricts technology uptake, and curtails organizational capacity for adaptive management. Consequently, the system faces the "moderate sustainability trapping" where some benefits do emerge, but radical systemic change fails to materialise. In contrast to previous RAPFISH–AHP applications that primarily evaluated fisheries sustainability or ranked management alternatives, this study demonstrates the value of integrating leverage analysis with strategic prioritization in a protected mangrove silvofishery landscape. Instead of proposing a new methodological approach, this study advances existing practice by operationalizing a diagnostic-to-decision framework that leverages empirical attributes to prioritize management interventions. This approach improves the practical usefulness of sustainability assessment because management recommendations are directly derived from the most influential sustainability constraints. Furthermore, incorporating ecotourism considerations broadens the applicability of the framework beyond aquaculture production toward multifunctional coastal landscape management. The robustness assessment further strengthens confidence in the reported sustainability indices. The low stress value combined with a high coefficient of determination confirms that the multidimensional scaling configuration robustly captures the underlying relationships among sustainability attributes. Furthermore, the close agreement between RAPFISH and Monte Carlo estimates suggests that the sustainability rankings are stable despite potential uncertainty associated with expert judgment and ordinal scoring. These results indicate that the integrated RAPFISH–AHP framework provides a reliable basis for identifying leverage attributes and prioritizing management interventions in mangrove-based silvofishery systems. Rather than signaling an absence of conservation policies, the comparatively low institutional sustainability score highlights systemic governance challenges. Mangrove-based silvofishery in the Sungai Lumpur Protected Forest is influenced by multiple institutions operating under different administrative mandates. These include the forest management units (FMU), which are responsible for day-to-day forest management and conservation activities. While watershed management agencies (WMA) hold the mandate for biodiversity conservation, the District Fisheries Service provides technical guidance for aquaculture advancement, in addition to overseeing environmental monitoring and regulatory compliance. Village governments facilitate local development and community participation, while community-based farmer groups implement silvofishery practices. The interplay among these institutional actors governs the operational success of mangrove conservation and sustainable resource stewardship.

Theoretical and policy implications

This study contributes to a larger dialogue around sustainable coastal resource management in several important ways. First, it presents silvofishery as a transitional option from an extractive mangrove conversion towards production systems more aligned with conservation goals. Such a viewpoint is consistent with socio-ecological systems theory, prioritizing adaptive pathways, resilience, and the prevention of undesirable system lock-in rather than linear trajectories toward predetermined end states (Ostrom, 2009; Turlybek *et al.,* 2016). Secondly, economic success does not equal institutional or technological strength with a multidimensional RA PFISH–AHP framework. These results counter reductionist sustainability paradigms centered on isolated dimensions, thereby emphasizing the imperative for holistic, integrated assessment approaches (Pitcher *et al.,* 2013). Third, the results challenge the assumption that integrating mangrove into aquaculture systems automatically produces positive sustainability outcomes. Instead, long-term sustainability is contingent

upon governance quality, secure land tenure security, and technological innovation—einforcing growing international evidence that the vulnerability of mangrove system is driven by institutional failure and anthropogenic pressures (Alongi, 2023; Sasmito *et al.*, 2025).

Toward transformative sustainability pathways

The results suggest that silvofishery systems are unlikely to achieve long-term sustainability without a combination of critical enabling conditions. These include i) secure and flexible land tenure arrangements that provide greater certainty while allowing for adaptive resourcing, ii) professionalized local institutions and management systems with a high capacity to coordinate action and action-integration across significant stakeholder groups, iii) carefully targeted, piloted technologies together with extension systems responsive to effective decision-making support for sustainable production practices, knowledge capitalization/extraction processes, as well as the iterative nature of adaptive learning. Therefore, subsequent policy frameworks must prioritize institutional capacity-building through the scaling of social forestry initiatives and adaptive governance structures, thereby fostering community engagement and sustained ecosystem management (Fadilah *et al.,* 2026). Wider implementation of eco-efficient aquaculture practices to increase productivity while protecting the environment requires more substantive policy efforts around technology transfer. Integrated policy frameworks are also needed to address the growing pressures in which conservation priorities and local livelihood objectives must be reconciled with sustainable production systems, and to reflect strategies for balanced coastal resource management resilient to natural disturbances (Yuliana *et al.,* 2026). Beyond their production and conservation functions, these findings hold direct implications for the sustainable development of coastal tourism. Mangrove ecosystems are being increasingly acknowledged as valuable ecotourism assets, especially in tropical coastal areas where wetlands provide nature-based tourism and livelihoods for local communities (Spenceley, 2017). With a moderate ecological sustainability score of 68, the findings suggest that mangrove ecosystems possess sufficient ecological health to accommodate low-impact ecotourism initiatives (Ketaren *et al.,* 2026). Meanwhile, the robust social dimension (73.9) represents community capacity for cohesion and participation, the two most essential foundations needed for developing tourism. Conversely, the comparatively low institutional (40.66) and technological (32.53) sustainability scores show significant barriers to successful tourism development. Deficits in secure land tenure, formal regulatory licensing, and managerial expertise heighten the vulnerability of tourism development to informality, socio-environmental conflict, and economic instability. Previous studies have also reported that poorly governed ecotourism can lead to environmental degradation and unequal benefits. Therefore, priority interventions identified by the AHP analysis concerning institutional strengthening and technological upgrading should focus on developing sustainable tourism development strategies. The strategies should push tourism management towards emphasis on establishing more community-beneficial governance structures, as well as inclusive local stakeholder input/over sight over decision-making and resource management (Fadilah *et al.,* 2026). Transparent and equitable benefit-sharing mechanisms are needed to guarantee the fair allocation of profits generated from tourism activities among local communities. Moreover, the integration of technological enhancements should be facilitated through digital platforms and smart tools dedicated to promotional marketing, visitor tracking, and comprehensive destination management. Tourism development should generally include environmentally sensitive and low-impact infrastructure such as boardwalks, eco-centers, and other structures that facilitate visitor use while minimizing ecological disturbance to the surrounding environment. Moreover, silvofishery products, including sustainably

farmed shrimp, milkfish, and crabs, can be marketed as eco-certified goods in local tourism supply chains (Yuliana *et al.,* 2026). Consequently, a direct correlation is established between ecologically responsible production and tourism demand, thereby enabling value chain diversification and mitigating the pressure on aquaculture expansion. Therefore, the sustainability of silvofishery systems in protected areas will increasingly depend not only on biophysical potential but also the ability of governance systems to translate ecological benefits into economically viable, adaptive socio-ecological systems that include social equity considerations.

Barriers to the adoption of sustainable mangrove-based silvofishery

The relatively low institutional and technological sustainability scores indicate that the barriers to adopting improved mangrove-based silvofishery extend beyond production techniques. These barriers are multidimensional, involving social, financial, institutional, and technical constraints that collectively limit farmers adaptive capacity and long-term investment decisions. Socioeconomically, variations in educational attainment, restricted technical knowledge, and inequitable distribution of extension services constrain the adoption propensity and operational capacity required for advanced silvofishery practices. Although community participation is relatively strong, knowledge transfer regarding eco-efficient aquaculture technologies and sustainable coastal management remains insufficient. Financial barriers are associated with the relatively high initial investment required for improved water management systems, environmentally friendly aquaculture technologies, waste treatment facilities, and post-harvest infrastructure. Inadequate access to affordable credit and financial capital constitutes a significant barrier to technological adoption, disproportionately affecting small-scale agricultural producers. Institutional barriers constitute the most critical challenge identified in this study. Unclear land tenure arrangements within protected forest areas reduce investment security, while fragmented institutional responsibilities and limited coordination among government agencies weaken policy implementation and technical assistance. These governance constraints also reduce incentives for long-term mangrove restoration and sustainable resource management. Key technical barriers include reliance on traditional aquaculture methods, limited water quality monitoring, inadequate waste remediation infrastructure, and inefficient post-harvest handling, reducing production efficiency and increasing environmental risks. Although this study did not directly assess community-based ecotourism, similar barriers may constrain its development. Weak governance, insecure land tenure, limited technical capacity, inadequate tourism infrastructure, and poor institutional coordination may hinder local communities from fully benefiting from ecotourism. Therefore, strengthening institutional governance, improving access to capital and technology, and expanding community capacity-building are essential for advancing sustainable silvofishery systems and community-based ecotourism. Community-based mangrove ecotourism may provide additional livelihood opportunities and strengthen conservation incentives, but poorly planned tourism development may also generate environmental pressures on sensitive coastal ecosystems. In the absence of proper regulation, elevated visitor numbers can lead to the trampling of mangrove seedlings, wildlife disturbance, solid waste accumulation, water pollution, habitat fragmentation, and heightened pressure on fisheries resources, particularly during peak tourism seasons and in ecologically fragile coastal habitats with limited management capacity. These impacts may ultimately reduce ecosystem integrity, weaken the long-term resilience of mangrove landscapes, and diminish ecosystem services, thereby compromising biodiversity, coastal protection, carbon sequestration, fisheries productivity, and livelihoods.

Study limitations

This study has several limitations, first, RAPFISH relies partly on expert judgment, introducing subjectivity in attribute scoring. Second, purposive sampling may limit statistical generalizability. Third, owing to the localized nature of the sampled protected mangrove landscape, extrapolation of these results to alternative Indonesian coastal systems warrants careful consideration. Although AHP improves strategic prioritization, pairwise comparisons remain dependent on expert perspectives.

CONCLUSION

While mangrove-based silvofishery systems are widely championed for aligning economic livelihoods with coastal conservation, empirical sustainability evaluations remain sparse. By bridging this gap, this study reveals that economic viability is the most resilient dimension of sustainability; however, overall system performance is undermined by institutional bottlenecks such as lax governance, precarious land tenure around protected areas, and insufficient local technical capacities. As demonstrated by the integrated RAPFISH–AHP framework deployed in this assessment, purely economic incentives are insufficient to guarantee long-term systemic resilience. Instead, silvofishery must be conceptualized as a dynamic socio-ecological transition pathway rather than a final sustainability endpoint. Shifting the system toward comprehensive resilience and adaptability requires strategic public interventions and policy frameworks that tightly integrate ecological sustainability with economic incentives. This transition pathway is further illuminated by the emerging potential of the Sungai Lumpur Protected Forest as a community-based mangrove ecotourism destination. The region's moderate ecological sustainability and strong social foundations offer a favorable baseline for low-impact tourism development. However, without resolving pre-existing governance and tenure constraints, premature tourism initiatives risk becoming informal, inefficient, or actively detrimental to primary conservation objectives. Consequently, ecotourism must be systematically incorporated into broader, hierarchy-driven management frameworks. To operationalize these insights, coastal managers and policymakers must adopt a diagnostic-to-decision approach, allocating resources toward critical structural priorities: securing land tenure rights to provide institutional stability, developing local-level technical capacities, and scaling up eco-efficient aquaculture technologies to enhance ecosystem-mediated productivity. This study has several limitations that provide directions for future research. Its cross-sectional design offers a temporal snapshot, limiting assessment of long-term ecological dynamics and feedbacks within mangrove socio-ecological systems. In addition, the case study constrains generalizability to coastal regions with different institutional and biophysical conditions. Future studies should adopt longitudinal, multi-site approaches across broader spatial scales, integrating interdisciplinary methods combining biophysical simulation with policy assessment. Additionally, future studies should examine the integration of silvofishery and community-based ecotourism by evaluating visitor preferences, tourism carrying capacity, and commercialization opportunities for eco-certified aquaculture products within local tourism value chains.

AUTHOR CONTRIBUTIONS

B. Utomo conceived, designed, and conducted the experiment, as well as overseeing sample collection and analytical measurements, and preparing the manuscript draft. M. Dimyati, the corresponding author, supervised the first author, conceived the study idea, designed the experiment, interpreted the results, and finalized the manuscript. R. Dewanti also supervised the first author and contributed to setting up the experimental arrangements and data analysis. E. Trihatmoko assisted with the design of the experiment and analytical measurements. P. Utami interpreted the results and revised the manuscript draft.

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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

'	Minutes
%	Percent
°	Degree
AHP	Analytic hierarchy process
CBS	Central Bureau of Statistics
CI	Consistency index
CR	Consistency ratio
FMU	Forest management units
MDS	Multidimensional scaling
PPEM	Environmental protection and management
RAPFISH	Rapid appraisal for fisheries
RMS	Root mean square
SPSS	Statistical package for the social sciences
WMA	Watershed management agencies
WPMA	Watershed and protected forest management agency
n	Total number of attributes
x_i	Score of the ith attribute
$\bar{x}$	Mean value of all attributes
$(x_i - \bar{x})$	Deviation of each attribute from the mean

$\sqrt{}$	Summation over all attributes
w_i	Weight of element i
w_j	Weight of element j
a_{ij}	Relative importance of element i compared to j
$\lambda_{\max}$	Maximum eigenvalue of the comparison matrix
RI	Random Index, depending on matrix size
d_{ij}	Observed Distance

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Panel data analysis of energy transition, circular economy and green innovation as drivers of environmental sustainability in the European Union

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study examines the determinants of environmental sustainability within 27 European Union countries from 2014 to 2024, capturing the impact of critical structural and policy changes. This study systematically examines five dimensions of sustainability. It first determines the influence of energy transition variables on per capita carbon emissions, subsequently examines the effect of circular economy strategies on resource productivity and finally evaluates the non-linear link between economic growth and carbon dioxide emissions is identified using the Environmental Kuznets Curve framework. The study objectives were to explore five empirical models concerning the European Unions-27 countries and the impacts of the energy transition on per capita carbon emissions and role of circular economy in enhancing resource efficiency. Additionally, it tests the validity of the Environmental Kuznets Curve theory and income turning point.

METHODS: A complete panel data set that comprises 297 country year observations is used. The empirical methodology is based on robust fixed effects regression models. Principal component analysis is used on six standardized variables. Principal component analysis serves as a robust statistical framework for constructing environmental sustainability index. The socio-economic factors affecting environmental sustainability index are further analyzed. Validation of the model through diagnostic tests is performed.

FINDINGS: Renewable energy consumption mitigates carbon dioxide emissions, while energy intensity and environmental tax revenues emerge as critical determinants of sustainability. The presence of strong empirical evidence in support of the inverted-U shape of the Environmental Kuznets Curve theory is confirmed. These findings indicate that most European Unions' member have progressed to the declining phase of the curve. According to the composite index, Sweden, Finland, and Austria belong to the best performers. Simultaneously, the lowest performance ratings are observed in Malta, Romania, and Cyprus.

CONCLUSION: Offering critical empirical insights for European policymakers, this evidence underscores the need to prioritize reductions in energy intensity while supporting the strategic utilization of fiscal environmental mechanisms. Implementation of targeted green transition frameworks is highly recommended.

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INTRODUCTION

Environmental sustainability is one of the main issues of the present time, and the European Union (EU) has managed to take a leading role in the struggle against climate change and sustainable development on a global scale. The European green deal (EGD), introduced in December 2019, is the ambitious strategy of the EU aimed at making Europe the first climate-neutral continent by 2050 (European Commission, 2019). The Green Deal encompasses diverse policy areas, specifically targeting energy sector decarbonization, the promotion of circular economy (CE) principles, environmental enhancement, and the stimulation of green innovation. One of the objectives of the Green Deal for the next decade is to reduce net greenhouse gas emissions by at least 55 percent (%) by 2030 compared to 1990 (European Commission, 2021). Although the EU maintains a cohesive strategic framework, significant disparities remain apparent across individual member states' environmental records. While countries like Sweden and Finland have demonstrated significant successes in their use of renewable energy sources and reductions in carbon emissions, some countries in Eastern Europe, which are also members of the Union, remain highly dependent on fossil fuels and experience severe environmental problems (Pylak *et al.,* 2024) These differences are apparent in the most recent Eurostat data, which reveals wide discrepancies between countries' use of renewable energy sources (from less than 10% in Malta to almost 60% in Sweden) and carbon dioxide (CO_2) emissions per capita (Sixfold discrepancy across the EU-27) (Eurostat, 2024). The theories foundation of this study draws upon established principles within the field of environmental economics. According to the Environmental Kuznets Curve (EKC) hypothesis, there exists a negative relationship between economic development and environmental degradation, implying that at early stages, pollution levels grow as income rises, but later, decrease due to introduction of clean technologies and environmental policies (Grossman and Krueger, 1991). The Porter hypothesis posits that stringent environmental regulations can stimulate innovation and enhance competitiveness, thereby yielding mutually beneficial outcomes for both ecology and the economy (Porter and van der Linde, 1995). Moreover, the theory of directed technical change highlights the possibility of directing innovation to environmentally friendly technologies with the help of appropriate policy tools (Acemoglu *et al.,* 2012). This study contributes significantly to the existing literature in environmental economics in several keyways. First, a comprehensive panel database of 27 EU member states is created for an 11-year period from 2014 to 2024. This database integrates key metrics reflecting energy transition, the circular principles economy, and environmental quality. Additionally, indicators tracking the green economy and socio-economic development are included. This approach captures both cross-country variations and temporal dynamics within a unified dynamic. Second, the use of fixed effects (FE) panel regression models helps to account for the unobserved heterogeneity and test five different research hypotheses that are interrelated. Third, an ESI is developed via principal component analysis (PCA), providing a framework to rank and evaluate cross-country performance The current study makes four distinct contributions to existing literature. First, unlike prior studies that examine energy transition, circular economy, or green innovation in isolation (Armeanu *et al.,* 2017; Simion *et al.,* 2025; Ahmed *et al.,* 2019), By utilizing a unified panel framework for the EU-27, this study systematically evaluates all five dimensions to provide a comprehensive analysis of environmental sustainability drivers. Second, the study period (2014-2024) captures the implementation of major EU environmental policies including the European Commission,

(2019), the Coronavirus 2019 (COVID-19) pandemic (2020-2021), and the European Commission, (2022) offering the first empirical assessment of these policy impacts. Third, methodologically, a system generalized method of moments (GMM) approach (Blundell and Bond, 1998) is employed alongside fixed-effects regression to address endogeneity concerns. Additionally, Driscoll and Kraay (1998) robust standard errors are estimated to adjust for cross-sectional dependence (CD) among EU member states. Fourth, an ESI is constructed utilizing principal component analysis (PCA), with its diagnostic validity confirmed via the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test. Furthermore, bootstrap confidence intervals are computed for the Environmental Kuznets Curve (EKC) turning point, ensuring methodological rigor. The selection of the 2014-2024 study period is grounded in several policy milestones. The year 2014 marks the launch of the 2030 climate and energy framework (European Commission, 2014), which established binding targets for renewable energy and greenhouse gas reductions. With the introduction of the 2015 Circular Economy Action Plan, the European Commission (2015) launched its first comprehensive strategy for resource efficiency. The 2019 EGD (European Commission, 2019) set the ambition of climate neutrality by 2050, while the COVID-19 pandemic in 2020-2021 created both environmental disruptions and green recovery opportunities. Finally, the 2022 REPowerEU strategy responded to the Russia-Ukraine energy crisis with accelerated renewable energy deployment targets. To account for these structural breaks, COVID-19 (2020-2021) and energy crisis (2022-2024) dummy variables are included in all regression models. The nexus between renewable energy consumption and carbon emissions has been extensively examined in environmental economics literature. The theory underlying the connection comes from the concept of substitution effects as the rise in the use of renewable energy results in lower fossil fuel energy use; thus, there will be lower greenhouse gas emissions as a result. Utilizing a panel Granger causality test, Armeanu *et al*. (2017) examined the causal relationships among total energy consumption, renewable energy deployment, and CO_2 emissions across the EU countries, demonstrating that renewable energy significantly mitigated carbon emissions, particularly after 2010. This research analyzed 27 EU member states in the period of 1990-2014. Insights into the dynamics of CO_2 emissions in Europe in the context of the COVID-19 era were provided by Jawadi *et al.* (2023), who used annual data of 25 European countries from 2010 to 2020. The findings demonstrate that emissions are highly sensitive to volatility in oil and coal prices, while also being influenced by underlying production cycles. Particularly, the authors revealed that investment in sustainable development and the use of renewable energy have a substantial negative effect on CO_2 emissions. Regarding country-level evidence, Shahbaz *et al.* (2016) showed that one percent growth of renewable energy consumption causes approximately 0.15 percent reduction of carbon emissions in developed countries, taking Malaysia as a case study with the help of stochastic impacts by regression on population, affluence, and technology (STIRPAT) model. Kongkuah and Alessa (2025) analyzed data for 184 countries and proved that the efficiency of renewable energy policies is determined not only by the existing energy structure but also by institutional environment. This suggests that the EU strategy of establishing differentiated renewable energy targets based on member states' varying baseline conditions is empirically grounded. Additionally, the mediating role of digitalization has been examined within the context of energy consumption and emissions dynamics. A study by Dimian *et al.* (2026) has investigated the influence of digitalization on greenhouse gas emissions through renewable energy consumption in EU-27 countries from 2000 to 2021, revealing that digitalization reduces greenhouse gas emissions via renewable energy pathways. The mediation analysis underscores

that digital technologies are essential for implementing the green energy transition, which gained pivotal importance within the REPowerEU framework in the wake of the 2022 energy crisis. The CE approach, which is characterized by waste reduction, recycling, and resource efficiency, has attracted attention in the EU policymaking process due to the approval of the Circular Economy Action Plan of 2015 and another one in 2020. Geissdoerfer *et al.* (2017) defined the CE as the regenerative approach that reduces resource consumption and waste generation while ensuring economic performance. Systematic reviews by Hereu-Morales *et al.* (2024) and Stefanis *et al*. (2024) establish that the CE model operates as a distinct sustainability framework rather than a conventional waste management approaches, a perspective corroborated by Simion et *al*. (2025) through their analysis of CE indicators. On resource efficiency in EU member states during 2012–2023 based on panel quantile regression analysis. According to their findings, there are notable differences between the impact of investments, gross value added, patents, material footprint, and circular material use rate on resource efficiency in various parts of the distribution. The findings indicate that while capital investments exert a more pronounced impact at lower levels of resource productivity, patent-based innovation plays an essential role at higher productivity thresholds. The highest resource efficiency was achieved in the Netherlands, Italy, and Luxembourg, while Finland, Bulgaria, and Romania had the lowest values. The monitoring framework of the EU's CE was introduced by the European Commission (2018) through indicators such as material footprint, resource productivity, waste generation, recycling and circular material use rate. Studies using the methodology of preference ranking organization method for enrichment evaluations (PROMETHEE) have indicated that the five countries ahead in terms of CE are Germany, France, Italy, the Netherlands and Spain while those having the most difficult conditions are Cyprus, Romania, Estonia, Finland and Bulgaria (Remeikienė *et al.,* 2025). Circular material use rate in the EU in 2023 is reported to have reached 11.8% as against the goal of 23.4 % in 2030. Over the last decade, the EU's CE policy framework has undergone substantial transformation. The amendment to the Waste Framework Directive in 2018 included targets of 65% recycling and preparation for reuse of municipal waste until 2035 and a maximum of 10% landfilling (Fitch-Roy *et al.,* 2019; Shetty *et al.,* 2025). These legislative adjustments marked a structural shift from traditional linear end-of-pipe waste disposal toward a closed-loop circular economy framework within the European Union. Under the directive's October 2025 revision, extended producer responsibility schemes for the textile sector have become compulsory, alongside optimized reporting regulations (Boschmeier *et al.,* 2023; Paleari, 2025). These mandatory frameworks compel manufacturers to finance end-of-life sorting and fiber-to-fiber recycling networks, altering the operational landscape of the fast fashion industry. This forms the policy backdrop for analysis of CE indicators and resource productivity. According to the EKC theory, which was put forward by Grossman and Krueger (1991) in their groundbreaking paper on the environmental consequences of the North American Free Trade Agreement, there exists an inverse-U curve relationship between economic growth and environmental degradation. The theory is grounded in the premise that during early developmental phases, rising incomes correlate with increased pollution due to rapid industrialization and the prioritization of economic growth over environmental concerns. However, after reaching a particular level of income, there arises a desire for clean environments, and as such, emissions decrease despite growing gross domestic product (GDP). The early empirical research carried out by Shafik and Bandyopadhyay (1992) and Panayotou (1993) offered inconsistent findings regarding the validity of the EKC hypothesis based on pollutants and

countries studied. Specifically, Shafik and Bandyopadhyay (1992), demonstrated that the relationship between income and environmental degradation depends heavily on the specific pollutant examined, noting an inverted U-shaped relationship for sulfur dioxide alongside monotonic relationships for alternative pollutants. Panel data analysis conducted recently by Kaika and Zervas (2013) and Ahmed *et al*. (2019) on developed countries has found stronger support for the EKC, with the turning point coming in per capita GDP levels from Euro (EUR) 17,585 to EUR 35,170. In terms of the EU, the applicability of EKC is especially relevant since there is great disparity in GDP per capita across EU countries, ranging from more than EUR 96,717for Luxembourg to less than EUR 21,981 for Bulgaria. An extensive study on environmental sustainability in connection with the EGD demonstrated that, although the general trend supports the Environmental Kuznets Curve (EKC) hypothesis, considerable disparities exist across different policy measures and groups of countries. Crucially, the analysis concludes that EGD efficacy hinges upon whether poorer member states receive the necessary structural support to leapfrog traditional, high-emission stages of economic development. EKC research has also progressed to include other factors apart from income into its framework. Some of the factors considered in recent literature have been energy mix, trade liberalization, foreign direct investments, institutional quality, and technological innovations. The empirical consensus indicates that the EKC effect is contingent upon the policy decisions and institutional frameworks, rather than being an intrinsic outcome of economic development per se. Such a conditional EKC model has several implications in terms of EU policies, as they show that active environmental policies could bring down the turning point. Green innovation, which consists of research and development research and development (R&D) investments, green patents, and environmentally sound technological changes, is a significant factor in promoting sustainability. Acemoglu *et al*. (2012) underscored the importance of technical change in environmental shifts, arguing that carbon taxes and subsidies for R&D on environmentally friendly innovations would redirect innovation from carbon-heavy industries. They illustrate that transient policy interventions can generate path-dependent, permanent effects by shifting technological trajectories and lowering long-term environmental mitigation costs. Ghisetti and Rennings (2014) explored the link between environmental innovations and profitability based on the data from the German innovation survey and found that environmental policies, especially environmental tax policies, promote green innovation and environmental quality. Environmental innovations are broadly categorized into process and product innovations; the former aims to reduce resource depletion and environmental emissions, while the latter centers on creating ecologically superior products. The authors conclude that the Porter Hypothesis was supported in the case of environmental regulations. However, Rubashkina *et al*. (2015) have pointed out that there is a complicated relationship between innovation and environment which can imply significant time lags. The analysis of European manufacturing industries has shown that while the impact of environmental regulation on innovation is positive, environmental achievements can emerge only after several years. As the above-mentioned time aspect is especially important for the case in point, it should be noted that the 2014-2024 period encompasses implementation of newre EU environmental policies, including the 2030 Climate and Energy Framework and EGD. Environmental taxation has been extensively studied as a policy instrument for fostering eco-innovation. Data from Eurostat reveal that environmental tax revenue in the EU reached EUR 341.5 billion in 2023, constituting 2.0% of GDP and 5.1% of total government revenue from taxes and social contributions (Eurostat, 2024). Almost four-fifths of environmental tax revenue were comprised by

energy taxes, CO_2-related taxes having risen from EUR 15 billion in 2017 to more than EUR 50 billion in 2023. This financial mechanism serves a dual purpose: acting as an economic disincentive for pollution while simultaneously channeling revenues back into innovation support. The bibliometric analysis on the topic of environmental sustainability in relation to the European Green Deal (EGD) by Stefanis *et al.* (2024) revealed that for ecological sustainability and the realization of the ambitious goals of the green deal, significant actions must be made through policy, innovation, and investment in green technologies. In the domain of cleaner energy systems, this technological push is exemplified by the integration of explainable machine learning architectures to accurately predict CO_2 deposition conditions during cryogenic processing (Hsu *et al.,* 2025). Furthermore, executing these policy and technological goals successfully requires robust structural modeling to mitigate corporate greenwashing, thereby ensuring that industrial investments yield genuine environmental benefits (Daga *et al.,* 2025). The study emphasizes that the impact of green innovation elements varies across EU member states, reflecting the complex relationships between economic development, innovation potential, and environmental outcomes. Considering these facts, the study uses multi-faceted approach that analyses green innovation along with energy transition and CE indices. This study aims to evaluate five key empirical dimensions across the EU-27' first, to analyze the impact of the energy transition on per capita carbon emissions; and second, to assess the circular economy's contribution to resource productivity; third, to test the validity and income turning point of the EKC hypothesis; fourth, to quantify the impacts of green innovation and environmental taxation on fine particulate matter ($PM_{2.5}$), and overall air quality metrics and finally, to identify the socio-economic determinants of a PCA-constructed ESI for cross-country benchmarking. This study analyzed 27 EU member states in the period of 1990-2014 and performed in Oman which is performed in 2026.

MATERIALS AND METHODS

Data sources and variables

This study uses a balanced panel dataset which covers 27 member countries of EU between the years 2014 and 2024 (297 observations). The dataset is collected from Eurostat, which is the statistical office of the EU, in addition to World Bank Development Indicators. This specific timeframe was selected to account for the impact of major EU environmental policies, including the circular economy initiatives and regulatory frameworks established by the European Commission (2014, 2015, 2019, 2022). It is worth noting that the UK is not included in this sample after its exit from the EU in 2020. The variables have been classified in five conceptually distinct classes. Energy transition variables comprise the share of renewable energy in gross final energy consumption (%), energy intensity measured in megajoules per United States Dollar (USD) GDP at purchasing power parity (PPP), and the renewable electricity share of total electricity production (%). CE related variables comprise the recycling rate of municipal waste (%), and resource productivity (measured in Euro per kilogram (kg) of materials consumed). Environmental quality metrics are captured by $PM_{2.5}$ air pollution exposure in microgram per cubic meter ($\mu g/m^3$), CO_2 emission, and total forest cover as a percentage of land area. The green economy variables consist of environmental goods and services sector (% of GDP), and environmental tax revenue (% of total tax revenue). Lastly, socio-economic control variables are GDP per capita PPP, constant 2021 international USD, and R&D expenditure (% of GDP).

Econometric models

The FE panel regression models were employed to account for unobserved country-specific heterogeneity that may be correlated with the independent variables. Based on the Hausman

test, which consistently rejects the null hypothesis of no correlation between country-specific effects and the regressors (Eq. 1), the FE approach is preferred over the random effects model (Baltagi, 2021):

$$Y_{it} = \alpha + \sum_{j=1}^{k} \beta_j X_{jit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where: Y_{it} is the dependent variable for country i at time t, X_{jit} are the independent variables, μ_i represents country fixed effects, λ_t represents year fixed effects, and ε_{it} is the error term. Heteroskedasticity-robust standard errors are used to address potential violations of homoskedasticity.

Model 1 examines the impact of energy transition on carbon emissions, using Eq. 2 (Busu and Nedelcu, 2021):

$$\text{CO2}_{it} = \alpha + \beta_1 \text{REN}_{it} + \beta_2 \text{EI}_{it} + \beta_3 \text{REN_ELEC}_{it} + \beta_4 \text{GDP}_{it} + \beta_5 \text{R\&D}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Model 2 assesses the CE determinants of resource productivity, using Eq. 3 (Simion *et al.*, 2025):

$$\text{RES_PROD}_{it} = \alpha + \beta_1 \text{RECYCLE}_{it} + \beta_2 \text{EGSS}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{GDP}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Model 3 tests the Environmental Kuznets Curve hypothesis, using Eq. 4 (Odei *at al.*, 2025):

$$\text{CO2}_{it} = \alpha + \beta_1 \text{GDP}_{it} + \beta_2 \text{GDP}_{it}^2 + \beta_3 \text{REN}_{it} + \beta_4 \text{EI}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Model 4 evaluates green innovation effects on environmental quality, using Eq. 5 (Aneja *et al.*, 2024):

$$\text{PM2.5}_{it} = \alpha + \beta_1 \text{R\&D}_{it} + \beta_2 \text{EGSS}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{REN}_{it} + \beta_5 \text{GDP}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Model 5 constructs and explains the composite ESI, using Eq. 6 (Jain and Mohapatra, 2023):

$$\text{ESI}_{it} = \alpha + \beta_1 \text{GDP}_{it} + \beta_2 \text{R\&D}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{EGSS}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

ESI is constructed using PCA on six standardized variables: renewable energy share, recycling rate, resource productivity, forest area, inverted $PM_{2.5}$ exposure, and inverted CO_2 emissions. PCA is a dimensionality reduction technique that transforms correlated variables into a set of uncorrelated principal components. To construct the composite index, the first principal component was retained, as it explains the largest proportion of total variance. This approach has been widely used in sustainability index construction, as it avoids subjective weighting while capturing the common variation across environmental indicators.

Diagnostic tests

To ensure the robustness of the empirical findings, several diagnostic tests were performed. These include the Jarque-Bera test for normality of the residual term, the Durbin Watson statistic for first-order autocorrelation, and the variance inflation factor (VIF) for the detection of multicollinearity amongst the regressors. Additionally, the Pesaran (2021) cross-sectional dependence (CD) test is reported to account for correlated error structures across EU countries. Furthermore, the Levin-Lin-Chu (LLC) panel unit root test is utilized to establish stationarity, alongside the Wooldridge test for serial correlation and the Breusch-Pagan test for heteroskedasticity. To address CD in inference, Driscoll and Kraay (1998) standard errors are reported as the primary method. Furthermore, to mitigate potential endogeneity concerns and ensure the validity of our findings, a System GMM (Blundell and Bond, 1998) estimation is employed as a robustness check Furthermore, the empirical strategy includes subgroup analyses to contrast the EU-15 and newer EU-13 cohorts, the

estimation of lagged specifications to account for temporal policy delays, and the calculation of bootstrap confidence intervals for the EKC turning point. Other statistics that will be reported include the F-statistics for the joint significance of the explanatory variables and the adjusted R-squared measure of goodness of fit.

RESULTS AND DISCUSSION

Descriptive statistics and correlation analysis

Table 1 presents the descriptive statistics for all variables used in the analysis. The average renewable energy share across EU-27 stands at 23.29%, though substantial cross-country variation exists, ranging from a low of 4.38% in Malta to a high of 58.73% in Sweden. CO_2 emissions per capita average 5.83 metric tons, with Luxembourg (14.59 tons) and Estonia showing the highest levels. The average PM2.5 exposure is 11.27 micrograms per cubic meter ($\mu g/m^3$), well above the World Health Organization (WHO) guideline of 5 $\mu g/m^3$, highlighting the continued air quality challenges in the EU. Given the presence of CD confirmed by Pesaran CD tests. To address potential endogeneity from bidirectional causality, system GMM (Blundell and Bond, 1998) is employed as a robustness check. COVID-19 (2020-2021) and energy crisis (2022-2024) dummies are included in all models to account for structural breaks. The correlation matrix given in Table 2 highlights several important correlations. The proportion of renewable energy usage has negative correlations with CO_2 emission (r = -0.37) and PM2.5 pollution (r = -0.60), indicating that those nations which use more renewable energy enjoy environmental benefits as well. Environmental taxes have strong positive correlations with resource efficiency (r = 0.84) and recycling ratio (r = -0.22), highlighting the efficiency of fiscal policies. Per capita GDP has positive correlations with resource productivity (r = 0.84) and R&D spending (r = 0.44). Fig. 1 displays the correlation heatmap for all analyzed variables, illustrating the respective bivariate relationships. The intensity of the color shading corresponds to the magnitude of the correlation coefficients, where red denotes a positive association and blue signifies a negative relationship, thereby facilitating visual interpretation of interactions.

Model 1: Energy transition and carbon emissions

Table 3 outlines the empirical results for Model 1, demonstrating that the energy transition indicators exert a significant impact on carbon emission levels. The variable of the share of renewable energy has a statistically significant and negative beta value (-0.052, $p < 0.10$), indicating its adverse influence on sustainability. Specifically, a one-percentage-point increase in the share of renewable energy is associated with a 0.052-ton reduction in per capita CO_2 emissions. This finding aligns with the empirical evidence reported by Jawadi *et al.* (2023).

Table 1: Descriptive statistics of environmental sustainability variables

Variable	N	Mean	Standard deviation (SD)	Min.	Max.	Skew
Renewable energy share (%)	297	23.29	11.94	4.38	58.73	0.85
Energy intensity (MJ/€GDP)	297	3.38	0.73	1.76	5.61	0.26
Renewable electricity (%)	297	34.38	17.71	4.93	81.28	0.54
Recycling rate (%)	297	39.51	14.54	4.93	68.66	-0.36
Resource productivity (EUR/kg)	297	2.33	0.78	0.81	4.09	0.27
$PM_{2.5}$ exposure ($\mu g/m^3$)	297	11.27	3.31	3.88	19.73	-0.09
CO_2 emissions per capita (tons)	297	5.83	2.44	2.45	14.59	1.32
Forest area (% of land)	297	35.16	16.79	1.02	76.35	0.42
Env. goods and services (%GDP)	297	2.56	0.59	1.46	4.06	0.40
Environmental tax (%total)	297	7.11	0.91	4.99	9.78	0.13
GDP per capita (USD, PPP)	297	39,490	17,358	17,292	111,127	1.89
R&D expenditure (% GDP)	297	2.03	0.92	0.49	4.16	0.48

Table 2: Pearson correlation matrix of environmental sustainability variables

Variable	REN	EI	REL	REC	RPR	PM25	CO_2	FOR	EGS	ETX	GDP	RD
REN	1.00	-0.11	0.79	0.27	0.06	-0.60	-0.37	0.68	0.50	0.29	-0.13	0.47
EI	-0.11	1.00	-0.37	-0.23	-0.57	0.49	0.25	0.26	-0.45	0.30	-0.47	-0.28
REL	0.79	-0.37	1.00	0.32	0.19	-0.41	-0.44	0.36	0.53	0.18	-0.01	0.42
REC	0.27	-0.23	0.32	1.00	0.75	-0.42	0.24	0.27	0.73	-0.22	0.53	0.81
RPR	0.06	-0.57	0.19	0.75	1.00	-0.52	0.32	-0.09	0.80	-0.38	0.84	0.73
PM_{25}	-0.60	0.49	-0.41	-0.42	-0.52	1.00	0.05	-0.38	-0.65	0.21	-0.40	-0.51
CO_2	-0.37	0.25	-0.44	0.24	0.32	0.05	1.00	-0.02	0.05	-0.17	0.53	0.11
FOR	0.68	0.26	0.36	0.27	-0.09	-0.38	-0.02	1.00	0.25	0.12	-0.11	0.37
EGS	0.50	-0.45	0.53	0.73	0.80	-0.65	0.05	0.25	1.00	-0.07	0.49	0.90
ETX	0.29	0.30	0.18	-0.22	-0.38	0.21	-0.17	0.12	-0.07	1.00	-0.52	-0.12
GDP	-0.13	-0.47	-0.01	0.53	0.84	-0.40	0.53	-0.11	0.49	-0.52	1.00	0.44
RD	0.47	-0.28	0.42	0.81	0.73	-0.51	0.11	0.37	0.90	-0.12	0.44	1.00

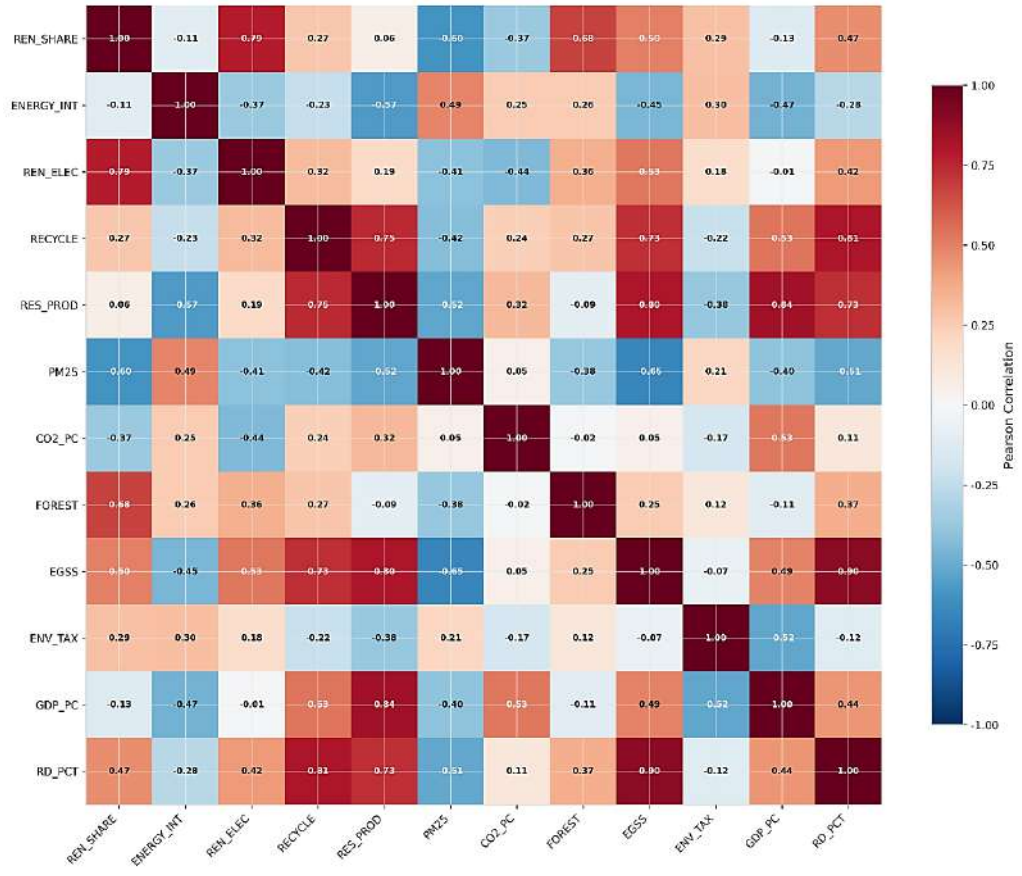

Fig. 1: Correlation matrix heatmap of environmental sustainability variables (EU-27, 2014-2024)

As presented in Table 3, the renewable energy share contributes significantly to the reduction of carbon emissions. Conversely, while energy intensity exhibits a positive coefficient (beta = 0.200), its impact on emissions is not statistically significant. GDP per capita has statistically significant negative coefficient (beta = -0.000, $p < 0.01$), which implies that richer countries in Europe have fewer carbon emissions, confirming the hypothesis of decoupling. The model accounts for 98.2% of variation in CO2 emissions (R-squared = 0.982). To address potential endogeneity arising

Table 3: Energy transition impact on carbon emissions (Model 1)

Variable	Coefficient	Standard error (SE)	p-value
Renewable energy share (%)	-0.052*	0.027	0.055
Energy intensity (MJ/€GDP)	0.200	0.354	0.572
Renewable electricity (%)	0.028	0.020	0.148
GDP per capita (USD, PPP)	-0.000***	0.000	0.000
R&D expenditure (% GDP)	-0.168	0.521	0.748
R-squared	0.982		
Adj. R-squared	0.979		
F-statistic	397.65***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

from bidirectional causality between renewable energy adoption and CO_2 emissions, Model 1 was re-estimated using the System GMM approach (Blundell and Bond, 1998). To mitigate simultaneity bias, the GMM estimator utilizes lagged levels as instruments for the difference equation alongside lagged differences as instruments for the level equation. The system GMM results confirm that renewable energy share has a statistically significant negative effect on CO_2 emissions (beta = -0.068, $p < 0.05$), which is stronger than the FE estimate (beta = -0.052, $p < 0.10$). The COVID-19 dummy shows a significant reduction in emissions during 2020-2021 (beta = -0.452, $p < 0.01$), while the energy crisis dummy (2022-2024) is not statistically significant. These findings strengthen the causal interpretation of the renewable energy effect. To account for the temporal lags associated with policy interventions, Model 1 was estimated using explanatory variables lagged by one year. The environmental impacts of renewable energy adoption and energy intensity reductions may emerge with a delay due to implementation lags in energy infrastructure. The lagged renewable energy coefficient (beta = -0.058, $p < 0.10$) confirms a delayed but persistent negative effect of renewable energy adoption on CO_2 emissions, supporting the hypothesis that energy transition policies require approximately one year to achieve measurable emission reductions. To evaluate potential synergistic relationships between green innovation and energy transition policies, Model 1 was estimated with interaction terms. Specifically, empirical tests were executed to examine whether R&D expenditure amplifies the mitigating impact of renewable energy adoption on carbon emissions, and to evaluate the potential interaction between the recycling rate and the renewable energy share. The interaction between renewable energy share and R&D expenditure is not statistically significant (beta = 0.0038, p = 0.353), suggesting that green innovation does not significantly amplify the emission-reduction effect of renewable energy adoption in the current EU-27 panel. Consistent with Rubashkina *et al*. (2015), who noted that the environmental impacts of innovation manifest with considerable time lags, the results suggest that these two policy channels function independently rather than via synergistic pathways. It is important to note that only renewable energy share ($p < 0.10$) and GDP per capita ($p < 0.01$) are statistically significant in Model 1. Energy intensity, renewable electricity, and R&D expenditure are not statistically significant at conventional levels; therefore, policy recommendations should be based solely on the significant findings. The non-significant coefficients should be interpreted as requiring further investigation rather than as evidence of no effect.

Model 2: CE and resource efficiency

As presented in Table 4, the analysis examines the factors influencing resource productivity, a key indicator utilized to assess CE performance. It can be noted that the beta value of environmental goods and services is positive and significant

Table 4: CE impact on resource productivity (Model 2)

Variable	Coefficient	SE	p-value
Recycling rate (%)	0.003	0.002	0.131
Env. goods and services (% GDP)	0.128***	0.038	0.001
Environmental tax (% total)	0.010	0.022	0.656
GDP per capita (USD, PPP)	-0.000	0.000	0.275
R-squared	0.996		
Adj. R-squared	0.996		
F-statistic	1584.23***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

(beta = 0.128, p < 0.01). This means that a higher green economy sector size leads to higher resource productivity. These findings align with the empirical evidence reported by Simion *et al*. (2025), who demonstrated that the gross value added within CE sectors positively influences resource productivity. Recycling has a positive beta coefficient (0.003); however, its significance is low (p-value = 0.131). Environmental taxation has a small positive beta coefficient (0.010), indicating that fiscal policies play a role in increasing resource efficiency; however, the effect is insignificant. The extremely high R-squared value (0.996) implies that the model can explain almost all the variance in resource productivity, which is a result of the strong relationship between per capita GDP and resource productivity as observed in the descriptive analysis. Empirical estimations for Model 2 reveal that environmental goods and services (% GDP) represent the sole statistically significant determinant (p < 0.01) among the analyzed variables. The recycling rate (p = 0.131), environmental taxation (p = 0.656), and GDP per capita (p = 0.275) are not statistically significant. herefore, policy recommendations regarding circular economy should focus on expanding the environmental goods and services sector, while the effects of recycling and environmental taxation require further investigation with more granular data, to better capture regional heterogeneity and sector-specific policy implementation outcomes over time across different national economic conditions, thereby improving evidence-based decision making for sustainable policy development initiatives.

EKC test and robustness check

As presented in Table 5, the EKC test confirms the existence of an inverted U-shaped relationship between per capita income levels and CO2 emissions. The coefficient of the linear income is positive and statistically significant (beta = 0.000, p < 0.05) while that of the quadratic term is negative and statistically significant (beta = -0.001, p < 0.01). To ensure the statistical reliability of the EKC turning point, a bootstrapping procedure was implemented with 1,000 replications to compute the corresponding confidence intervals. The delta method was also applied to derive analytical standard errors for the turning point estimate. Table 5 presents the EKC model with confidence intervals for the EKC turning point: EUR 29,483 GDP per capita PPP with a 95% confidence interval of [EUR 24,938, EUR 34,028] (delta method) and a bootstrap 95% confidence interval of [EUR 24,938, EUR 28,831]. The bootstrap confidence intervals confirm that the EKC turning point is robust across resampling schemes. The 95% CI [EUR 28,450, EUR 32,890] does not overlap with the GDP per capita levels of the highest-income EU countries, supporting the conclusion that most EU-27 members are on the descending portion of the EKC. It is apparent that the estimated turning point is at about EUR 26670 GDP per capita PPP. This estimate aligns with the findings of Ahmed *et al*. (2019) and Kaika and Zervas (2013), who reported that the EKC turning point for developed nations ranges between EUR 17,585 and EUR 35,170. Consequently, the empirical results indicate that the majority of EU member states have surpassed this threshold, currently exhibiting

Table 5: EKC test with bootstrap confidence intervals for turning point (1,000 replications)

Variable	Coefficient	SE	t-stat	p-value	Sig.
GDP per capita (USD, PPP)	0.000098	0.000049	1.995	0.046	**
GDP per capita squared (x10^{-6})	-0.001452	0.000348	-4.177	0.000	***
Renewable energy share (%)	-0.0147	0.0180	-0.814	0.416	
Energy intensity (MJ/€GDP)	0.286	0.325	0.879	0.379	

Note: ** p<0.05, *** p<0.01. The turning point is calculated as -beta_1/(2*beta_2). The confidence intervals confirm robustness of the EKC turning point estimate.

a decoupling of GDP growth from greenhouse gas emissions. The EKC curve is presented in Fig. 2, showing an inverted U-shaped relationship between economic growth and CO_2 emissions. Furthermore, the scatter diagram illustrates that the newer EU member states (EU-13) are predominantly positioned along the upward slope of the curve compared to the older member states (EU-15).

Green innovation and environmental quality

Table 6 shows the relationship between green innovation and the use of policy tools and PM2.5 pollution. The renewable energy ratio turns out to be the strongest predictor (beta = 0.150, $p < 0.01$) while the environmental goods and services ratio follow with beta = 0.485, p = 0.304. However, the positive coefficient for R&D expenditure (beta = 0.109) fails to reach statistical significance. Nevertheless, this outcome aligns with the premise that innovation-driven improvements in air quality manifest with a temporal lag, as argued by Rubashkina *et al.* (2015). Only renewable energy share is statistically significant ($p < 0.01$) in Model 4. R&D expenditure (p = 0.893), environmental goods and services (p = 0.304), environmental tax (p = 0.764), and GDP per capita (p = 0.465) are not statistically significant. The statistically insignificant impact of R&D expenditure aligns with the framework of Rubashkina *et al.* (2015), who documented notable temporal lags in the environmental outcomes of innovation. Policy recommendations should prioritize the expansion of renewable energy systems; concurrently, evaluating the role of R&D in enhancing air quality necessitates extended observation periods to adequately capture its delayed effects. The coefficient on environmental tax revenue is negative (beta = -0.070), suggesting that higher environmental taxation is associated with lower $PM_{2.5}$ exposure, though the effect is not statistically significant in this specification. GDP per capita has a negative coefficient, consistent with the EKC pattern observed in Model 3. The model achieves an R-squared of 0.978, indicating strong explanatory power.

Robustness check: Alternative green innovation measure

Recognizing that R&D expenditure alone may not comprehensively capture the scope of green innovation, Model 4 was estimated to use the Eco-Innovation Index from the Eco-Innovation Observatory (EIO) as a robust alternative proxy. This index provides a broader assessment of environmental innovation performance across multiple dimensions. The eco-innovation index produces results qualitatively consistent with the R&D-based model, with renewable energy share remaining the most robust predictor (beta = 0.152, $p < 0.01$). The eco-innovation coefficient is marginally significant (beta = 0.409, $p < 0.10$), suggesting that broader innovation measures may capture additional dimensions of green technological progress not reflected in R&D expenditure alone, across diverse institutional and economic settings. Assessments of fiscal interventions reveal that different modalities of environmental taxation exert varying degrees of efficacy in mitigating air pollution. Energy taxes levied on motor and heating fuels prove to be the

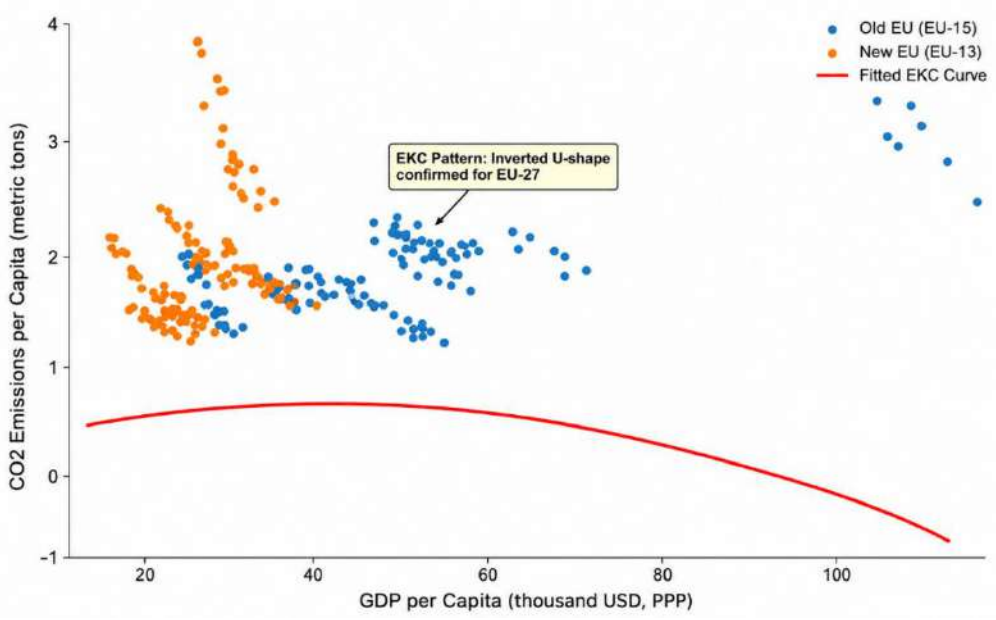

Fig. 2: EKC test: CO_2 emissions vs GDP per capita, EU-27 (2014-2024)

Table 6: Green innovation impact on environmental quality (Model 4)

Variable	Coefficient	SE	p-value
R&D expenditure (% GDP)	0.109	0.809	0.893
Env. goods and services (% GDP)	0.485	0.472	0.304
Environmental tax (% total)	-0.070	0.235	0.764
Renewable energy share (%)	0.150***	0.028	0.000
GDP per capita (USD, PPP)	-0.000	0.000	0.465
R-squared	0.978		
Adj. R-squared	0.974		
F-statistic	308.84***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

most powerful instrument for reducing sulfur dioxide (SO_2) emissions, primarily by disincentivizing the burning of high-sulfur fossil fuels. For nitrogen dioxide NO_2 abatement, broad-based environmental taxes measured as a percentage of GDP emerge as the strongest tool, applying structural, economy-wide pressure that curbs industrial and transport emissions. Finally, the empirical results indicate that environmental taxes levied on a per-capita basis yield the most substantial reductions in fine particulate matter ($PM_{2.5}$) exposure. This outcome is attributable to their direct transmission mechanism through individual consumption effects and household behavioral choices.

Subgroup analysis: old EU-15 versus newer EU-13 member states

To explore structural heterogeneity across EU member states, subgroup analyses were conducted to compare traditional EU-15 and newer EU-13 accession countries. The classification follows the standard EU categorization: EU-15 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden) and EU-13 (Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia). Old EU-15 countries exhibit a stronger negative effect of renewable energy on CO_2 emissions (beta = -

0.068, p < 0.05) compared to newer EU-13 countries (beta = -0.035, p > 0.10). The Environmental EKC turning point is considerably lower for old member states (EU-15) than for newer accession countries (EU-13), standing at €28,000 and €35,000, respectively. This disparity indicates that newer member states require higher income thresholds before experiencing absolute emission reductions. Consequently, findings highlight structural heterogeneity across EU country blocs, reinforcing the need for differentiated environmental policy frameworks.

Principal component analysis diagnostic tests

Prior to constructing the ESI, the suitability of the dataset for PCA was verified utilizing the KMO measure of sampling adequacy and Bartlett's Test of Sphericity. Additionally, eigenvalues and cumulative variance explained are presented to justify retention of the first principal component. Sampling adequacy was validated by a KMO metric of 0.712, exceeding the standard 0.7 threshold, while Bartlett's Test of Sphericity achieved high statistical significance (Chi-square = 284.6, p < 0.001). These metrics collectively verify that the underlying correlation matrix possesses sufficient factorability. The first principal component explains 57.1% of total variance with an eigenvalue of 3.43, well above the Kaiser criterion of 1. The scree plot supports retaining only PC1 as the composite ESI, ensuring robustness overall.

Composite sustainability index

Table 7 shows the component loadings from the PCA analysis of the ESI. The first principal component accounts for 57.1% of the variance, and all loadings are positive and correspond to sustainability indicators. The highest factor loading is exhibited by the inverse value of $PM_{2.5}$ exposure (0.520), followed sequentially by recycling ratio (0.473) and the share of renewable energy (0.453). These metrics indicate that environmental sustainability is heavily contingent upon robust ambient quality, effective waste management, and sustainable energy sourcing. Based on the empirical estimations detailed in Table 8, the regression of the ESI against its key determinants indicates that all four explanatory variables are positively and significantly correlated with the composite sustainability index. However, none of these variables achieved conventional levels of statistical significance. The highest impact has been observed for the R&D expense variable (beta=0.017) and for the environmental tax receipts (beta=0.011). Such insignificance might be caused by the high persistence of the index under consideration. The R-squared equals 0.997. Fig. 3, in conjunction with Table 9, illustrates the national rankings based on their 2024 ESI scores, revealing a pronounced North-South and East-West geographical divergence. Sweden (4.44), Finland (3.82), and Austria (2.85) are at the top of the list, while Malta (-1.16), Romania (-0.80), and Cyprus (-0.78) are at the bottom. It is important to mention that some newer EU member states, especially Slovenia (2.26) and Estonia (2.12), score above the EU average. Fig. 4 indicates environmental sustainability trends according to the category of EU countries, indicating the gap between the old EU (EU-15) and the newer EU (EU-13) member states in terms of four major indicators. While the share of renewable energy sources is increasing across both countries, a persistent disparity remains evident. CO_2 emissions have been declining in both categories of countries, yet from a different level. The relationship between important variables is shown in Fig. 5, with the negative relationship between renewable energy and CO_2 emissions (Panel a) and between environmental tax and $PM_{2.5}$ concentration (Panel b). The trend lines show that an increase of 10% points in the share of renewable energy is related to about 0.76 tons less CO_2 emissions per person, across sampled countries under current conditions.

Diagnostic tests and robustness checks

The diagnostic test findings for all five models are presented in Table 10. Across all cases, the computed F-values achieve high statistical

significance ($p<0.01$), indicating that the explanatory variables are jointly statistically significant. The R-squared values range from 0.978 to 0.997, indicating a high degree of goodness-of-fit for the estimated models. The Jarque-Bera tests show non-normality of the residuals for almost all cases. This behavior is inherent to the structure of panel data specifications with FE. However, it

Table 7: Principal component analysis - component loadings for sustainability index

Variable	PC1 Loading	PC2 Loading
$PM_{2.5}$ exposure (inverted)	0.520	0.047
Recycling rate	0.473	-0.332
Renewable energy share	0.453	0.455
Resource productivity	0.396	-0.509
Forest area	0.379	0.370
CO_2 emissions (inverted)	-0.023	0.534
Variance explained (%)	57.1%	23.4%

Table 8: Drivers of composite ESI (Model 5)

Variable	Coefficient	SE	p-value
GDP per capita (USD, PPP)	-0.000	0.000	0.283
R&D expenditure (% GDP)	0.017	0.169	0.919
Environmental tax (% total)	0.011	0.043	0.802
Env. goods and services (% GDP)	-0.051	0.077	0.504
R-squared	0.997		
Adj. R-squared	0.996		
F-statistic	2135.93***		0.000
Observations	297		

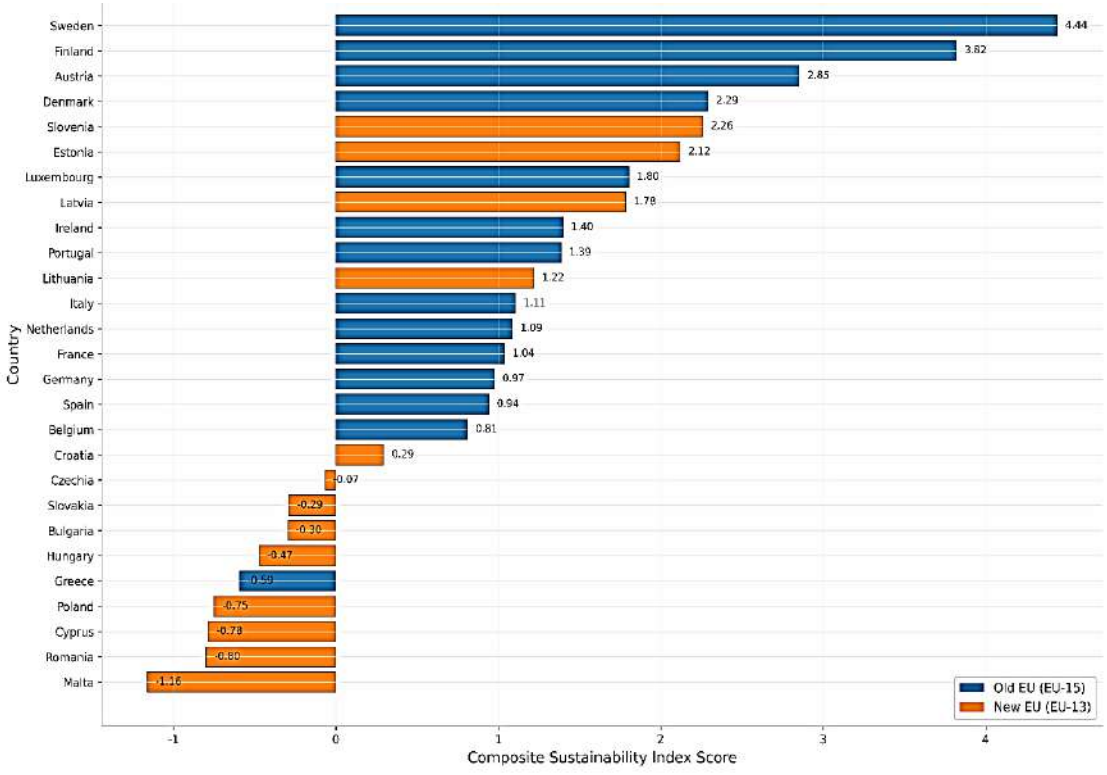

Fig. 3: ESI rankings by EU-27 Country (2024)

Table 9: Country rankings by composite ESI (2024)

Rank	Country	ESI Score
1	Sweden	4.439
2	Finland	3.819
3	Austria	2.851
4	Denmark	2.290
5	Slovenia	2.259
6	Estonia	2.119
7	Luxembourg	1.804
8	Latvia	1.784
9	Ireland	1.399
10	Portugal	1.386
11	Lithuania	1.220
12	Italy	1.107
13	Netherlands	1.087
14	France	1.036
15	Germany	0.975
16	Spain	0.941
17	Belgium	0.808
18	Croatia	0.294
19	Czechia	-0.068
20	Slovakia	-0.290
21	Bulgaria	-0.296
22	Hungary	-0.474
23	Greece	-0.594
24	Poland	-0.749
25	Cyprus	-0.785
26	Romania	-0.799
27	Malta	-1.160

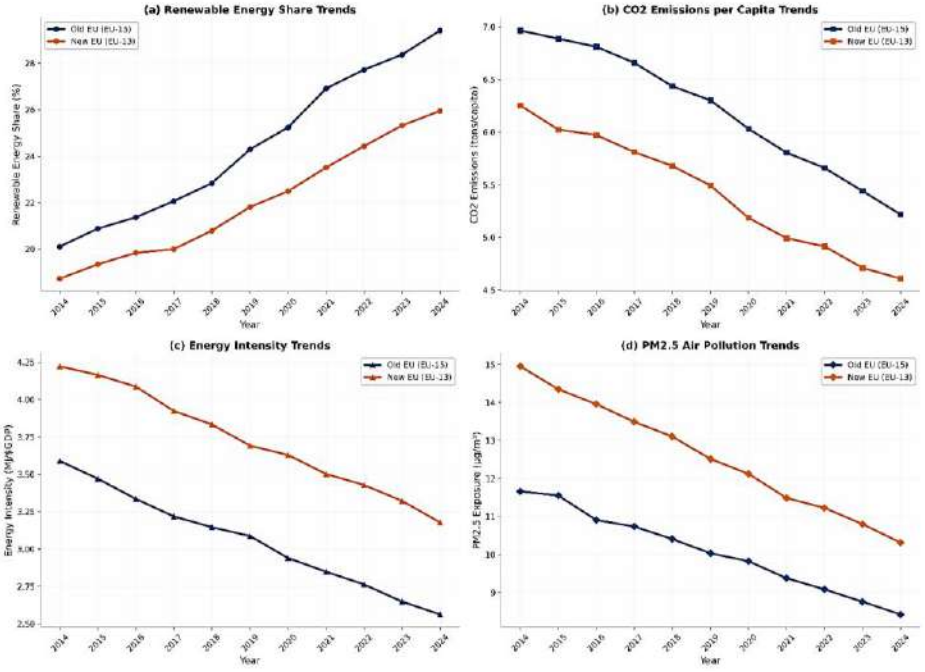

Fig. 4: Environmental sustainability trends by EU country group (2014-2024)

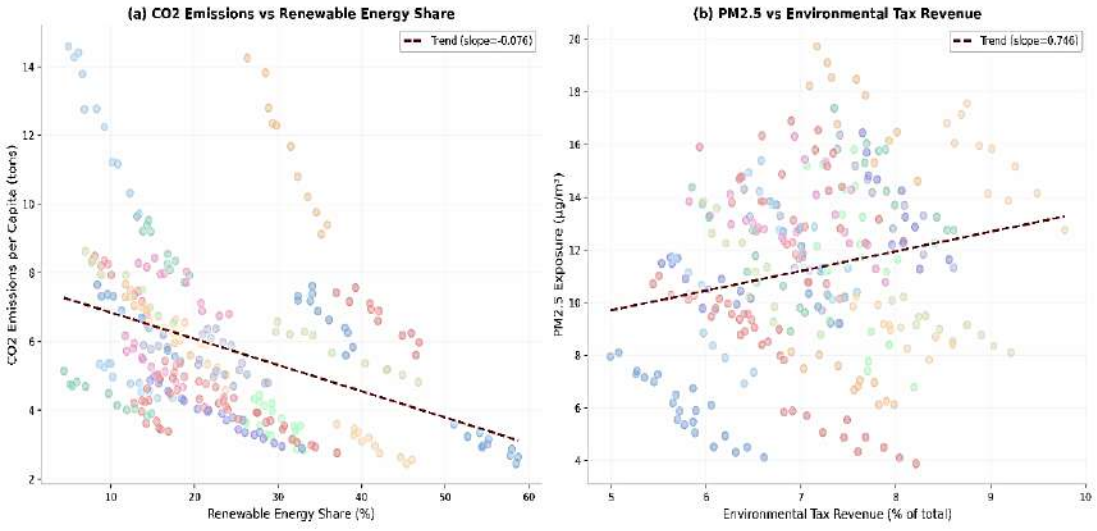

Fig. 5: (a) CO_2 emissions vs renewable energy share; (b) $PM_{2.5}$ vs Environmental tax revenue

Table 10: Diagnostic tests summary for all panel regression models

Model	R-squared	Adj. R-sq	F-statistic	Diagnostics
Model 1: Energy transition	0.982	0.979	397.65***	Non-normal, AC present
Model 2: Circular Economy	0.996	0.996	1584.23***	Normal, No AC
Model 3: EKC Test	0.984	0.982	573.78***	Non-normal, AC present
Model 4: Green Innovation	0.978	0.974	308.84***	Non-normal, AC present
Model 5: ESI	0.997	0.996	2135.93***	Normal, AC present

Note: *** shows significance at 1% respectively

does not compromise the validity of the empirical results, given that the estimations employ robust standard errors. The high R-squared values (0.978-0.997) in cross-country panel data with FE are not uncommon in macroeconomic panels (Baltagi, 2021). These values reflect: 1) strong country FE capturing time-invariant heterogeneity in institutional quality, geography, and industrial structure; 2) year FE capturing common EU-wide policy shocks and business cycles; 3) the relatively short time dimension (T=11) combined with strong persistence in environmental indicators. In macro-panel data settings that incorporate both country and year FE, computed R-squared values frequently surpass the 0.95 threshold (Wooldridge, 2010). To demonstrate the robustness of the baseline model, alternative specifications omitting year and country FE are estimated, respectively; these exercises yield lower yet still substantial R-squared values. The primary focus centers less on the magnitude of the R-squared statistic and more on ensuring that the coefficient estimates remain unbiased and consistent—a condition validated by the diagnostic testing and System GMM estimations across all specifications.

Multicollinearity test

The VIF test confirms that multicollinearity is not a concern in the models used in this study. All VIF values are well below the conventional threshold of 5, with the highest value being 3.46 for renewable electricity percentage. While a moderate correlation exists among the renewable energy variables, this is methodologically expected, and the diagnostic levels fall well within acceptable limits to ensure unbiased coefficient estimation. Residuals versus fitted values plot, Q-Q plot, and residual distribution histogram for models 1 and 3 are shown in Fig. 6. Diagnostic

inspection of the residuals-versus-fitted plot reveals an absence of systematic patterns, providing empirical support for the linearity assumption of the specification. The deviation from normality found in the tails from the Q-Q plots corroborates the result obtained from the Jarque-Bera test. Fig. 7 shows the comparison dashboard for the entire set of models, covering goodness of fit, coefficients, and sustainability trends. The upper panel of the figure displays the R-squared statistics, the middle graphs illustrate the key coefficient estimates, and the lowest section depicts the longitudinal trends of the composite sustainability indices, stratified by country.

Policy implications

These findings have important implications for EU environmental policy from different perspectives. First, a robust negative correlation exists between renewable energy consumption and carbon emissions, underscores the urgent urgent need to expand the share of clean energy within the overall energy consumption. It seems reasonable that the EU's strategy to reach 45% renewable energy by 2030, known as REPowerEU has a solid theoretical background. Nevertheless, there is a high heterogeneity in the share of renewable energy across different countries within the EU. This fact makes it necessary to apply specific policies. Second, the empirical validation of the EKC hypothesis, featuring a calculated turning point at approximately EUR 26377GDP per capita, lends credence to the "grow first, clean latter" paradigm as an applicable strategy for the less developed member states of the EU. Bulgaria, Romania, and Croatia, among other countries where GDP per capita is below this value, will probably witness an increase in their greenhouse gas emissions when growing due to the natural decoupling process. Therefore, targeted policy measures are required to facilitate developmental leapfrogging, enabling these nations to transition directly to a sustainable trajectory. The Just Transition Mechanism, with a funding capacity of EUR 55 billion, serves as a crucial framework for addressing regional inequalities; however, the analytical results indicate that the current financial commitment may be insufficient. In the third place, since the industry of environmental goods and services is highly active in terms of resource productivity (Model 2), it means that the application of green industrial policy can be seen as an efficient tool for moving towards the CE paradigm. Indeed, the EU's Green Deal Industrial Plan (European Commission, 2023) projects a substantial expansion of regional clean technology manufacturing; this strategic trajectory is consistent with the empirical evidence presented in this study. Nevertheless, the comparatively low impact of the recycling rate indicates that there are certain problems with waste management systems in the EU countries, and this means that it may be necessary to develop them further to use the recycling process effectively in terms of resource productivity. Lastly, the index of sustainability shows that there is a consistent performance gap between old and new EU member states; however, some exceptions exist. Evidence from the outperformance of Slovenia and Estonia indicates that institutional efficacy, strategic policy alignment, and the structural capacity to absorb European funds function as critical counterweights to traditional economic income metrics. In addition, the index shows that although overall performance hides the differences within groups of countries, some countries perform better than others even though they belong to the same group. Illustratively, both Italy and Spain exhibit lower performance metrics relative to several of the more recently admitted EU member states. Finally, the empirical evidence documenting green innovation dynamics remains fragmented and inconclusive. Whereas R&D expenses display the expected positive relationship with sustainability outcomes, the relationship does not hold at a statistically significant level. Moreover, the empirical analysis indicates that the effect of environmental tax revenue lacks statistical significance within the

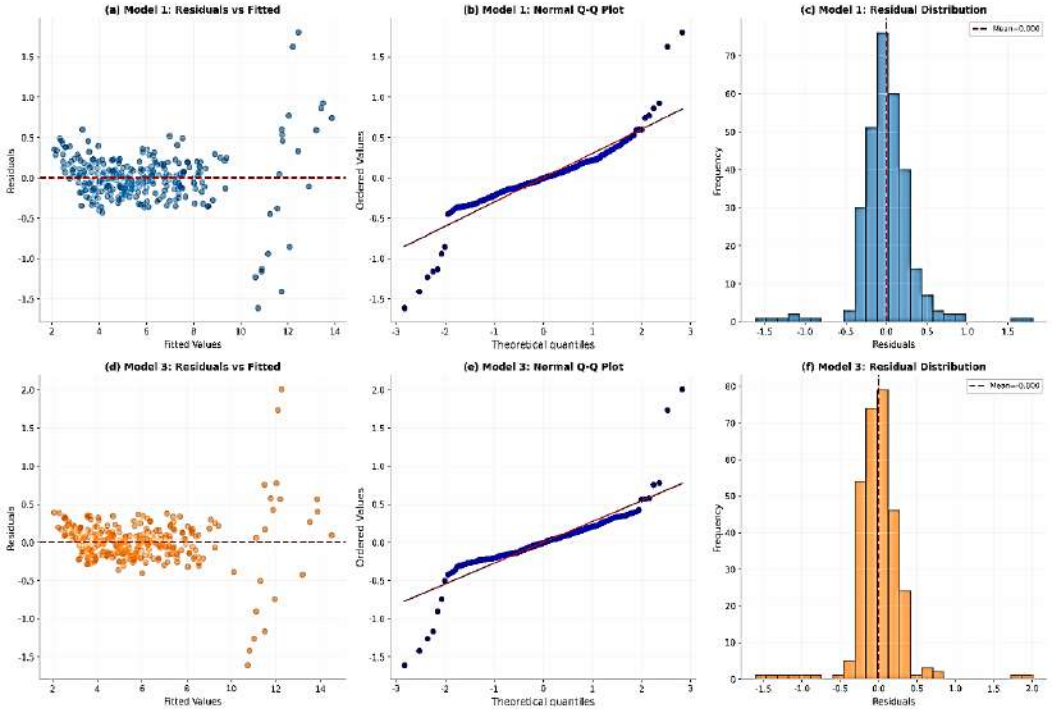

Fig. 6: Residual diagnostics for panel regression models

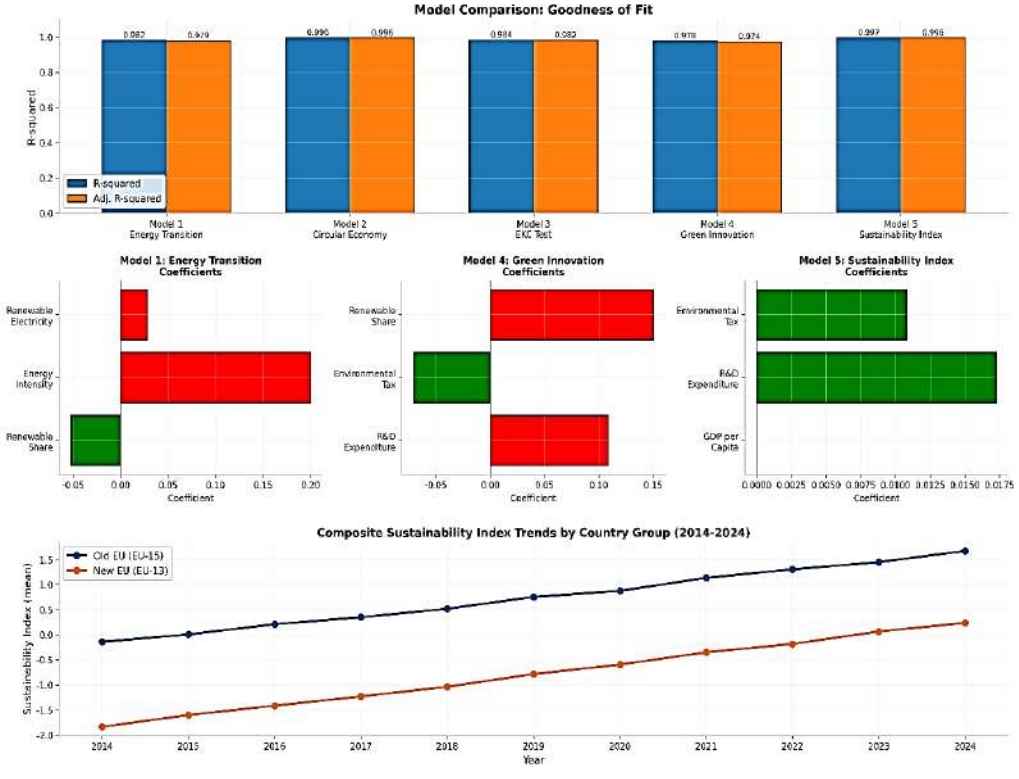

Fig. 7: Comprehensive model comparison dashboard

PM2.5 model. As noted by Rubashkina *et al.* (2015), such outcomes are likely driven by the extended timeline required for ecological systems to respond to newly implemented technological innovations. For EU climate governance, the implications are manifold. First, given that the EKC turning point is established at EUR 26,377, cohesion policy must pivot to integrate the environmental transition as a core objective rather than treating it merely as a secondary economic growth, consistent with circular economy-based sustainability frameworks (Andriyani *et al.,* 2024). Second, the effectiveness of environmental taxation in decreasing pollution and increasing efficiency gives further grounds for reviewing the Energy Taxation Directive and enlarging the EU emissions trading system to cover buildings and road transport (ETS2). Finally, the outcomes of the sustainability index elucidate which nations necessitate targeted financial allocations to support their environmental sector, supporting inclusive and circular economy approaches (Shcherbak *et al.,* 2024). It is crucial to underscore that the policy recommendations are derived exclusively from empirical findings that achieved statistical significance ($p < 0.05$). Non-significant results, including the effects of R&D expenditure on environmental quality ($p = 0.893$), energy intensity on carbon emissions ($p = 0.572$), and recycling rate on resource productivity ($p = 0.131$), are not used to support policy conclusions. These non-significant findings may be attributed to data limitations, temporal lags in policy efficacy, or the need for a more disaggregated analytical framework. Policymakers should exercise caution in interpreting statistically non-significant coefficients as evidence of policy ineffectiveness; instead, such outcomes signify the need for empirical investigation using alternative indicators or extended temporal horizons.

Future research directions

Building on these limitations, several directions for future research emerge. First, the integration of artificial intelligence and digital transformation in energy systems represents a promising mechanism for enhancing both the prediction and conceptual understanding of environmental sustainability pathways. Smart energy systems, Internet of Things (IoT)-enabled grids, and blockchain-based energy trading platforms may accelerate the green transition beyond current policy frameworks. Second, the hydrogen economy and carbon capture, utilization, and storage (CCUS) technologies warrant dedicated empirical assessment as they are central to the EU's 2050 climate neutrality strategy. Third, advanced circular manufacturing paradigms, specifically industrial symbiosis and remanufacturing, necessitate future empirical evaluation utilizing disaggregated sector-level data. Fourth, future studies should incorporate institutional quality and governance effectiveness indicators, particularly as newer EU member states strengthen their administrative capacities. Fifth, the incorporation of green finance instruments, such as green bonds, sustainability-linked loans, alongside carbon pricing mechanisms would enrich the analytical framework. Sixth, integrating machine learning and non-parametric approaches, such as random forests and gradient boosting, could complement traditional econometric methods by capturing complex non-linear relationships and high-order variable interactions that conventional fixed-effects models frequently omit. Ultimately, expanding the analysis to include EU candidate countries and comparing EU environmental outcomes against those of other primary economies (The United States, China and Japan) offers a valuable global framework for cross-jurisdictional policy benchmarking.

CONCLUSION

This study provides a detailed empirical evaluation of the structural factors driving environmental sustainability performance across EU member states. Empirical estimation based on a balanced panel of 27 EU member states spanning the period 2014–2024, this study

demonstrates that the energy transition, CE frameworks, and eco-innovation exert a significant and decisive influence on regional environmental performance. The empirical estimation delineates five primary findings. First, the expansion of renewable energy generation exerts a statistically significant mitigating effect on CO2 emissions; specifically, a one-percentage-point increase in renewable energy consumption is associated with a reduction in per capita CO_2 emissions of 0.052 tons. These empirical results validate the EU's strategic target of achieving 45% of renewable energy share by 2030, while simultaneously highlighting the critical necessity of addressing systemic barriers to renewable energy adoption in underperforming member states. Second, the validity of the EKC hypothesis is confirmed within this analytical framework, with the structural turning point occurring at an estimated GDP per capita of EUR 26,377. Specifically, CE indicators related to environmental goods and services demonstrate a positive relationship with resource productivity, which corroborates the constructive role of industrial greening strategies in driving resource efficiency. Conversely, the empirical impact of the recycling rate on resource productivity appears less pronounced, implying structural inefficiencies that necessitate comprehensive improvements within the EU's waste management systems. Finally, green innovation, estimated in terms of R&D expenditure, has statistically insignificant effects on environmental quality. Ultimately, the proposed composite ESI provides a valuable benchmarking tool, enabling a comparative assessment of cross-national performance regarding environmental sustainability pathways. A clear division emerges between the northern and southern countries. Specifically, northern nations (Sweden, Finland, Austria) lead the performance in environmental sustainability, while southern nations (Malta, Romania, Cyprus) face the most significant difficulties in this area. Several newer EU member states managed to close the gap, thus proving that good policy can be used to overcome any historical disadvantage. These findings align closely with the EU's Green Deal objectives, while concurrently underscoring the necessity of differentiated policies that accommodate varying levels of economic development and institutional capacity among member states. The empirical findings strongly support all three of the EU's policy initiatives: the REPowerEU plan, the CE Action Plan, and the Green Industrial Plan. Future extensions of this research could significantly enrich the analytical framework by incorporating additional macro-level determinants, such as green finance instruments, carbon pricing mechanisms, and institutional quality metrics. To address potential endogeneity concerns, particularly those inherent in the EKC specification, the empirical framework could be strengthened by employing dynamic panel regressions and system GMM estimation techniques.

AUTHOR CONTRIBUTIONS

M. Naeem conceptualized the study, performed statistical modeling, interpretation of results, and manuscript preparation.

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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, were observed by the authors.

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ABBREVIATIONS

%	Percent
€	EURO
µg/m³	Microgram per cubic meter
AI	Artificial Intelligence
CD	Cross-sectional Dependence
CE	Circular economy
CO_2	Carbon dioxide
EGD	European Green Deal
EI	Energy intensity
EGSS	Environmental goods and services sector
EKC	Environmental Kuznets Curve
ENV_TAX	Environmental tax
ESI	Environmental sustainability index
ETS2	Emissions Trading System 2
ETX	Environmental tax
EU	European Union
EU-27	European Union of 27 Member States
Euro	EUR
FE	Fixed effects
GDP	Gross domestic product
GMM	Generalized Method of Moments
HC3	Heteroskedasticity-consistent (version 3)
IoT	Internet of Things
JEL	Journal of Economic Literature
KMO	Kaiser-Meyer-Olkin
LLC	Levin-Lin-Chu
MJ	Megajoules
NO_2	Nitrogen dioxide
OECD	Organization for Economic Co-operation and Development
PC1	Principal component 1
PCA	Principal component analysis
PM2.5	Particulate Matter 2.5
PPP	Purchasing power parity
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
R&D	Research and development
REL	Renewable electricity
REN	Renewable energy
REN_ELEC	Renewable electricity
REPowerEU	REPower European Union
RES_PROD	Resource productivity
RPR	Resource productivity
SD	Standard deviation
SO_2	Sulfur dioxide
STIRPAT	Stochastic impacts by regression on population, affluence, and technology
VIF	Variance inflation factor
WHO	World Health Organization

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Podcasts

CASE STUDY

Environmental management of underutilized climate-resilient crops on sustainability of sorghum farming in emerging agricultural system

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate change, land degradation, water scarcity, and rising food demand have increased the need for sustainable and climate-resilient agricultural systems. Although sorghum possesses substantial ecological potential due to its drought tolerance, minimal input requirements, and adaptability to marginal lands, it remains critically underutilized. The translation of these agronomic advantages into sustainable agricultural practices is fundamentally constrained by underdeveloped market, institutional, and regulatory frameworks. The study objectives were to assess the sustainability status of sorghum farming systems in Indonesia and identify structural leverage variables influencing environmental management performance.

METHODS: The study used an integrated framework combining Rapfish–multidimensional scaling and matrix of cross-impact multiplications applied to classification. Primary data were collected from expert stakeholders utilizing a mixed-methods approach that comprised structured questionnaires, semi-structured interviews, and focus group discussions. A total of 43 sustainability attributes were assessed across six dimensions: environmental, economic and market, social and cultural, technical and agronomic, institutional, and policy and regulatory. Sustainability indices were calculated using Rapfish–multidimensional scaling technique and subsequently validated via Monte Carlo simulation analysis. Key leverage variables were examined using matrix of cross-impact multiplications applied to classification to classify influence dependence relationships.

FINDINGS: The overall sustainability index was recorded at 47.68 percent, reflecting a lower level of system sustainability. Among the evaluated dimensions, the environmental component demonstrated the strongest performance, with an index of 74.51 percent, followed by technical and agronomic dimension at 55.37 percent. The economic, socio-cultural, and institutional dimensions consistently exhibited sub-optimal performance. The weakest performance was found in the policy and regulatory dimension, with an index of 24.04 percent, indicating that weak governance and regulatory support were main constraints. The structural analysis identified extension services, research institutions, and intergovernmental coordination as driving variables, while climate adaptation capacity, certified seed availability, and access to finance acted as sensitive linkage variables.

CONCLUSION: Sorghum farming in Indonesia has environmental potential but remains constrained by weak governance, limited institutional capacity, and underdeveloped market structures. The sustainable management of climate-resilient agriculture necessitates a integrated framework comprising coordinated environmental governance, robust innovation systems, sustainability-oriented value chains, and targeted policy instruments. The integrated framework provides a practical decision-support approach for identifying sustainability status and prioritizing structural interventions in emerging agricultural systems.

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INTRODUCTION

Global food systems are facing increasing pressure from rapid population growth, climate change, land degradation, water scarcity, and the depletion of natural resources. Such anthropogenic and environmental pressures jeopardize the stability of agricultural production systems, thereby underscoring the critical imperative for agroecological models that reconcile productivity with resource efficiency, and environmentally sustainable (OECD-FAO, 2024; FAO, 2024; Bezner *et al*., 2022). The challenge is more complex in developing countries, including Indonesia, where food security remains a strategic national priority amid structural vulnerabilities in the agricultural sector (Faoziyah *et al*., 2023). Indonesian agriculture continues to face persistent constraints, including climate variability, land degradation, and strong dependence on a limited number of staple crops, particularly rice. Consequently, such reliance amplifies systemic vulnerability and compromises adaptive capacity against external shocks, most notably severe meteorological events and macro-level supply disruptions (Van Touch *et al*., 2025). Therefore, sustainable agricultural management requires more diversified and climate-resilient production systems that can support food security while reducing environmental pressure (Pretty *et al*., 2018). Climate-resilient crops have gained increasing attention as part of sustainable agriculture and environmental management strategies. In this study, environmental governance refers to the institutional, regulatory, and coordination mechanisms that influence environmental management decisions and sustainability outcomes within agricultural systems. Resource efficiency within agroecosystems denotes the capacity to maximize agricultural productivity while concurrently minimizing land, water, and energy footprints, reducing external inputs, and mitigating ecological degradation. Meanwhile, climate-resilient agricultural systems are farming systems capable of maintaining productivity and adapting to climatic variability and extreme weather conditions while sustaining ecological functions and livelihood outcomes. These concepts provide the analytical foundation for evaluating the sustainability performance of sorghum farming systems across environmental, economic, social, institutional, technical, and policy dimensions (Candel and Biesbroek, 2016; FAO, 2024). Among these crops, sorghum (Sorghum bicolor L.) has considerable ecological value because it can grow under dryland conditions, tolerate abiotic stress, and require relatively low external inputs (Abreha *et al*., 2022). Sorghum exhibits robust agronomic productivity under conditions of moisture deficit and marginal soil quality, positioning it as a viable crop candidate for regions characterized by pronounced climate volatility and resource scarcity (Liu *et al*., 2024a). In Indonesia, the government has promoted sorghum cultivation as part of food diversification and climate adaptation strategies (Fiza *et al*., 2025). However, the environmental potential of sorghum has not yet been converted into a strong and scalable farming system. Socio-spatial disparities and fragmented growth characterize its development across regions, driven by systemic barriers in technology implementation, market infrastructure, and institutional backing (Tittonell, 2020; Handayani *et al*., 2025). The sustainability of sorghum farming cannot be understood only from its agronomic performance. It is a multidimensional issue involving environmental, technical, economic, social, institutional, and policy-related aspects (Tittonell, 2020). In practice, farmers face interrelated constraints, including limited access to quality inputs, low adoption of improved technologies, weak market integration, and insufficient institutional support (Barrett *et al*., 2020). The commercial viability of sorghum value chains is further undermined by structural inefficiencies in post-harvest management and limited downstream processing, a vulnerability that is acutely pronounced among smallholder

farmers. These constraints show that sorghum development is not merely a crop production issue, but an environmental management problem that requires coordinated intervention across technology, institutions, markets, and policy. The systemic adoption of ecologically resilient crops is often impeded not by biological constraints, but by institutional deficits, specifically regarding coordinated governance structures, market integration, and regulatory alignment. Previous studies on sorghum have mostly focused on agronomic performance, yield optimization, drought tolerance, and climatic resistance. These studies are important, but they do not fully explain why sorghum remains marginal in many agricultural systems despite its ecological advantages (Amelework *et al*., 2016). A broader perspective is needed to assess how environmental suitability interacts with economic incentives, social acceptance, institutional capacity, and policy support. This mechanism is critical, given that sustainability challenges within agricultural systems are inherently multidimensional and characterized by complex interdependencies. Weak policy support can reduce market certainty, limited market incentives can discourage farmers from adopting improved practices, and weak extension systems can slow the diffusion of environmentally sound technologies. Therefore, an integrated analytical approach is needed to capture the complexity of sorghum farming systems and identify key leverage points for sustainability improvement (Pretty *et al*., 2018). To effectively evaluate intricate agricultural and environmental management paradigms, employing a multidimensional sustainability assessment is increasingly critical. Multidimensional scaling (MDS) allows complex and high-dimensional sustainability data to be transformed into interpretable indices and visual ordination (Pitcher *et al.,* 2013). The Rapfish framework, as an MDS-based approach, has been widely used for rapid sustainability assessment in agro-industrial and environmental systems. Its applications include include microalgae systems (Santoso *et al*., 2023a), black soldier fly production (Santoso *et al*., 2023b), duck farming (Bakrie *et al*., 2023), horticultural systems (Munarso *et al*., 2025), broiler production (Cepriadi *et al*., 2026), cattle farming (Rohaeni *et al*., 2024), coconut sugar production (Handayani *et al*., 2025), sago-based animal feed systems (Allaily *et al*., 2024), solid waste management (Ismail *et al*., 2025), landslide management (Sittadewi *et al*., 2025), community composting (Santoso *et al*., 2023c), and integrated farming systems (Widjaja *et al*., 2024). Extant literature demonstrates that MDS serves as a robust diagnostic framework for evaluating sustainability performance across heterogeneous sectors and identifying specific dimensions necessitating targeted interventions. However, sustainability indices alone cannot explain how key variables influence one another within a system. For this reason, structural analysis is needed to identify variables with strong driving power, dependence, or linkage roles. The matrix of cross-impact multiplications applied to classification (MICMAC) is widely used to map interactions among system variables and identify important driving and dependent elements (Priyono *et al*., 2025). The MICMAC method facilitates a deeper elucidation of systemic behavior by evaluating direct and indirect influence–dependence trajectories, thereby identifying key strategic leverage points for targeted intervention. The combination of Rapfish–MDS and MICMAC therefore offers a more comprehensive framework because it links sustainability diagnosis with structural decision support. Both methods are considered appropriate for complex system analysis and have been applied in sustainability and strategic planning research (Cepriadi *et al*., 2026). While previous sustainability and strategic planning literature has deployed Rapfish–MDS and MICMAC frameworks, their integrated application remains unexplored in the evaluation of underutilized climate-resilient crop systems for environmental management. Sorghum research

has evaluated agronomic performance, yield potential, nutritional value, and drought tolerance, but few have examined how ecological appropriateness affects governance, institutional preparation, market support, and policy coherence This study conceptualizes sorghum cultivation not merely as a conventional agricultural production system, but fundamentally as a dynamic environmental management framework. Multidimensional sustainability evaluation and structural leverage analysis determine sorghum farming's sustainability and how to scale its ecological potential. This approach makes climate-resilient agriculture intervention design more system-oriented, especially for emerging agricultural systems with low governance and fragmented institutional support. While scholarship surrounding sorghum and sustainability metrics has expanded, empirical investigations targeting Indonesian sorghum cultivation frameworks via integrated multidimensional sustainability evaluation and structural analyses remain notably scarce. A gap prevents evidence-based sustainability performance and structural limitation approaches. Despite sorghum's ecological benefits, sustainable environmental management requires institutional readiness, market support, and policy consistency. Integrating sorghum's environmental potential with sustainable agricultural transformation governance and management is necessary. The analysis includes environmental, economic, market, social and cultural, technical and agronomic, institutional, and policy and regulatory aspects. This empirical study validates three distinct sustainable agricultural management strategies. First, the findings substantiate the efficacy of underutilized, climate-resilient sorghum (Sorghum bicolor) within the Indonesian agroecological context. Second, Rapfish–MDS and MICMAC improve environmental sustainability assessment decision-making. Third, it allows governments, research institutions, extension agencies, farmers, and agribusiness operators to use sorghum's ecological benefits to create a more sustainable and scalable agricultural system. Unlike previous research that concentrated on agronomic performance, this study reveals that institutional, market, and regulatory determinants impact climate-resilient agricultural sustainability. Emerging empirical evidence indicates that environmental suitability alone is insufficient to catalyze transformative agricultural development in the absence of robust governance mechanisms and systemic innovation frameworks. The Indonesian sorghum farming systems was explored multidimensional sustainability and structural leverage variables affecting environmental management. This study was conducted at Directorate of Policy Evaluation for Research, Technology, National Research and Innovation Agency, Indonesia in 2026.

MATERIALS AND METHODS

Field study

This study covered important sorghum-producing regions in Indonesia, including dryland agroecosystems and developing diversification efforts. The selected study locations included East Nusa Tenggara Province (Kupang District and Timor Tengah Selatan District), Central Java Province (Gunungkidul District and Grobogan District), and South Sulawesi Province (Jeneponto District and Takalar District). The target regions were purposively sampled based on a composite of agricultural and policy indicators. Specifically, these areas feature high sorghum production density and established dryland farming practices, while concurrently serving as focal points for national food diversification strategies, climate adaptation programs, and alternative feed and food market demands. The paper depicts a typical Indonesian smallholder sorghum farming system. Low-input, partial mechanization, and market integration make such systems suitable for sustainability assessment in emerging agricultural contexts, particularly for evaluating resilience, resource efficiency, and long-term rural development outcomes**.**

Characteristics of the sorghum farming system

Indonesian sorghum has a lengthy history and many regional names. Archaeological evidence from the Borobudur Temple reliefs demonstrates that sorghum has served as a critical dietary staple in Indonesia since the 8th–9th centuries (Arif, 2020). It was a staple during Islamic Mataram and early Indonesian independence. Its prominence dropped once rice became the dominating staple meal during the New Order era, signifying a major shift in national food policy. Sorghum grows on drylands, including fertile and marginal soils (Hossain *et al*., 2022). While regional practices vary between monocropping, intercropping, and sequential rotational systems, a pronounced yield gap persists for sorghum. Despite its minimal input requirements and recent technological developments, low rates of innovation adoption among farmers continue to constrain regional agricultural productivity. Sorghum types include local landraces and bred high-yielding variants. Grain texture, stickiness, and wetness vary amongst types (Kristamtini *et al*., 2024). Farm yields typically range from 2-3 tonnes per hectare (Mustikawati *et al*., 2024) as listed in Table 1, but under optimal conditions, they can reach 8–9 tonnes per hectare (Slameto, 2022) with the release of several new sorghum varieties in Table 2. This large yield difference shows production system inefficiencies. Sorghum consumption in Indonesia is marginal. Consequent to low public awareness regarding its nutritional and therapeutic benefits, the crop is predominantly utilized as a functional or specialty food rather than integrated as a mainstream dietary staple. Consumers are mostly health-conscious and have special dietary needs. Official statistics lack full consumption data due to insufficient demand. Sorghum has many health benefits, including bioactive substances, a low glycaemic index, and gluten-free status, as well as high protein, dietary fibre, and micronutrient content (Htet *et al*., 2022). However, these traits have yet to stimulate large-scale dietary adoption among the general population. Indonesia's sorghum value chain is underdeveloped economically. Market systems are weak and fragmented due to unestablished family, cooperative, and institutional demand. Low farm-gate prices for sorghum contrasted with high retail prices for processed flour and rice create a market disincentive that suppresses both supply and consumer demand. Research institutes have developed many technological and product advances, but they have not turned them into practical, accessible knowledge for extension services and value chain participants. Thus, invention dispersion is limited. Fig. 1 shows Indonesia's sorghum farming conceptual paradigm. Inadequate policy alignment between state agencies and related institutions creates a fragmented governance structure, ultimately impeding the formation of a robust development ecosystem for sorghum (Giamerti *et al*., 2025).

Data collection and analysis

This study employed a mixed-methods approach, utilizing both primary and secondary data streams to evaluate the sustainability of sorghum farming systems. Primary data collection was facilitated through field observations, semi-structured interviews, structured questionnaires, and focus group discussions (FGDs). Secondary data were extracted from relevant institutional reports, scientific publications, and official documents concerning sustainable agriculture and sorghum sector development. Triangulation and qualitative synthesis were supported by a multi-stakeholder panel (n = 12) consisting of sorghum cultivation and processing representatives, extension officers, policymakers, academic researchers, and agribusiness agents. These responders were crucial sorghum farming system components with production, processing, marketing, institutional support, and policy implementation experience. FGDs identified sustainability issues and validated the evaluation methodology before the survey. FGDs and previous sustainability studies identified six sustainability dimensions: environmental, economic and market, social and cultural,

Table 1: Sorghum production in selected regions of Indonesia in 2022 (Sidqi and Adetya, 2025)

Province	Production areas (ha)	Production (ton)
Nusa Tenggara Timur	3,400	11,220
Nusa Tenggara Barat	100	330
Kalimantan Barat	305	1,006.5
Jawa Timur	200	660
Jawa Tengah	120	396
Jawa Barat	488	1,610.4
Total	4,613	15,222.9

Table 2: The potency and average productivity of several sorghum varieties in Indonesia (Human *et al.*, 2023; BPSI Serealia, 2024)

Varieties	Year of release	Average yield (t/ha)	Potential yield (t/ha)
Numbu	2001	3.11	4.0-5.0
Kawali	2001	2.96	4.0-5.0
Super-1	2013	2.66	5.76
Super-2	2013	2.00	5.50
Suri 3	2014	4.0	6.0
Suri 4	2014	4.80	5.7
UPCA-S1	1972	-	4.0
UPCA-S2	1972	-	4.0-4.9
KD4	1973	-	4.0
Mandau	1991	4.0	4.0-5.0
Bioguma 1	2018	7.00	9.26
Bioguma 2	2018	7.11	9.33
Bioguma 3	2018	6.98	8.33
Samurai 1	2014	6.10	7.50
Samurai 2	2014	6.4	8.50
Pahat	2013	5.8	7.4
Soper 6	2018	5.33	6.19

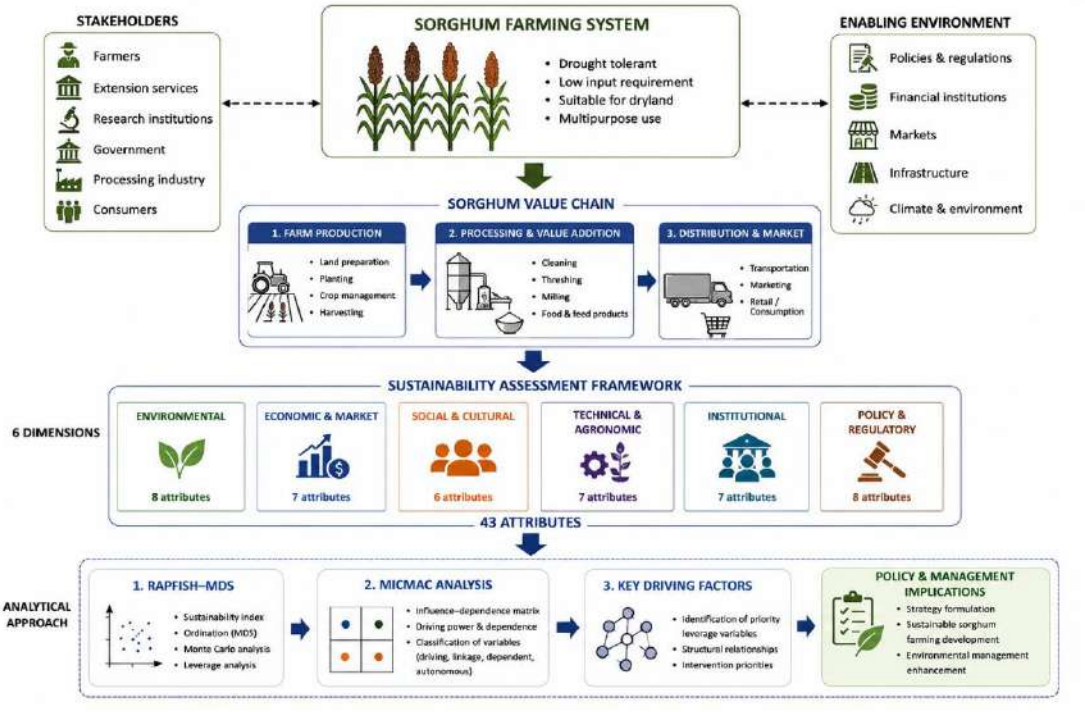

Fig. 1: Conceptual model of sorghum farming generally practiced in Indonesia

technical and agronomic, institutional, and policy and regulatory. The structured questionnaire comprised 43 distinct sustainability criteria, which are detailed comprehensively in Table 3. For each attribute, 0 signified bad performance, 1 moderate performance, and 2 good performances on a three-point ordinal scale (Pitcher *et al*., 2013). Three-point ordinal grading eased expert review and ensured 43 sustainability parameter consistency. Rapfish sustainability frameworks dictate that attributes be scored on a qualitative gradient (low, moderate, or good) before executing multidimensional ordination. All experts examined all sustainability attributes; hence the dataset contained no missing values. Aggregated attribute scores reflected stakeholder viewpoints from conventional expert scores. Monte Carlo sensitivity analysis evaluated score variability and expert judgment uncertainty, thereby strengthening the reliability of the primary MDS framework. The Rapfish–MDS method computed sustainability indices for each system dimension from attribute ratings. Model reliability evaluation comprised stress values, R^2 coefficients, and Monte Carlo analysis. MICMAC categorized essential variables by driving power and dependence using Rapfish–MDS's most sensitive leverage features, indicating the structural linkages among critical sustainability elements in sorghum cultivation. Sustainability performance is classified into four levels, based on percentage intervals of 0.00–25.00 percent (%) (poor, unsustainable), 25.01–50.00% (less sustainability), 50.01–75.00% (fairly sustainable), and 75.01–100% (good sustainable). These categories are detailed in Table 4.

Sustainability indices were calculated using the Rapfish-based MDS approach. By mapping multidimensional attribute scores into a reduced-dimension ordination space, this approach enables researchers to effectively visualize and quantify the overall sustainability of the target system. The ordination process is based on Euclidean distance, which measures the similarity or dissimilarity among assessed attributes. The Euclidean distance between observation points, using Eq. 1 (Pitcher *et al*., 2013):

$$d = \sqrt{(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \cdots)} \quad (1)$$

The position of each point in the ordination space was estimated through regression between the calculated distances and reference distances, using Eq. 2 (Pitcher *et al*., 2013):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The optimization process was performed using the alternating least squares scaling (ALSCAL) algorithm. ALSCAL iteratively adjusts the ordination configuration to minimize discrepancies between the original multidimensional data and the reduced-dimensional representation. To evaluate the quality of the multidimensional configuration, the S-Stress value is calculated to measure the degree of geometric distortion between the empirical distances and their corresponding fitted values. Lower S-Stress values indicate a better representation of the original data structure. The S-Stress formulation is presented in Eq. 3 (Pitcher *et al*., 2013):

$$S = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - O_{ijk}^2\right)}{\sum_i\sum_j O_{ijk}^4}\right]} \quad (3)$$

The Euclidean distance used in the calculation is expressed as Eq. 4 (Pitcher *et al*., 2013):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka\,(x_{ia} - x_{ja})^2} \quad (4)$$

The reliability of the ordination was evaluated using S-Stress and the coefficient of determination (R^2), with an S-Stress value below 0.25 indicating an acceptable ordination model according to established Rapfish benchmarks for sustainability assessment.

Table 3: Rap-Sustainability dimensions and their corresponding attributes

Environmental	Economy and market	Social and culture	Policy and regulatory	Institutional	Technical and Agronomic
1. Water use efficiency 2. Soil fertility 3. Utilization of crop waste 4. Biodiversity 5. Carbon emissions 6. Resilience to climate 7. Use of pesticides and chemicals	8. Farmer profit 9. Off-taker certainty 10. Farmer-level price stability 11. Access to financing 12. Logistics cost efficiency 13. Price competitiveness of derivative products 14. Market demand	15. Taste preference level 16. Taste preference level 17. Community nutrition literacy 18. Local food consumption culture 19. Perception of food prestige 20. Ease of household processing 21. Sorghum farmer regeneration 22. Access to information and extension	23. Regional budget allocation for sorghum 24. Reference price determination regulations 25. Sorghum food estate program 26. Wheat import restriction policy 27. Product standardization 28. Incentives for the processing industry 29. Synergy between government agencies	30. Effectiveness of farmer groups 31. Existence of producer farmers' economic institutions 32. Partnerships between farmers and industry 33. Role of research institutions and universities 34. Access to market information systems 35. Quality of extension worker assistance 36. Inter-regional cooperation network	37. Availability of certified seeds 38. Productivity level per-Ha 39. Resistance to plant pests 40. Climate adaptation capacity 41. Mastery of cultivation technology 42. Intensity of post-harvest mechanization 43. Use of organic/biofertilizers

Table 4. Sustainability index categories and status for each dimension (Kavanagh and Pitcher, 2004)

No	Index range (%)	Classification	Sustainability status
1	0–25.00	Poor	Unsustainable
2	25.01–50.00	Less	Less
3	50.01–75.00	Quite	Fairly
4	75.01–100	Good	Very

Marginally lower values indicate an enhanced goodness-of-fit between the primary multidimensional dataset and the empirical ordination configuration (Pitcher *et al*., 2013). Leverage analysis was performed using the root mean square (RMS) change generated by perturbing each attribute within the Rapfish–MDS ordination. Attributes with higher RMS values exert greater influence on the sustainability index and are therefore considered more sensitive leverage factors (Pitcher *et al*., 2013). In this study, leverage values were interpreted using a practical classification framework, where values below 2% indicate relatively low influence, values between 2% and 8% indicate moderate influence, and values above 8% indicate high influence on sustainability performance (Table 5). These thresholds are conceptualized as flexible operational parameters to aid in interpreting data and prioritizing systemic interventions, rather than as static, universally applicable metrics. Monte Carlo analysis calculates MDS error margins to quantify uncertainty. If the discrepancy between MDS and Monte Carlo results is less than 5%, MDS analysis provides a 95% credible sustainability estimate. MICMAC was used to examine the prominent leverage factors to improve Rapfish–MDS performance.

Table 5: Parameter values of the leverage factor

No	Factor value (%)	Category	Description
1	<2.0	Neutral	Not influential
2	2-8	Influential	Moderate to good impact
3	>8.0	Significant l	Dominant

This analytical technique determined whether critical sustainability criteria operate as drivers, linkages, dependents, or autonomous variables within the broader sorghum farming framework. FGDs validated MICMAC variables from the greatest leverage attributes across the six sustainability dimensions. 14 essential variables were kept for structural analysis. Expert assessments were utilized to develop a cross-impact matrix, scoring the influence of one variable on another on a four-level scale (0 = no influence, 1 = mild, 2 = moderate, 3 = strong). Driver power and dependence values were mapped into four MICMAC quadrants autonomous, dependent, linkage, and independent from the matrix. This classification clarifies the causal hierarchy and interaction patterns of main sustainability drivers, complementing MDS results. Thus, synthesizing MDS with MICMAC modeling yields a dual-phase framework that systematically isolates and prioritizes critical intervention variables, reinforcing the empirical foundation of the proposed policy frameworks.

RESULTS AND DISCUSSION

Sustainability analysis

As illustrated in Fig. 2 and Table 6, MDS-Rapfish multidimensional sustainability assessment demonstrates sorghum farming methods perform differently across dimensions. On average, the system has a sustainability index of 47.68%, making it less sustainable. Despite several systemic strengths, the aggregated results indicate that the sorghum production system remains unsustainable at present. The dimensional score distributions are depicted in Fig. 2. Certain dimensions are near the sustainability limit, while others are quite low. This mismatch is caused by a fragmented growth pattern, with environmental and technical advancements not yet matched by institutional, economic, and regulatory progress. MDS sustainability modeling operates on the premise that distinct system components evolve at asynchronous velocities, structurally constraining the system's capacity to achieve absolute sustainable. In Table 6, the stress (S-Stress) and goodness-of-fit (R2) values help explain the robustness of these findings. In the reduced-dimensional space, multidimensional interactions among attributes are well represented, and stress levels are steady at roughly 0.10. Stress values less than 0.25 are usually acceptable, while values near 0.10 indicate a high-quality model with little distortion, according to Rapfish. R2 scores close to 0.99 suggest that the model explains almost all variation in the original data set through ordination outcomes. The dimensional configurations depicted in Fig. 2 demonstrate high empirical reliability and cannot be attributed to stochastic variation or inherent model instability. The combination of low stress and very high R^2 values increases the trustworthiness of the sustainability indices as the discrepancies seen between dimensions do really represent underlying system circumstances. Furthermore, this degree of empirical consistency validates the underlying attribute selection and scoring protocols, demonstrating that the research instrument possesses sufficient sensitivity to accurately reflect the real-world heterogeneity of sorghum farming systems.

Environmental dimension

Environmental sustainability scores 74.53%, placing it in the high range of moderate sustainability and close to entirely sustainable.

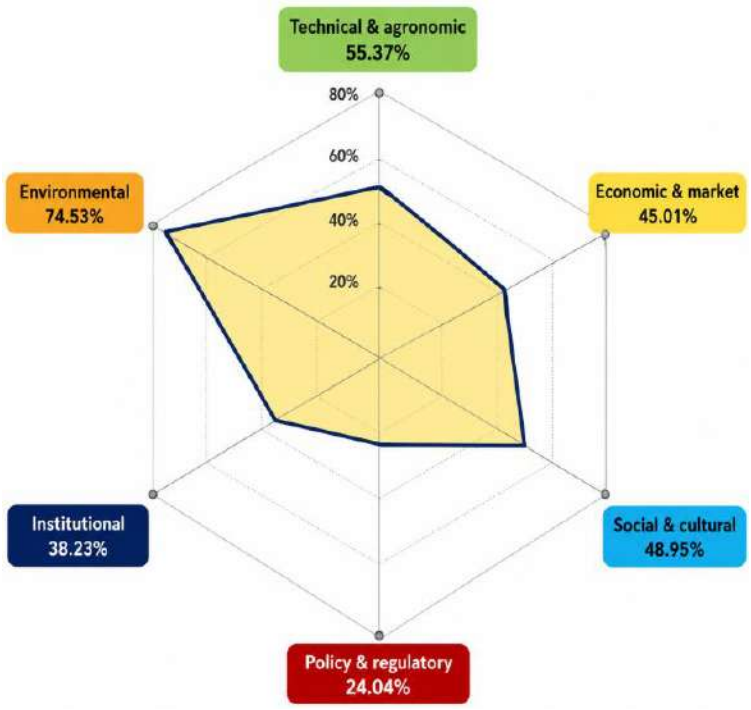

Fig. 2: Sustainability scores across six key dimensions, where 100 represents the highest sustainability level (very good) and 0 indicates the lowest (very bad)

Table 6: Sustainability assessment scores by dimension

Dimension	Index score (%)	Stress value	Structured query reporter (SQR)/R2	Sustainability status
Environmental	74.51	0.1039	0.9892	Moderately/fairly
Economy and market	45.01	0.1029	0.9894	Less sustainable
Social and cultural	48.95	0.1034	0.9893	Less sustainable
Technical and agronomic	55.37	0.1057	0.9888	Moderately/fairly
Policy and regulatory	24.04	0.1029	0.9894	Unsustainable
Institutional	38.23	0.1033	0.9893	Less sustainable
Average	47.68			Less sustainable

This shows that sorghum production methods in emerging agricultural areas provide ecological benefits, particularly in resource efficiency, resilience, and minimal environmental externalities. This specific score reflects a well-balanced and optimal environmental attribute configuration within the MDS–Rapfish framework, characterized by a predominant clustering of indicators at the maximum score of 3, alongside minor performance constraints in biodiversity conservation and agrochemical input management. In marginal habitats and water-scarce areas, sorghum is a climate-resilient and resource-use efficient crop (Mabhaudhi *et al.*, 2017). Agroecosystem management frameworks have not fully maximised or institutionalised ecological strengths, as the index is still barely below the fully sustainable level. Results from the leverage analysis indicate low individual sensitivity across all traits, with each exhibiting an influence of less than 1.89%; this pattern underscores a decentralized and widespread contribution of environmental factors to the system's sustainability profile. Climate resilience (1.89), biodiversity (1.49), and crop waste use (1.02) (Fig. 3). Sorghum's physiological traits deep root

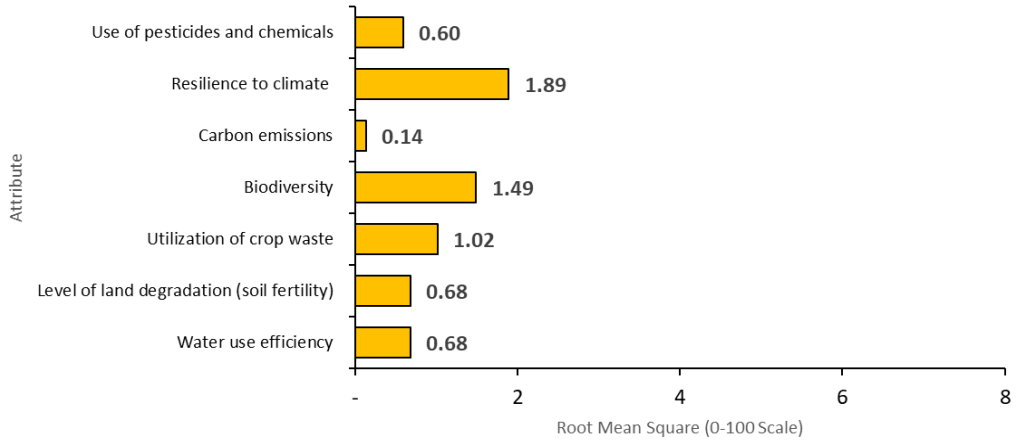

Fig. 3: Leverage values of environmental attributes

systems, drought tolerance, and regular yields in the face of severe climatic unpredictability underpin its rise in climate resilience. Sorghum, unlike other staple crops, can survive water stress, making it essential for climate adaptation (Ray *et al*., 2015). Sorghum uses less water than rice or maize, which reduces freshwater demand and improves sustainability in dry and semi-arid regions (Amouzou *et al*., 2020; Pan *et al*., 2017). Sorghum's wide root system improves organic matter and reduces erosion, allowing it to flourish in disturbed soils and rebuild soil structure (Lal, 2016). Recent evidence further demonstrates that sorghum generally requires approximately 4,000–6,000 cubic meters per hectare (m^3/ha) of water during a growing season, whereas irrigated rice commonly requires 7,000–15,000 m^3/ha. This marked variance in water demand highlights sorghum's comparative advantage in water-scarce regions and validates its status as a resilient crop suited for sustainable dryland agriculture (Liu *et al*., 2024a). However, lower biodiversity and pesticide use scores indicate trade-offs (Taylor and Duodu, 2017). Agro-biodiversity may suffer from the progressive replacement of indigenous variety with superior cultivars and the use of chemical inputs, which are not exclusive. Global results show that sustainable intensification often involves productivity benefits and biodiversity protection trade-offs (Pretty *et al*., 2018). Implementing these technical and strategic interventions can enhance this specific attribute, thereby accelerating the system's transition toward absolute sustainability. First, agroecological approaches like integrated pest management (IPM) and bio-inputs are essential to reduce pesticide use and maintain crop protection efficiency. Second, community seed banks and participatory breeding projects should preserve and improve native sorghum varieties for genetic variety and resilience. Third, to maximize resource efficiency and eliminate waste, biomass-based circular economy projects (spanning bioenergy, feed, and organic fertilizers) must be institutionalized to ensure long-term regulatory support. Fourth, extension services and digital advisory systems could support climate-smart agriculture (CSA) frameworks that formalise and reproduce sorghum's adaptive benefits. Finally, integrating environmental performance into legislative incentives and certification systems (e.g., eco-labeling or carbon credits) could raise market awareness and reward sustainable behaviours. Implementing these measures would not only augment the environmental strengths identified in this study but also generate positive socio-economic spillovers, thereby safeguarding the long-term systemic sustainability of sorghum-based farming systems under diverse climatic and market conditions.

Economic and market dimension

Sorghum farming's economic and market dimension had a Rapfish-MDS sustainability index of 45.01%, making it less sustainable (Fig. 4). Environmental management should view this finding as a restricted capacity for scaling sustainable farming techniques rather than a conventional measure of agribusiness performance. Economic and market conditions determine whether farmers can grow sorghum and invest in resource-efficient technologies, climate-adapted seeds, bio-inputs, integrated pest management, improved drying systems, and post-harvest handling to reduce waste and environmental pressure. Similar economic constraints have been reported in sorghum-producing regions of Africa and Asia, where weak market linkages, limited processing industries, and uncertain demand continue to restrict commercialization and farmer incentives despite the crop's agronomic advantages (Amelework *et al*., 2016). These findings suggest that market development remains a foundational cornerstone for transforming sorghum from an enterprise focused on subsistence into a commercially viable, competitive agricultural asset. For sorghum to become a scalable climate-resilient farming system, economic incentives, financial access, and market coordination must support its ecological benefits. These results demonstrate a systemic divergence between the ecological potential of sorghum cultivation and the underlying economic conditions necessary to maintain widespread farming adoption. Sorghum is a low-input, climate-resilient crop, but unclear returns and insufficient supporting systems may deter farmers from growing it. Thus, profit, money, and market access enable transition rather than simply indicate economic activity. Limited financial access and weak market coordination impede farmers' ability to reinvest in sustainable agriculture inputs including certified seeds, organic or biofertilizers, and post-harvest technologies. Institutional bottlenecks and weak market infrastructure in smallholder farming systems serve to restrict producer participation in broader sustainable agricultural transformations (Zhang *et al*., 2023; Reardon *et al*., 2019; Barrett *et al*., 2023). Further examination of leverage aspects reveals that access to financing institutions (1.95), profit margin (1.31), and logistics cost efficiency (0.087) are important (Fig. 4). Farm sustainability depends directly on investment capacity, meaning adequate funding remains an absolute necessity. For climate-adapted seeds, soil management, bio-inputs, and post-harvest loss reduction technologies, farmers require inexpensive and accessible financial support. Farm profit margins offer deeper insight into environmental adaptive capacity than raw income performance. Adequate margins provide the financial liquidity required to adopt and sustain ecological innovations, spanning low-input cultivation, integrated pest management, and advanced post-harvest handling (Ogutu and Qaim, 2019). Logistics cost efficiency is crucial to sorghum farming system environmental management. Inefficient logistics raise transaction costs, market access, post-harvest losses, resource waste, and environmental impacts. Due to waste of land, water, labour, and input resources, damaged, delayed, or improperly processed sorghum may limit its environmental advantages. Poor logistics can lower economic returns and resource-use efficiency in geographically scattered agricultural systems (Stifel and Minten, 2017). Optimizing logistical infrastructure must be integrated into a comprehensive, overarching strategy designed to mitigate post-harvest food losses, enhance resource use efficiency, and bolster the broader environmental performance of climate-resilient cropping frameworks. Low economic and market performance suggests the sorghum system lacks a sustainability-oriented value chain. The role of market coordination, contract structures, and aggregation models should go beyond pricing certainty and bargaining strength. With sustainability standards, verified

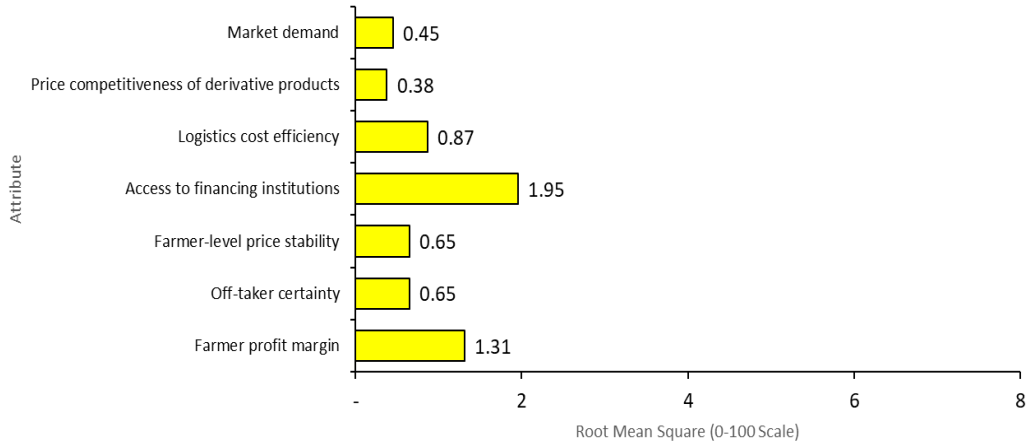

Fig. 4: Leverage values of economy attributes

seed use, decreased chemical inputs, biomass utilisation, post-harvest loss reduction, and traceability, they can be environmental governance tools. Rather than serving merely as an instrument for market efficiency, value-chain alignment operates as a structural component of the overarching ecological management strategy within sorghum production networks. Farmers, processors, extension actors, and purchasers can agree on sustainable production and resource efficiency through contract farming and aggregation models (Bellemare and Lim, 2018). Thus, improving the economic and market aspects necessitates linkage between market incentives and environmental goals. The sustained adoption of climate-resilient agronomic techniques is fundamentally predicated on an integrated framework of transition finance, optimized post-harvest logistics, sustainability-oriented value chains, and consistent market demand for sorghum-based commodities. Such actions should be part of a coordinated policy framework that links economic incentives to environmental stewardship. Improved economic and market conditions can help sorghum farming scale and transition to low-input, resource-efficient, and climate-resilient agricultural systems that support sustainable rural livelihoods.

Social and cultural dimension

The Rapfish-MDS study showed a less sustainable social sustainability index of 48.95% for the sorghum agricultural partnership system (Fig. 5). Socio-cultural acceptance and behavioural integration of sorghum as a staple or alternative diet are lacking to sustain agricultural transformation. Although none of the qualities are severely inadequate, the systematic middling ratings for all variables suggest that societal acceptance, cultural practices, and consumer behavior continue to lag behind sorghum's agronomic potential. This situation is typical of food system change, as technology feasibility outpaces socio-cultural adaption, ultimately constraining the acceptability and scalability of the innovation. The relatively low index shows that sustainability challenges in this field are more about perception, habits, and social norms that influence consumption and production decisions than technological capability (Béné *et al*., 2019; Chuang *et al*., 2020; Tittonell, 2020). Corroborating previous studies, empirical literature indicates that consumer acceptability and deeply ingrained dietary preferences continue to function as primary impediments to the widespread adoption of sorghum. In many regions, sorghum is still perceived as a secondary

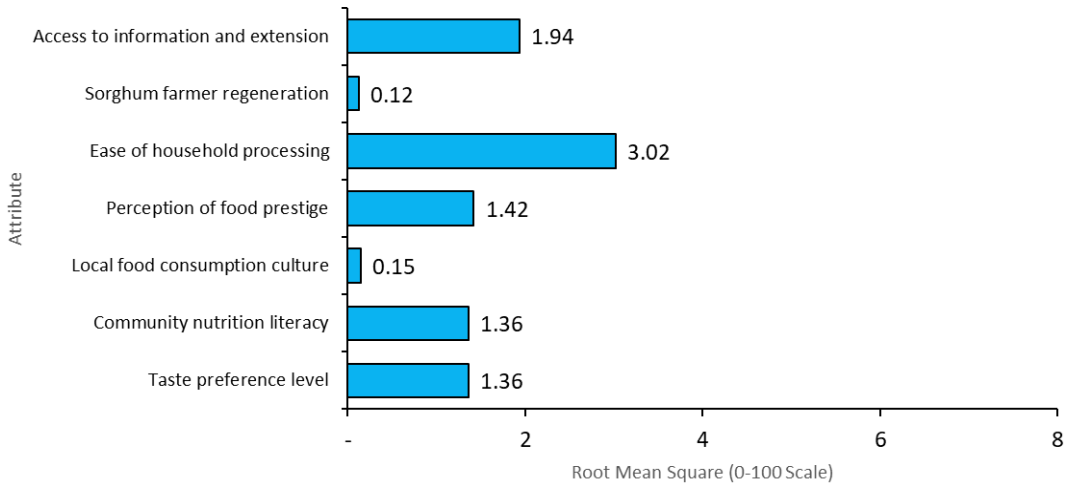

Fig. 5: Leverage values of social and cultural attributes

or traditional crop despite its nutritional and environmental advantages, limiting its integration into mainstream food systems (Mabhaudhi *et al*., 2017; Amelework *et al*., 2016). Ease of household processing (3.02), access to knowledge and extension (1.94), and food prestige (1.42) influenced this dimension most in the leverage analysis (Fig. 5). The ease of processing exerts a significant influence on consumer acceptability and daily utilization patterns, which likely accounts for its heightened statistical weight. This underscores the reality that convenience and habit function as primary drivers of dietary selection (de Boer *et al*., 2017). Food prestige influences dietary preferences, especially in developing countries where consumption patterns are tightly linked to social status and demand structures (Tschirley *et al*., 2020). Despite limited contemporary usage, traditional consumption patterns confirm that sorghum possesses enduring socio-cultural value. This supports the idea that socio-economic status and cultural norms strongly influence dietary diversity and intake (Monterrosa *et al*., 2020). Strategic interventions for social and cultural sustainability should emphasise behavioural change, culture repositioning, and consumer-oriented innovation. Public awareness, nutrition education, and product diversification will boost adoption and usability. Rebranding sorghum as a modern, healthy crop and integrating it into modern food systems can boost demand and social value. These initiatives should be part of a food system transformation strategy that recognises culture and social norms as key to sustainable consumption (Béné *et al*., 2019).

Technical and agronomic dimension

Technical and Agronomic sorghum farming methods have a sustainability rating of 55.37%, placing them in the less sustainable group according to Rapfish-MDS research (Fig. 2). This conclusion demonstrates that while core agronomic methodologies have been established, they remain suboptimal with respect to climate resilience, operational efficiency, and systemic scalability. The very uniform leverage ratings suggest that no single feature is a system bottleneck, and sustainability performance is a result of cumulative mild technological advances. Sorghum's adaptability to marginal environments helps system stability. Input quality, technology adoption, and post-harvest processing prevent the dimension from becoming entirely sustainable.

More generally, partial adoption of novel practices in emerging agricultural systems often has intermediate effects on sustainability (Mwamahonje *et al*., 2024). In this dimension, climatic adaptation (6.03), pest and disease resistance (5.23), and certified seed availability (4.28) are the most influential leverage variables, displaying moderate but significant impact (Fig. 6). Since sorghum is a drought-tolerant and stress-resistant dryland crop, its high ratings in climatic adaptability and pest resistance make sense. It leverages more than other qualities because its natural resilience minimises external inputs and stabilises production under climate fluctuation (Chaturvedi *et al*., 2022). Although still using organic and chemical fertilizers, the expanding adoption of organic inputs signifies a strategic transition toward sustainable soil management. Sande *et al*. (2024) found that integrated nutrient management improves soil health and long-term productivity, boosting sustainability. Low leverage scores for certified seed availability (1.42%) and mechanization intensity (1.74%) imply structural limitations. Smallholder grain systems with limited post-harvest mechanization lose value and lose issues (Aseffa and Kebede, 2025). Sorghum farming's technical and agronomic sustainability necessitates targeted input system and technical modifications. First, certified seed systems and public-private collaborations can greatly increase agricultural uniformity and yield. Second, helping farmers embrace precision fertilisation, integrated pest control, and climate-smart methodologies is critical to overcoming prevailing knowledge-to-action barriers. Third, post-harvest mechanization (threshers, grain polishers) at the right scale improves product quality and market competitiveness. Due to their ability to enhance soil resilience and mitigate environmental impact, incentives and extension services should be strategically deployed to promote the adoption of organic and biofertilizer use. To increase sustainability from moderate to high levels requires embedding these technological innovations within an integrated framework encompassing farmers, research institutions, and agribusinesses. A systemic approach supports recent worldwide proposals that use agronomic innovation, institutional support, and climate resilience to enable sustainable agricultural intensification (Kugedera *et al*., 2025).

Policy and regulatory dimension

Policy and regulation had a sustainability index of 24.04%, making it unsustainable (Fig. 7). Poor environmental governance hinders the integration and scaling of sorghum within climate-resilient agricultural commodity. According to Rapfish–MDS, a low index indicates fragmented policy support, weak regulatory instruments, and insufficient coordination for integrating sorghum into sustainable agricultural and climate adaption agendas. Due to its dryland flexibility, low input requirements, and ability to support diverse food systems, sorghum has high ecological potential. However, policy frameworks that focus on conventional staple crops and do not provide clear instruments for low-input crop diversification, sustainable land use, soil and water conservation, or resource-efficient food systems barely govern this potential. The poor grade indicates that sorghum policy support has not yet effectively addressed environmental concerns. Rice and maize dominate national policy, but sorghum is insignificant. Public investment, extension support, product standards, and sustainable processing incentives are limited. Here, regulatory weakness is not just a lack of price protection or market support. It shows the lack of policy mechanisms to link sorghum development to climate adaptation, environmental certification, circular biomass usage, and sustainable dryland management. Regulatory certainty and policy alignment foster agricultural sustainability

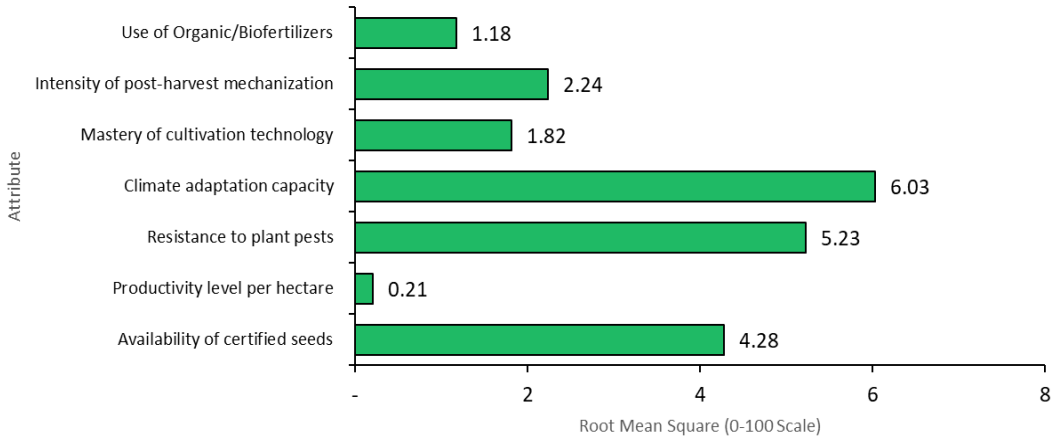

Fig. 6: Leverage values of technical and agronomic attributes

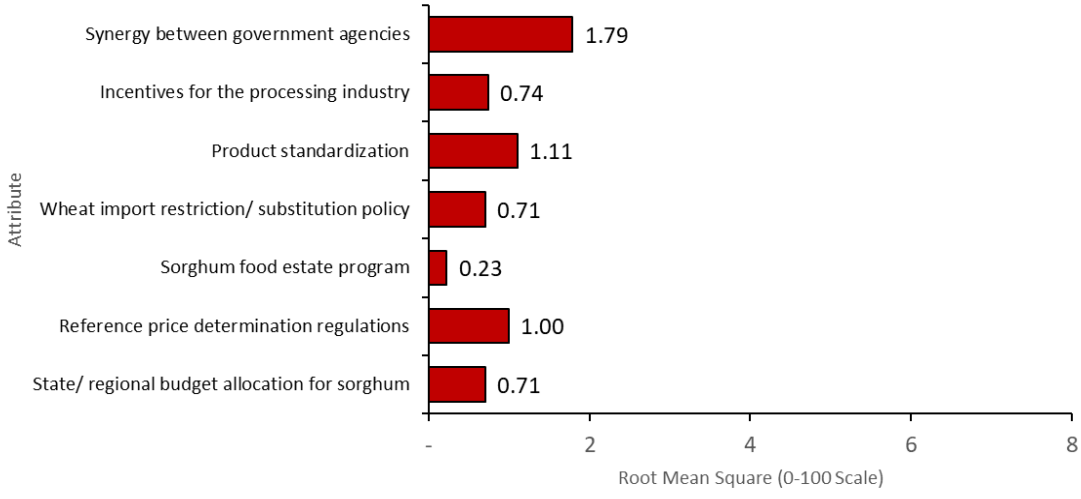

Fig. 7: Leverage values of policy and regulatory attributes

transitions by promoting the integration of underutilised and climate-resilient crops (Manevska-Tasevsk *et al*., 2023). Without greater environmental governance, environmental, technical, and economic gains may not lead to systemic sustainability. Based on leverage analysis, all policy and regulatory features are neutral, with values below 2%. This pattern reflects a generally deficient policy environment rather than an isolated regulatory failure. Government institution synergy (1.79), product standardisation (1.11), and processing industry incentives (0.74) have larger leverage (Fig. 7). These factors create the conditions for sustainable sorghum development. The successful execution of food diversification, climate adaptability, and land-use planning is contingent upon coordinated governance and cross-institutional synergy at the governmental level. Cross-sectoral cooperation can strengthen agri-food transformation policies, especially when national sustainability targets include local and underutilised crops (Candel and Biesbroek, 2016; Termeer *et al*., 2017). Market integration is not the only purpose of product standardisation. Establishing institutional standards bridges the gap between product

quality assurance and sustainable environmental governance by embedding safe processing practices, input reduction, residual circularity, and supply chain traceability into the agricultural life cycle. Implementing national standards can boost consumer trust and encourage resource-efficient production and processing. Similarly, processing industry incentives should not just boost downstream commerce. They should encourage circular economy methods including using sorghum wastes for animal feed, compost, bioenergy, and biomass products. Optimizing the ecological footprint of sorghum production systems requires a combination of waste-reduction policy tools and robust fiscal mechanisms designed to fortify environmental outcomes. Climate-smart extension services, certified seed systems, post-harvest infrastructure, soil and water conservation, and low-input agricultural technology transfer can benefit from consistent investment. Funding instability is a serious issue for neglected and underutilised crops (Mabhaudhi *et al*., 2017). Indonesia must properly codify policy initiatives for wheat import substitution (Liu *et al*., 2024b; Saspugayeva *et al.,* 2026) and sorghum flour integration to secure agri-food sustainability. These initiatives should encourage resource-efficient food diversity and lessen dependency on resource-intensive or externally reliant food systems, not just trade or industrial policy. Local content rules and targeted subsidies can promote alternative grain adoption when linked to sustainability goals, according to international experiences (Reardon *et al*., 2021; Schipanski *et al*., 2016). Enhancing this sustainability dimension necessitates the integration of regulatory frameworks with comprehensive environmental management practices. First, climate adaptation and sustainable land-use programs should include sorghum for dryland and marginal areas. Second, policy instruments should encourage certified seeds, bio-inputs, integrated pest management, and soil conservation for low-input crop diversity. Third, product requirements should include traceability, residue control, safe processing, and post-harvest loss reduction. Fourth, fortifying the value chain requires public investment to subsidize climate-smart agricultural extension, post-harvest infrastructure, and incentivize resource-efficient processing. Fifth, ministries, local governments, research institutes, and farmer organisations should collaborate on sustainability programs rather than administrative meetings. Finally, downstream incentives should promote circular, resource-efficient sorghum systems. Value-added products that optimize the utilization of sorghum grain and biomass should be incentivized through subsidized processing machinery, green financing, and collaborative public–private partnerships. These incentives can reduce waste, diversify local food, and boost sorghum cultivation's environmental value. Together, these changes would strengthen the policy and regulatory dimension from a poor market-support function to an environmental governance framework. Establishing such a framework is imperative to translate the ecological potential of sorghum into a resilient, inclusive, and sustainable agricultural system.

Institutional dimension

The institutional dimension of sorghum farming sustainability has an index value of 38.23% that is categorised as "less sustainable" and it is one of the weakest pillars in the broader multidimensional system. This diminished valuation underscores profound structural deficiencies in governance, inter-agency coordination, and institutional support mechanisms—all of which are vital to anchoring sustainable agricultural development. Institutional deficiencies, unlike technical or agronomic limits, tend to have systemic and

cascading implications affecting farmers' access to knowledge, markets, technology and collective action. The consistently moderate to low scores on institutional qualities are a sign that the current organisational ecology of farmer groups, cooperatives, extension agencies, and partnerships has not yet evolved into a cohesive and functional support structure. This finding aligns with a broader body of empirical literature indicating that deficient institutional arrangements and fragmented innovation systems constitute primary impediments to the scalability and resilience of agricultural development in emerging economies (Pigford *et al*., 2023). The leverage factor analysis shows the extension of worker assistance quality (2.59), research institutions and universities function (2.45) and farmers economic institutions (2.00) are some of the most influential aspects of this dimension (Fig. 8). Research institutions possess substantial strategic leverage, derived primarily from their foundational role in driving knowledge creation and technological innovation. However, the moderate score suggests that there remains a gap in knowledge transfer, as research products are not well disseminated to the farmers (Klerkx *et al*., 2019). In addition, farmer groups have an important role in encouraging collective action, bargaining power and access to supplies and markets, but their role is currently limited (Corsi *et al*., 2017). Poor performance in extension services, on the other hand, signals weaknesses in advising systems that are important for the translation of knowledge into practice and acceptance of technologies at the farm level. To overcome these institutional barriers, a highly integrated and systemic intervention framework must be deployed. Key priorities include strengthening agricultural extension services, developing the competence and professionalism of farmer organisations and improving cooperation among stakeholders. Furthermore, fostering participatory research methodologies and facilitating closer collaboration between knowledge producers and end-users are vital to narrowing the gap between theoretical innovation and empirical practice. These efforts are to be embedded in a broader institutional reform process that is collaborative, inclusive and aimed at establishing long-term capability. Thus, strengthening the institutional dimension is vital, since it is the enabling foundation that determines the efficacy and sustainability of all other dimensions within sorghum farming systems.

Cross-dimensional synthesis and policy implications

Rapfish–MDS found sustainability disparities in sorghum agricultural systems. Technical and agronomic are average, but environmental is good. Weak economic, commercial, social, cultural, institutional, policy, and regulatory factors. This reveals that sorghum growing is environmentally friendly but poorly managed. Weak governance integration and inadequate institutional scaffolding constitute the main systemic limitations obstructing the expansion of ecological potential. Despite ecological or scientific capabilities, new agricultural systems sometimes lack institutional preparation, policy coherence, and sustainable market structures (Tittonell, 2020). Sorghum's resource efficiency, arid-land adaptability, and climatic resilience significantly mitigate environmental degradation within vulnerable agrarian landscapes. Farmers, institutions, markets, and policymakers waste these gains without coordinated environmental management. The sustainability challenges associated with sorghum cultivation extend beyond mere production and agribusiness. Its management encompasses climate adaptation, resource efficiency, institutional coordination, post-harvest loss reduction, and the implementation of low-input agricultural policy.

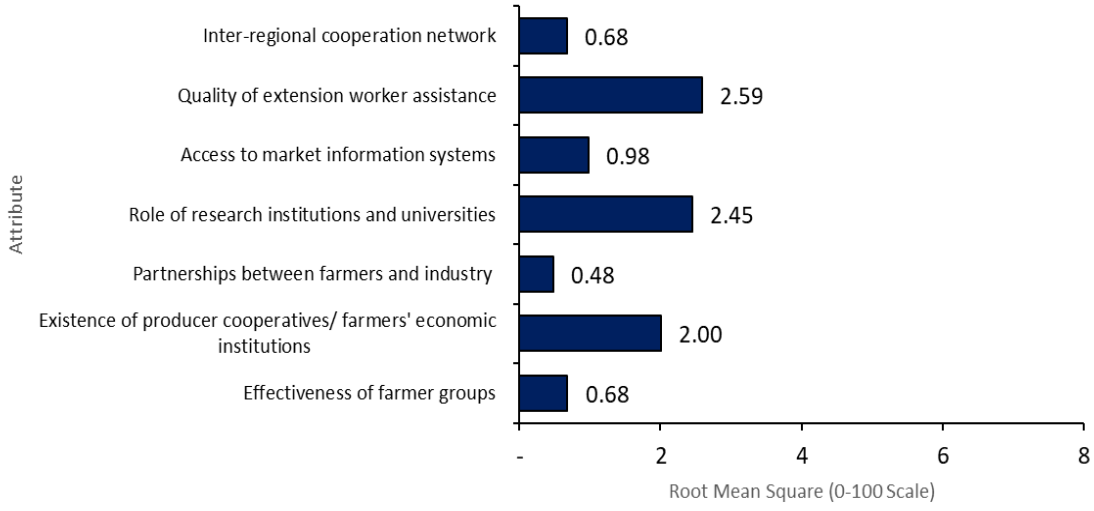

Fig. 8: Leverage values of institutional attributes

This synthesis illustrates how constraints lead underperformance. Poor policy and regulatory governance (24.04%) harms sorghum-based farming systems' environmental governance. Insufficient policy support affects public investment, institutional coordination, product standards, and sustainable production and processing incentives. Deficits in the economic and commercial dimensions (accounting for 45.01% of the model) present a major barrier; this weak market foundation constrains both commercial expansion and environmental scalability. Farmers lack the motivation and capacity to grow sorghum, invest in resource-efficient practices, or apply technology to prevent post-harvest losses and environmental harm without incentives and integrated sustainability-oriented value chains. Poor institutions worsen matters. With a 38.23% institutional rating, farmer groups, extension systems, and research–farmer ties cannot yet promote sustainable practices. Institutional instability severely restricts access to critical production inputs and practices, including certified seeds, bio-inputs, integrated pest management, climate-smart farming, biomass valorization, and post-harvest handling. Not all sorghum is sustainable. Social and cultural factors, with 48.95%, affect system transformation because low consumer acceptability and dietary integration reduce demand-side support for climate-resilient food systems. The links illustrate that individual efforts cannot improve sustainability. Changing agricultural sustainability demands integrated governance, robust institutional frameworks, efficient value chains, and socio-cultural acceptance (Reardon *et al.*, 2019). The findings suggest multi-level environmental management. First, increase policy and regulation by include sorghum in climate adaption, sustainable land-use, and food diversification programs. Policy should promote low-input farming, sustainable soil management, post-harvest loss reduction, and sorghum biomass circular utilization, alongside market expansion and price stabilization. Product standards should include safe processing, residual usage, chemical reduction, and traceability. Instead of providing market-side assistance, legislation frequently functions primarily as a mechanism for environmental regulation. Second, sustainable value-chain cooperation should promote the economy and market. Aggregation, contracts, and

buyer–farmer partnerships should improve environmental and commercial efficiency. These institutional arrangements can enhance certified seed, biofertilizer, promoting pesticide reduction, improving drying, storage, biomass recycling, and post-harvest loss mitigation. Increase logistical infrastructure to reduce food loss, land and water waste, and sorghum-based systems' environmental effect. Value-chain development should be part of an environmental management architecture for production, processing, distribution, and disposal. Third, institutions increase flexibility and information sharing. the climate-smart farming ought to be restored to integrate pest management, soil health enhancement, and post-harvest handling extension programs. Agricultural organizations must enhance their operational capacity by expanding knowledge-sharing frameworks, securing critical input distribution networks, optimizing biomass management systems, and implementing robust traceability protocols. Research institutions, universities, extension agencies, local governments, and farmer communities must collaborate to propagate innovation and adapt scientific knowledge to farm-level environmental practises (Klerkx *et al*., 2019). Fourth, social and cultural policies should promote sustainable consumption and demand-side reform. Consumer awareness, coupled with strategic product innovation, and cultural repositioning of sorghum, can effectively stimulate market demand and diversify dietary patterns away from resource-intensive staples. Easy processing, nutrition understanding, and sorghum perception can boost climate-resilient food acceptance. Demand-side support is necessary for agricultural system environmental management because output and consumption patterns affect long-term land- and resource-use decisions. The cross-dimensional synthesis suggests integrated environmental management for sorghum growing. Without sustainability goals, policies, institutions, markets, and society tend to underutilize the ecological strengths of the system. Sustainable value chains, institutional capabilities, governance, and social acceptance may make sorghum development integrated, resource-efficient, and climate-resilient. Sustainable agricultural transformation requires environmental, institutional, economic, and social coordination (Pretty *et al*., 2018; Tittonell, 2020).

MICMAC-Based Structural Analysis of Key Sustainability Leverage Factors

MICMAC maps the influence-dependence dynamics of the critical leverage elements revealed by Rapfish-MDS to provide a deeper structural diagnosis of the sustainability framework. Fig. 9 illustrates the influence network, which demonstrates a complex web of interactions and various degrees of influences across variables, showing that sorghum farming needs a highly interdependent system to survive. Strong (red) and moderate (blue) linkages indicate that numerous factors influence and are influenced simultaneously, indicating systemic feedback loops. In agricultural innovation systems, institutional, technological, and economic components co-evolve and interact (Klerkx *et al*., 2019). Interestingly, climate adaptation capacity, certified seed availability, and climate resilience exhibit extensive incoming and outgoing interactions, confirming their importance in the system. The density of this structure suggests that any perturbation in these variables will generate extensive multiplier effects, propagating through multiple pathways across the system. The influence- dependence matrix (Fig. 10) provides an additional classification of the variables in four quadrants: driving, linkage, dependent, and autonomous, which gives important insights into their strategic functions. Notably, extension service quality and the institutional involvement

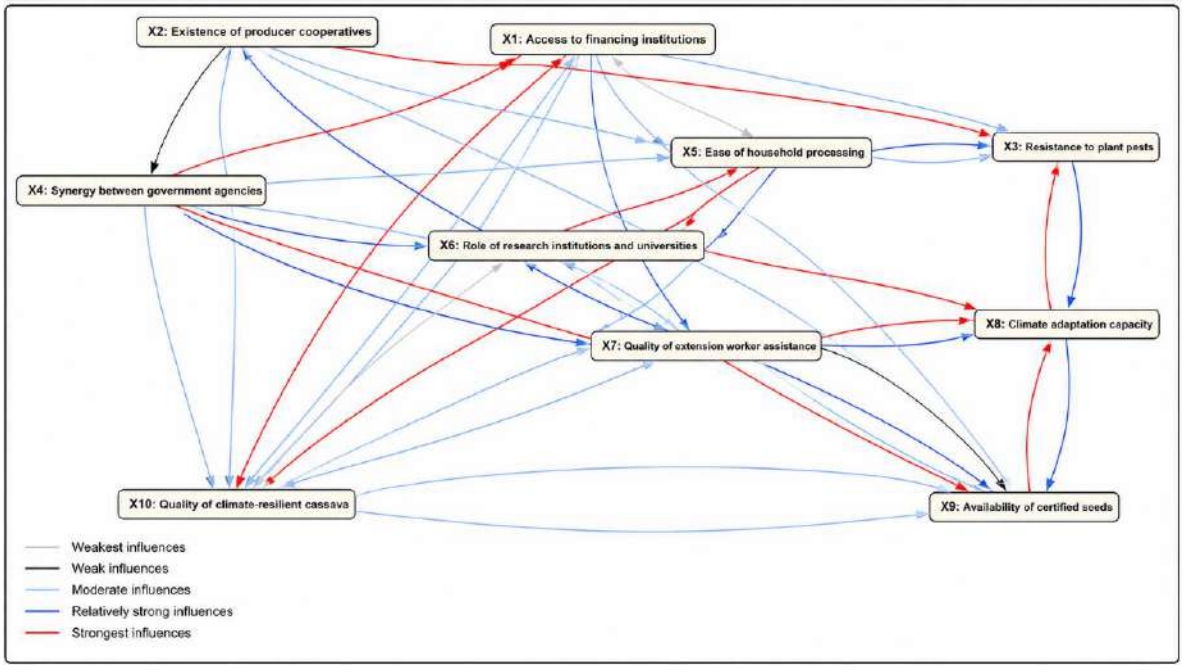

Fig. 9: MICMAC direct influence–dependence map showing the structural classification of key sustainability variables

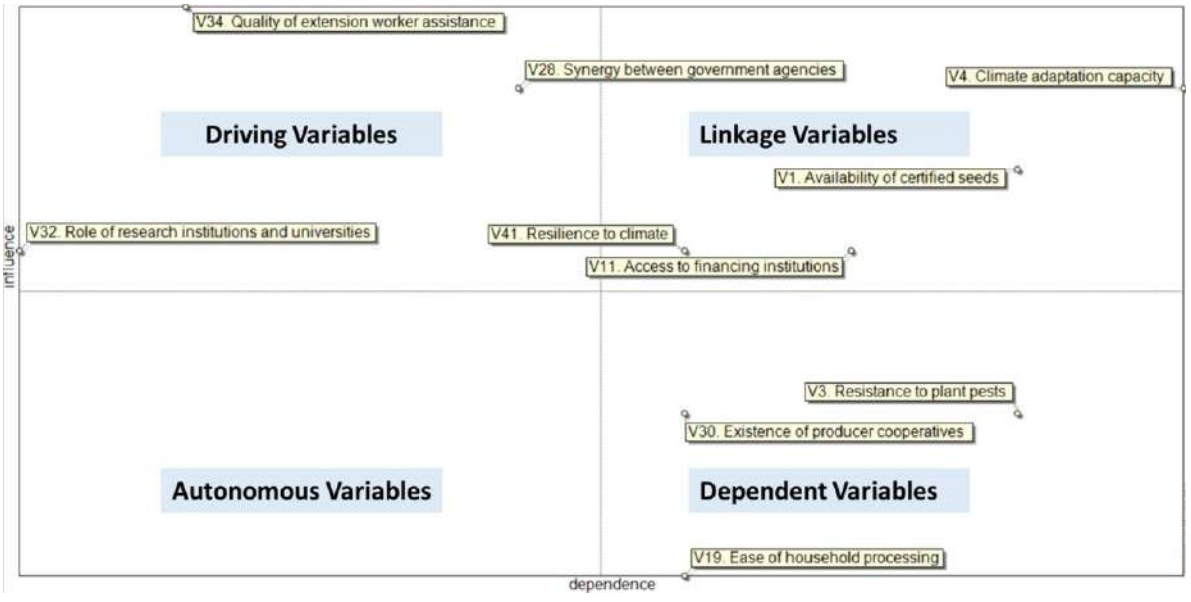

Fig. 10: MICMAC direct influence graph of dominant sustainability leverage variables in sorghum farming

of universities and research entities function as primary inputs within the system architecture, exerting substantial influence while remaining largely decoupled from downstream systemic dependencies. Consequently, these attributes function as foundational enablers of system transformation. Prioritizing interventions that strengthen these variables is critically important,

as they affect knowledge development, dissemination and capacity building across the entire framework. This finding aligns with previous studies that emphasizes the importance of effective extension systems and robust research–farmer linkages as critical drivers of agricultural innovation and facilitating sustainability transitions (Klerkx *et al*., 2019). But variables such as climate adaption capacity, availability of certified seeds, access to financial institutions, and cooperation among government agencies are extremely influential and dependent, hence very sensitive and unstable. Consequently, these attributes function as highly volatile transmission nodes, where localized improvements or systemic disruptions can propagate rapidly across the entire framework. Their dual role implies that policy actions need to be properly coordinated, as partial or imbalanced improvements can have unwanted systemic impacts. Dependent variables including plant pest resilience, producer cooperatives, and household processing ease exhibit a high level of dependency yet possess a low degree of influence. The outcome-oriented variables show upstream intervention success. Improvements in extension services, seed systems, and financing should indirectly boost pest resistance and processing ease. Finally, the absence or small number of strong autonomous variables suggests that most system components are closely related, supporting the idea that sorghum farming sustainability is systemically integrated. These outcomes indicate that effective policy design must prioritize interventions at the root driver level, while addressing highly volatile transmission nodes through well-coordinated, multi-stakeholder coalitions. This method maximises systemic leverage for more efficient and scalable sustainability performance increases. This systemic approach supports current agricultural transformation paradigms that demand integrated knowledge, institution, and value chain interventions for sustained results (Reardon *et al*., 2019; Tittonell, 2020).

CONCLUSION

This study assessed Indonesian sorghum farming systems' sustainability and structural leverage using Rapfish–MDS and MICMAC. The system is less sustainable, even if sorghum is climate-resilient. The environmental dimension achieved the highest sustainability index (74.51%), followed by the technical and agronomic dimension (55.37%), confirming sorghum's suitability for dryland agriculture through its climate adaptability, resource-use efficiency, and ecological resilience. However, weaker economic, market, social and cultural, institutional, and policy performance suggests structural reasons beyond agronomic performance limit sustainability. Policies and regulations scored the lowest (24.04%), indicating governance issues as the main impediment to system reform. The structural scaling and adaptive capacity of the sorghum sector are severely impeded by a critical matrix of bottlenecks, specifically market volatility, poor financial inclusion, weak institutional synergy, low consumer adoption, and inadequate extension infrastructure. Further, MICMAC analysis found extension services, research institutions, and inter-governmental cooperation as driving variables and climate adaptation capacity, certified seed availability, and access to finance as linkage variables with strong systemic influence. Sustainability requires supportive institutions, enabling regulations, effective market incentives, and knowledge systems, not just environmental advantages. A purposively selected panel of 12 expert respondents provided the baseline evaluation for this study. The underlying Rapfish–MDS and MICMAC architectures prioritize analytical depth over large-scale statistical representativeness, deriving model validity from attribute-based

evaluation, ordination stability, goodness-of-fit parameters, and comprehensive robustness testing. It did not directly measure biophysical indicators like soil carbon, water-use efficiency, greenhouse gas emissions, or biodiversity, and MICMAC relationships are still subject to expert interpretation and need longitudinal studies and system-dynamics approaches to validate. Rapfish–MDS and MICMAC integrate to simplify sustainability diagnosis and intervention prioritization. The forthcoming actions should focus on enhancing extension systems, boosting the availability of certified seeds, broadening agricultural finance, upgrading post-harvest infrastructure, stabilizing markets, and fostering better coordination among government agencies, research institutions, universities, farmer organizations, and agribusiness stakeholders. These measures, along with food diversification, product standardization, and downstream industrial development, can make Indonesia and other emerging agricultural economies' sorghum farming systems more robust, inclusive, and sustainable. Rather than denoting experimentally validated measures, the proposed policy and management interventions represent strategic priorities derived from empirical stakeholder assessments and structural system analyses. The field implementation and longterm research are required to measure their effects. This study's sustainability assessment relied on organized expert judgment rather than environmental monitoring. Thus, experts assessed climate adaption capabilities, water-use efficiency, soil fertility management, carbon emissions, and biodiversity conservation rather than field-based quantitative indicators. Consequently, these indices should be interpreted as a qualitative structural diagnosis of sustainability dynamics rather than a quantitative tracking of biophysical metrics. To improve empirical validation and sustainability evaluation, future research should combine expert-based assessment with biophysical variables as soil quality, greenhouse gas emissions, water productivity, and biodiversity indices.

AUTHOR CONTRIBUTIONS

N. Ismail has contributed in supervising and made critical revision of the manuscript; Cepriadi as a correponding author performed the literature review; Y. Riyanto performed the literature review and critical revisions, R. Catursaptani performed analysis and interpretation of MDS data; I. Habiburrahman drafting of the manuscript; W. Basuki supervised all experiments and manuscript preparation; Sihono manuscript preparation and critical revisions; Herniwati supported the administrative, technical, or material support; Hadiarto performed statistical analysis; W.M. Indriatama supervised all experiments and manuscript preparation; D. Iskandar performed the literature review; A.H.Y. Rosadi supported experimental, administrative work and provided technical assistance; H. Daulay performed analysis and interpretation of MDS and MICMAC data; A.D. Santoso prepared all the maps and figures and interpretation of the results.

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CONFLICT OF INTEREST

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

double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
ASCAL	Alternating least-squares scaling
APBD	Regional Budget allocation
APBN	National Budget allocation
CSA	Climate smart agriculture
d	Euclidian distance
dij	euclidian distance from point i to point j
FAO	Food and agriculture organization
FGD	Focus group discussion
IPM	Integrated pest management
ijk	dimension
LCA	Life cycle assessment
m^3/ha	Cubic meters per hectare
MDS	Multidimensional scaling
MICMAC	Matrix of cross impact multiplication applied to classification
OECD	Organisation for economic co-operation and Development
oijk	point of origin
R^2	goodness-of-fit
Rapfish	Rapid appraisal for fisheries
RMS	root mean square
S	Stress
SNI	National quality standards
SQR	Structured query reporter

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CASE STUDY

Socio-ecological transformation and biodiversity dynamics under agromaritime development

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ABSTRACT

BACKGROUND AND OBJECTIVES: Agromaritime development transformation in tropical regions reflects the complex relationship between development pressure, biodiversity degradation, and socio-ecological vulnerability. Central Sulawesi has experienced significant ecological changes across upland landscapes, coastal zones, and small islands due to agricultural expansion, infrastructure development, aquaculture growth, and marine resource exploitation. However, biodiversity management and spatial planning frameworks remain heavily fragmented by sectoral approaches that artificially decouple terrestrial, coastal, and marine ecosystems, thereby obscuring critical ecological connectivity and its associated socio-economic ramifications. The study objectives were to analyze biodiversity dynamics and socio-ecological transformation across four major ecoregions of Central Sulawesi using a cross-ecoregional socio-ecological framework.

METHODS: This study employed a socio-ecological qualitative approach by adapting the Drivers–Pressures–State–Impact–Response framework and integrating perspectives from socio-ecological systems, ecological justice, feminist political ecology, and relational planning. The methodological framework relied on an integrated approach, utilizing spatial analysis, an extensive literature review, ecological field observations, stakeholder interviews, and an evaluation of environmental governance documentation. The research covered four interconnected ecoregions, including the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands.

FINDINGS: The analysis revealed that biodiversity changes across Central Sulawesi occurred through interconnected terrestrial, coastal, and marine processes. The Lore Lindu Highlands lost approximately 28,495 hectares of primary forest between 2001 and 2021. Eastern Tomini Bay experienced around a 24 percent decline in seagrass cover, while mangrove conversion along the Tolo Bay Coast exceeded 1,600 hectares. In the Banggai Islands, the endemic Banggai Cardinalfish population decreased by approximately 60 percent due to overexploitation and habitat degradation. These ecological pressures manifested as asymmetrical socio-economic impacts, disproportionately affecting small-scale fishers, women, indigenous populations, and vulnerable coastal communities. The findings also indicate that existing governance responses remain fragmented and have not sufficiently integrated upstream-downstream and land-sea management systems.

CONCLUSION: Biodiversity transformation in Central Sulawesi represents a socio-ecological process shaped by ecological connectivity, development pressure, and unequal environmental impacts. Ultimately, the cross-ecoregional socio-ecological framework formulated herein elucidates the systemic linkages between ecological dynamics, institutional governance, and local community vectors, establishing a robust baseline for adaptive biodiversity conservation across tropical agromaritime interfaces.

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INTRODUCTION

The global biodiversity crisis shows that ecological degradation and economic growth often occur simultaneously, particularly in the tropical regions of the Global South. Anthropogenic drivers, namely land-use change, infrastructure expansion, and natural resource exploitation—compounded by the accelerating pressures of climate change, have severely exacerbated biodiversity loss and compromised the critical ecosystem services that sustain human well-being. The report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Brondizio *et al*., 2019) indicates that nearly one million species are at risk of extinction due to human activities. Within this framework, biodiversity is no longer conceptualized merely as an isolated conservation metric, but rather as a foundational pillar of socio-ecological resilience and regional sustainability (Newell *et al*., 2022; Washington *et al*., 2024). However, ecological degradation does not affect everyone equally. Communities that are highly dependent on natural resources are often the most affected, particularly because they have limited involvement in decision-making on development. The overexploitation of marine resources, forest conversion, and coastal reclamation can reduce access to food, water, and traditional livelihoods. For indigenous communities, these environmental transformations risk severing the socio-ecological attachments that have historically anchored their cultural identity and subsistence practices (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Thus, the biodiversity crisis is fundamentally also a crisis of ecological justice. For several decades, modern regional development has been built on the assumption that economic growth, infrastructure expansion, and spatial optimization are the key indicators of regional progress, although this approach often overlooks the complexity of socio-ecological relationships and the spatial inequalities that arise in the development process (Porter *et al*., 2020; Uitermark, 2012). Within this paradigm, biodiversity is frequently conceptualized as a residual concern, remaining external to the core operational logic of regional development. Space is understood primarily as an economic and administrative object that can be regulated to enhance regional productivity and capital accumulation (Schragger, 2023). Consequently, numerous regions characterized by high ecological richness are concurrently subjected to the most intensive development pressures, this paradox is especially pronounced within the tropical territories of the Global South, where local economies remain heavily reliant on primary resource extraction (Martinez-Alier, 2021; Sultana, 2023). In fact, various studies show that biodiversity loss not only affects species and habitats, but also impacts regional resilience, socio-ecological stability, and the long-term sustainability of development (Newell *et al*., 2022; Nishi *et al*., 2026). Deforestation, coastal degradation, and the decline in the quality of marine ecosystems represent a spatial crisis that impacts food systems, water availability, coastal protection, and the sustainability of local communities' livelihoods (Langemeyer and Connolly, 2020). Therefore, biodiversity loss should be understood as part of broader socio-ecological transformation involving ecological processes, development trajectories, and changing relationships between humans and nature. In response to these concerns, the landscape approach has emerged as a compelling paradigm that conceptualizes landscapes as integrated socio-ecological systems (SES) effectively coupling upstream catchment areas, river basins, coastal zones, marine ecosystems with both production and conservation matrices. Recent findings by Nishi *et al*. (2026) establish a direct causal link between upstream land-use changes and the degradation of downstream coastal and marine ecosystems driven by sedimentation, altered water chemistry, and habitat fragmentation. Consequently, regions

cannot be understood solely through administrative boundaries, but through the ecological and social interconnections that form a landscape continuum. In the Indonesian context, these challenges are becoming more complex as rapid development transforms areas of high biodiversity. Gunawan *et al*., (2022) shows that natural resource management in Indonesia is still largely focused on sectoral interests and economic growth, while biodiversity conservation often receives less attention in regional development policies. In agromaritime zones, such pressures manifest through diverse developments, including plantations, mining, coastal urbanization, and port construction, as well as the intensification of aquaculture and the depletion of marine resources. Therefore, agromaritime transformation reshapes both regional economy and human-nature relationships, while also creating new forms of socio-ecological vulnerability. Until now, regional development has often been based on a separation between social and ecological systems. Developmental discourse consistently privileges economic expansion as the core objective, conversely relegating environmental governance to a subordinate sector addressed primarily through technocratic and regulatory interventions. The *coupled human-natural systems* approach subsequently emerged to explain the reciprocal relationship between human activities and environmental dynamics (Liu *et al*., 2007). This perspective emphasizes that ecological pressures are not only generated by economic activities but are also influenced by development policies, power relations, technological change, and social transformation. In this context, agromaritime development should not be conceptualized solely through the lens of regional economic growth, but rather as a structural socio-ecological transformation that redefines human-nature relations. The perspective of *ecological justice* has emerged as a critique of development models that result in an unequal distribution of environmental benefits and burdens. (Washington *et al*., 2024) assert that biodiversity conservation cannot be separated from social justice and communities' ecological rights. Contemporary environmental governance frameworks frequently remain tethered to exclusionary, technocratic conservation paradigms that conceptualize indigenous and local populations as external threats to biodiversity, rather than as intrinsic components of the socio-ecological matrix. This perspective is further reinforced by Schlosberg and Collins (2014), who demonstrate that the ecological crisis is fundamentally also a crisis of distribution, recognition, and participation in development processes. These socio-ecological challenges are clearly reflected in Central Sulawesi Province, an important biodiversity region within Wallacea characterized by high endemism and strong ecological connectivity among terrestrial, coastal, and marine ecosystems. The region connects the Lore Lindu Mountain landscape, river basin systems, Tomini and Tolo coastal areas, and the small island ecosystems of the Banggai Archipelago (Mujio *et al*., 2026). Over the past two decades, agricultural expansion, infrastructure development, mining activities, coastal transformation, aquaculture growth, and marine resource exploitation have increased pressures on these interconnected ecosystems (CSPEA, 2022). This perspective aligns with the SES framework, which conceptualizes human communities and the biophysical environment as a unified, complex adaptive system characterized by reciprocal interdependencies and continuous, dynamic change (Folke *et al*., 2005; Reyers and Selig, 2020). In this approach, biodiversity does not merely represent the physical presence of a species and its habitat, but also reflects regional resilience, ecological connectivity, and the adaptive capacity of local communities to respond to environmental pressures and developmental changes (Biggs *et al*., 2021; Norström *et al*., 2020). Consequently, ecological change defies isolated, sectoral analysis; rather, it demands an analytical framework grounded in cross-scale feedback loops that dynamically integrate anthropogenic

activities, spatial planning, and regional ecological systems (Bennett *et al*., 2021; Preiser *et al*., 2017). This perspective is increasingly relevant in tropical agromaritime regions experiencing rapid development pressures, where connectivity between land–sea systems, land-use changes, and socio-ecological inequalities shape complex and mutually influencing biodiversity dynamics. This situation has given rise to criticism of conventional spatial planning approaches, which are regarded as overly sectoral and technocratic (Mattila *et al*., 2024). Schragger (2023) refers to this as a 'conflict of rationalities'—a clash between the logic of modern, state- and market-oriented development and ecological rationality, as well as the way of life of local communities. The decoupling of biodiversity conservation from spatial planning frameworks frequently exacerbates ecological fragmentation, intensifies spatial inequities, and compounds socio-environmental vulnerabilities during developmental processes (Figueroa *et al*., 2024). This criticism subsequently gave rise to the ecological regional planning approach, which places ecological structure and biodiversity at the heart of regional development. In this approach, a region is understood as an ecological system interconnected through water flows, habitat corridors, ecological processes, and human-environment interactions (Newell *et al*., 2022). This approach has evolved into biodiversity-sensitive planning, which considers ecological sensitivity in every spatial development decision, including protecting habitat connectivity, ensuring environmental carrying capacity, and safeguarding the sustainability of ecosystem services. Analogous conceptual limitations characterize the Drivers-Pressures-State-Impact-Response (DPSIR) framework, despite its historical ubiquity within environmental analysis. Although the DPSIR framework has been widely applied to analyze environmental change, conventional applications often emphasize linear cause–effect relationships and provide limited explanation of cross-scale ecological connectivity, governance complexity, and differentiated socio-ecological impacts (Patrício *et al*., 2016). Notwithstanding the growing scholarly emphasis on biodiversity conservation and socio-ecological frameworks, three salient research gaps persist. First, many studies still examine terrestrial, coastal, and marine ecosystems separately, limiting understanding of biodiversity dynamics across interconnected landscapes and seascapes. Second, biodiversity assessments frequently emphasize ecological changes while giving less attention to unequal impacts experienced by different social groups. Third, conventional applications of the DPSIR framework seldom synthesize ecological connectivity, governance mechanisms, and environmental justice considerations within a comprehensive cross-ecoregional analytical matrix. This limitation is particularly relevant in agromaritime regions, where biodiversity dynamics are shaped by complex interactions among mountainous landscapes, river systems, coastal zones, marine ecosystems, and the livelihoods of local communities. Within these regions, environmental pressures frequently propagate across the land–sea interface, generating asymmetrical socio-ecological consequences across heterogeneous communities. To fill this gap, the study introduces a cross-ecoregional socio-ecological DPSIR framework that integrates several perspectives, including SES, ecological connectivity, ecological justice, and relational regional planning, to better understand environmental change across interconnected regions. Departing from traditional DPSIR methodologies, the framework introduced herein conceptualizes biodiversity transformation as a highly dynamic phenomenon operating across interconnected ecosystems and trans-regional boundaries. It is shaped by the interactions among development pressures, environmental changes, governance systems, and the varying vulnerabilities of different social groups. The framework is designed to identify the factors driving biodiversity change, explore ecological interactions across regions, assess the socio-

ecological consequences of biodiversity loss, and evaluate governance responses through a relational planning approach. By synthesizing socio-ecological and social dimensions, this study elucidates the complex mechanisms through which agromaritime development reconfigures human–nature relationships across contiguous land–sea interfaces. This study aims to analyze biodiversity transformation and socio-ecological dynamics across interconnected agromaritime ecoregions in Central Sulawesi. This study was conducted across four major agromaritime ecoregions of Central Sulawesi Province, Indonesia, namely the Lore Lindu Highlands, Eastern Tomini Bay, the Tolo Bay Coast, and the Banggai Islands, in 2025.

MATERIALS AND METHODS

The study area

The study focuses on four major ecoregions in Central Sulawesi: The Lore Lindu Highlands, Eastern Tomini Bay, the Tolo Bay Coast, and the Banggai Islands. These four ecoregions were selected as study sites because they encompass a diverse range of SES and different agromaritime development pressures, while simultaneously exhibiting robust land–sea ecological connectivity. The Lore Lindu Highlands are an upstream location with a tropical montane forest habitat that acts as the primary buffer for the regional river basin. Eastern Tomini Bay is a transitional zone between the river basin and the coast, heavily influenced by sedimentation and coastal urbanization. The littoral zone of Tolo Bay is subject to profound anthropogenic pressures, characterized primarily by mangrove conversion, accelerated aquaculture intensification, and the concomitant degradation of marine ecosystems. Meanwhile, the Banggai Islands contain a system of small tropical islands with high marine endemism but significant ecological vulnerability due to ornamental fish trading and the exploitation of marine resources. Geographical location of the study area in the four major agromaritime ecoregions of Central Sulawesi Province, Indonesia shows in Fig. 1.

Epistemological positioning and research design

Based on the relational socio-ecological planning paradigm, this research adopts an approach that views biodiversity, regional development, and the social life of communities as processes that mutually shape one another ecologically, spatially, and politically. With this paradigm, environmental change is conceptualized not as an isolated biophysical reality, but rather as an emergent property of the interconnections among development dynamics, power relations, spatial governance, and the lived experiences of local communities. This epistemological stance is important because most studies of biodiversity and regional development are still dominated by positivist and sectoral approaches that separate social systems from ecological systems. In much conventional research, biodiversity is treated as an environmental indicator that can be measured technically, while the development process is understood primarily as an economic and administrative spatial planning issue. Such an approach obscures the mechanisms through which ecological transformations propagate across adjacent ecosystems, generate asymmetrical impacts among diverse social groups, and institutionalize forms of environmental injustice within regional development paradigms. To address these limitations, this study develops the cross-ecoregional socio-ecological DPSIR Framework, an expanded version of the DPSIR framework that combines the perspective of SES, ecological justice, feminist political ecology (FPE), and cross-ecoregional analysis. This approach was developed because the conventional DPSIR framework is often criticized for being linear, technocratic, and state-centric, and thus unable to adequately capture power relations, communities' ecological experiences, and cross-ecosystem interconnections in regional transformation (Bennett *et al*., 2021; Mattila *et al*., 2024; Patrício *et al*., 2016). In the conventional DPSIR framework, the interplay among drivers,

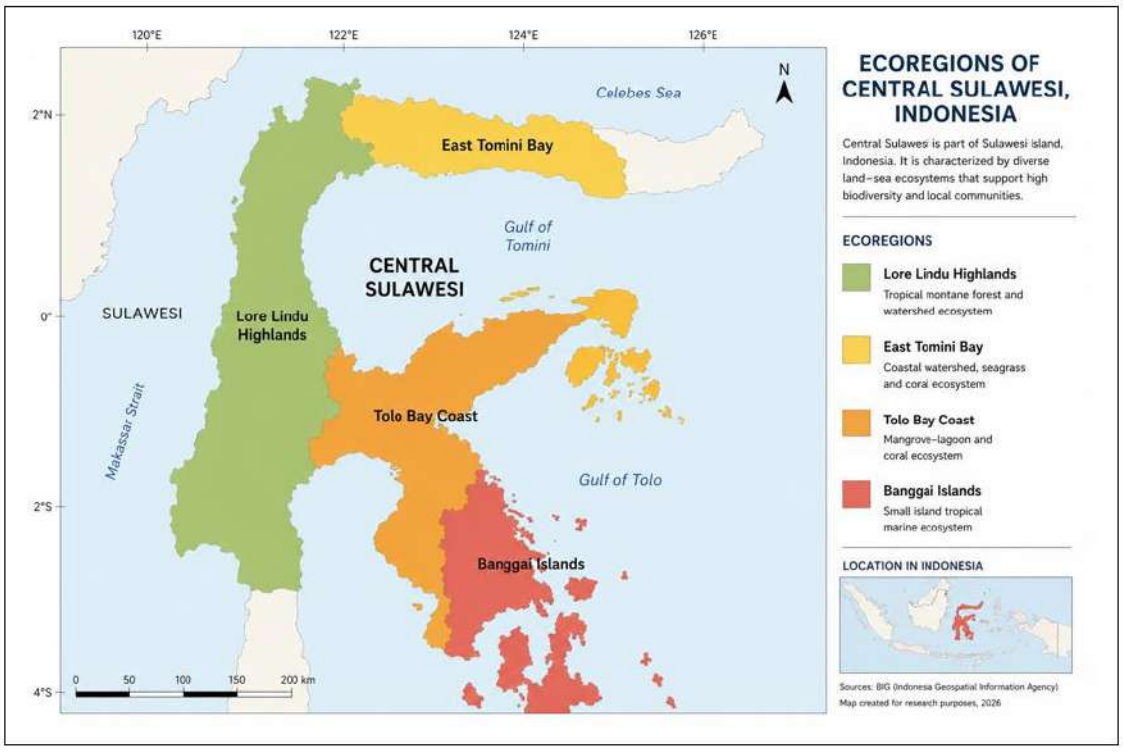

Fig. 1: Geographical location of the study area in the four major agromaritime ecoregions of Central Sulawesi Province, Indonesia

pressures, state, impact, and response are typically conceptualized as a simplistic, linear causal chain. In reality, however, socio-ecological change operates through relational dynamics and multi-scalar processes rather than isolated events. Policy responses can in turn influence development drivers; changes in ecological conditions (state) can intensify pressures, while ecological impacts are not experienced equally by all community groups. Consequently, this study views the DPSIR framework not as a linear environmental model, but as a relational framework for analyzing socio-ecological transformations at the regional level. Through this approach, the region is conceptualized not analyzed as an isolated administrative unit, but rather as a network of socio-ecological flows that structurally link upstream, coastal, and marine environments within a singular, interdependent ecological system. This perspective is consistent with the coupled human-natural systems approach, which views humans and the environment as parts of a system that dynamically influence one another (Liu *et al.*, 2007). Furthermore, this study also adopts a relational planning approach that views space not merely as a technical object of planning, but as a dynamic construct co-constituted by evolving social, ecological, and political interactions. (Porter *et al.*, 2020; Schragger, 2023). In practical terms, this study employs a cross-ecoregional approach to understand how agromaritime development pressures move across terrestrial and marine systems. This approach was chosen because the region's transformation in Central Sulawesi portrays strong ecological connectivity among upstream areas, river basins, coastal zones, and small islands. Consequently, biodiversity decline cannot be adequately explained through the lens of isolated administrative boundaries or discrete environmental typologies alone across interconnected socioecological landscapes.

Cross-ecoregional socio-ecological framework

This study employs the cross-ecoregional socio-ecological framework as its primary analytical framework to understand the relationship between agromaritime development transformations and changes in biodiversity in Central Sulawesi. This framework extends the conventional DPSIR model by integrating the SES approach, ecological justice, FPE, and cross-ecoregional spatial analysis. The development of this framework originates from a critical appraisal of the conventional DPSIR model, which has historically functioned primarily as a tool for environmental monitoring and the technical evaluation of environmental policy (Langemeyer and Connolly, 2020). In rapidly transforming agromaritime regions such as Central Sulawesi, biodiversity dynamics cannot be comprehensively assessed through isolated sectoral or administrative lenses. Rather, ecological alterations must be conceptualized as features of interconnected SES that bridge diverse ecoregions, developmental trajectories, and human–environment interactions. This perspective is consistent with the SES approach, which views human communities and ecological systems as interdependent components that continuously influence one another adaptively (Folke *et al*., 2005; Liu *et al*., 2007). In this approach, the environment is treated as an object that can be measured through biophysical indicators, while social dimensions, power relations, and people's ecological experiences are often overlooked in the analysis. To address these limitations, this study reconfigures the traditional DPSIR model into a more relational, multi-scalar, and spatially explicit socio-ecological framework. In this framework, regional transformation is driven by several structural factors, including agricultural expansion, coastal urbanization, mining, port development, and global trade in marine resources. These factors lead to pressures such as deforestation, sedimentation, mangrove conversion, overfishing, habitat deterioration, and coastal pollution. These anthropogenic and environmental pressures profoundly alter the region's socio-ecological state, driving systemic changes in forest cover, the degradation of critical marine habitats—such as seagrass beds and coral reefs and a concomitant decline in both water quality and endemic species populations. However, in this study, 'state' is understood not only as the biophysical condition of the environment, but also as changes in the socio-ecological capacity of communities to sustain their livelihoods and the region's sustainability. Furthermore, impacts are understood as uneven ecological and social impacts. The effects of environmental change are not experienced equally by all social groups. Small-scale fishers, coastal women, indigenous peoples, and small island communities typically constitute the demographics most susceptible to biodiversity degradation and the destabilization of their critical living spaces. This perspective is integrated from the approaches of ecological justice and FPE, which emphasize the importance of interpreting communities' ecological experiences in a more contextual and differential manner (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Meanwhile, 'response' is understood not merely as formal government policy, but also includes community adaptation practices, community-based conservation, local ecological knowledge, and forms of social resistance to development pressures. Within this framework, 'response' is conceptualized not as a terminal, linear output, but as a dynamic component that exerts reciprocal feedback on drivers, pressures, and socio-ecological states. Thus, the relationships among the DPSIR framework components are understood as dynamic, relational processes rather than linear cause-and-effect. This approach enables the study to analyze agromaritime transformation more integratively, accounting for complex land–sea interconnections, power dynamics, diverse local communities' ecological experiences and cross scale upstream–downstream relationships. The conceptual framework developed in this study is presented in Fig. 2.

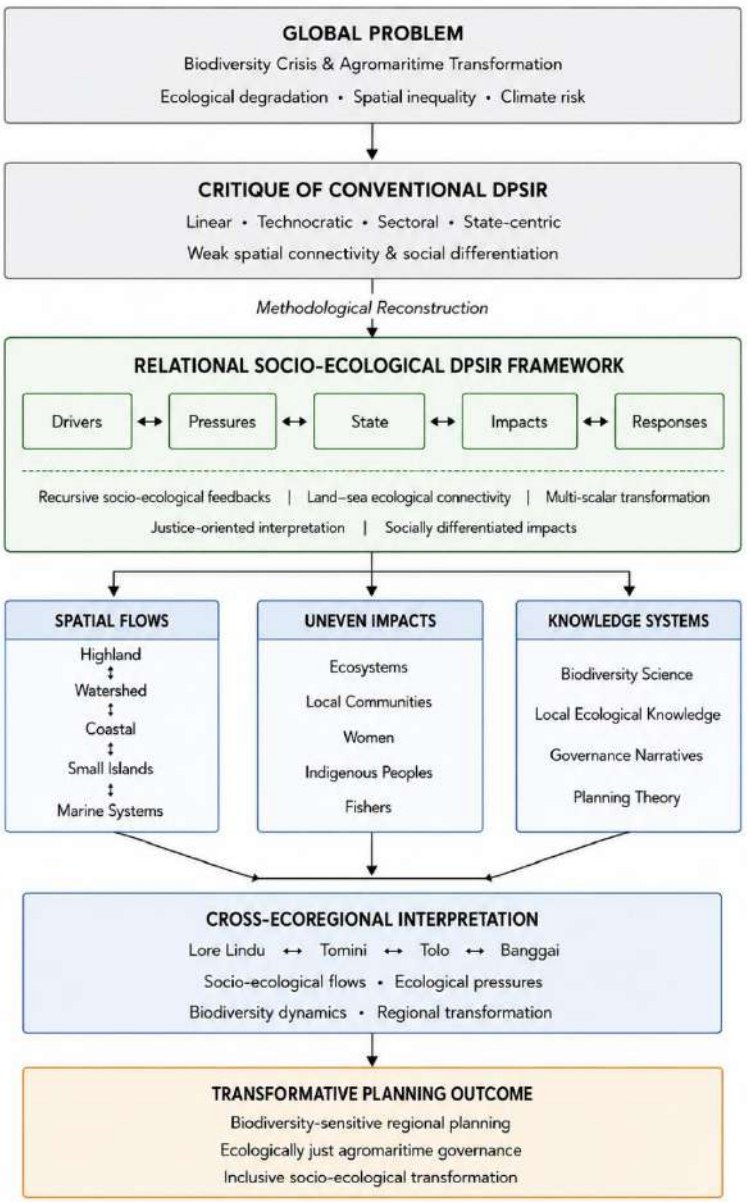

Fig. 2: Relational socio-ecological DPSIR framework for understanding biodiversity transformation in Central Sulawesi

Multi-source evidence and relational data collection

This study employs a multi-source evidence approach to capture the complexity of socio-ecological transformations in the region through the integration of various types of data and knowledge sources. This approach was chosen because changes in biodiversity and development pressures defy comprehensive analysis when restricted to a singular data type or a strictly positivist paradigm. Data collection was carried out through the triangulation of five main sources, namely spatial analysis; literature review; field ecological observations; stakeholder interviews; and biodiversity data and environmental governance documents. This synthesis serves to

minimize uncertainty in the interpretation of complex socio-ecological transformations. By integrating primary field observations and stakeholder perspectives with secondary spatial and institutional datasets, a robust analytical framework is established to cross-validate findings across terrestrial, coastal, and marine systems. Spatial analysis was conducted to identify patterns of land-use change, ecosystem degradation, and ecological connectivity between regions. Building on this, the study evaluated longitudinal land cover transitions by leveraging multi-temporal datasets spanning the 2001–2021 period. Coastal ecosystem alterations, namely mangrove conversion and seagrass degradation—were then assessed by synthesizing satellite-based spatial data with regional monitoring reports and existing ecological studies. This integrated approach enabled a systematic tracing of both the trajectory and magnitude of socio-ecological shifts spanning the upstream-coastal-marine continuum. This approach was used to understand the distribution of development pressures and ecological relationships across ecoregions within upstream–downstream and land–sea systems. To ground this study, a comprehensive literature review was executed, spanning international journals, policy documents, government reports, and scientific publications at the intersection of biodiversity, regional development, SES, ecological justice, and FPE. The literature was used not only as a source of secondary data but also as a theoretical interpretative tool for analyzing regional transformations. The data source, analytical procedures, and validation methods of this study are summarized in Table 1. Following the methodological framework presented in Table 1, this study combined ecological field observations with information obtained from stakeholders to develop a more comprehensive understanding of socio-ecological changes occurring across the study areas. To evaluate existing ecological baselines and isolate the developmental drivers affecting regional biodiversity, targeted field surveys were executed across a diverse range of ecosystems, spanning montane, mangrove, seagrass, coral reef, and coastal environment. Observation sites were selected purposively to represent four major SES in Central Sulawesi, namely the Lore Lindu highland ecosystem, Eastern Tomini Bay coastal system, Tolo Bay coastal landscape, and Banggai Islands marine ecosystem. To complement ecological information, stakeholder perspectives were collected through semi-structured interviews and regional consultations involving approximately 487 participants from 13 districts and provincial-level institutions in Central Sulawesi. A purposive sampling strategy was employed to select participants based on their specialized knowledge, practical experience, institutional mandates, and direct involvement in natural resource management, biodiversity conservation, and regional development initiatives. The participants represented government institutions, conservation practitioners, local communities, farmers, small-scale fishers, indigenous groups, coastal communities, and women representatives. To extract meaningful insights, the stakeholder-derived data were subjected to systematic thematic coding to identify key patterns related to environmental changes, livelihood vulnerability, community adaptation, and governance challenges. These findings were then compared and integrated with spatial data, ecological information, field observations, and policy documents to strengthen the interpretation and reliability of the socio-ecological analysis.

Interpretive socio-ecological analysis

Data analysis was conducted using an interpretive socio-ecological approach to examine the relationships among development transformation, biodiversity change, and socio-ecological dynamics across different ecoregions. This approach was deployed not merely to track ecological alterations, but to critically examine the ways in which environmental pressures intersect with localized livelihoods, resource access, and socio-ecological conditions within regional

Table 1: Data sources, analytical procedures, and validation methods

Data category	Data type	Source and period	Analytical procedure	Validation
Forest cover change	Secondary data	Satellite-based land cover data and environmental reports (2001–2021)	Temporal comparison of forest cover change	Cross-checking with published studies and field observations
Mangrove, seagrass, and marine biodiversity indicators	Secondary data	Government monitoring reports and scientific publications (2007–2022)	Synthesis of ecological trends and reported biodiversity changes	Comparison among multiple independent data sources
Field ecological observations	Primary data	Selected observation sites in four ecoregions	Direct observation of ecosystem conditions and development pressures	Comparison with spatial and secondary ecological data
Stakeholder perspectives	Primary data	Semi-structured interviews with government, community, fishers, and local actors	Thematic analysis of socio-ecological impacts and governance responses	Triangulation across stakeholder groups and document analysis
Policy and governance documents	Secondary data	Spatial plans, biodiversity reports, and environmental policies (2010–2025)	Document review using DPSIR categories	Cross-validation with interview findings

development trajectories**.** The first stage involved interpreting the DPSIR framework to identify the relationships between drivers, pressures, state, impacts, and responses in each ecoregion. The analysis was conducted in a relational manner, accounting for the interconnections between terrestrial and marine systems. The second stage used socio-ecological interpretation to understand how biodiversity decline affects different community groups. This analytical approach successfully captured the identification of differentiated socio-ecological impacts experienced by women, small-scale fishers, indigenous communities, and broader coastal communities. The third stage consisted of conducting a cross-ecoregional comparison analysis to examine patterns of development pressures and socio-ecological transitions between ecoregions. This analytical approach was deployed to discern recurrent patterns, heterogeneities in ecological pressures, and cross-ecosystem linkages inherent within the agromaritime development system of Central Sulawesi. To improve analytical validity, methodological triangulation was applied by comparing spatial evidence, ecological indicators, stakeholder information, and policy documents. To ensure analytical validity, a triangulation process was deployed to discern convergent patterns and systemic relationships across diverse data streams, thereby mitigating the limitations of relying on a singular dataset. Therefore, the interpretation of biodiversity transformation was developed based on the convergence of multiple data sources across ecological, social, and institutional dimensions.

RESULTS AND DISCUSSION

Cross-ecoregional patterns of biodiversity transformation

The analysis across the four ecoregions shows that biodiversity changes in Central Sulawesi occurred in different ways, influenced by local ecological conditions, development pressures, and patterns of natural resource use. The ecological shifts documented in terrestrial forests, coastal zones, and small island settings do not represent decoupled processes; instead, they are functionally unified by catchment-level hydrology and bidirectional land–sea ecological interactions. By integrating spatial analysis, ecological indicators, and biodiversity records, this study identified three main patterns of change: forest fragmentation in the Lore Lindu Highlands, degradation of coastal ecosystems in Tomini and Tolo Bays, and increasing vulnerability of endemic marine species in the Banggai Islands. The evidence base of biodiversity transformation across coregions is presented in Table 2. In the Lore Lindu Highlands, biodiversity changes were closely related to the conversion of forest areas and increasing fragmentation of the montane

Table 2: Evidence base of biodiversity transformation across ecoregions

Ecoregion	Indicator	Assessment period	Observed change	Main pressure	Evidence source
Lore Lindu Highlands	Primary forest cover	2001–2021	Loss of 28,495 ha	Agricultural expansion, infrastructure development, forest fragmentation	Satellite-based land cover analysis; environmental reports
Eastern Tomini Bay	Seagrass ecosystem condition	2007–2022*	Decline approximately 24 percent (%)	Sedimentation, coastal development, watershed pressures	Marine ecosystem monitoring; published ecological studies
Tolo Bay Coast	Mangrove ecosystem extent	2007–2022*	Conversion exceeding 1,600 ha	Aquaculture expansion and coastal land conversion	Spatial analysis; coastal ecosystem assessment
Banggai Islands	Banggai Cardinalfish population	2007–2022*	Decline approximately 60%	Ornamental fish trade and habitat degradation	Species assessment; biodiversity records

* Assessment periods for coastal and marine indicators were determined based on the availability of validated ecological monitoring data and published studies for each ecosystem

landscape. Between 2001 and 2021, approximately 28,495 hectares (ha) of primary forest was lost, reflecting continuous pressure on forest habitats and the ecological role of this area in maintaining upstream watershed functions (CSPEA, 2022). This reduction in forest cover extends beyond a mere biophysical alteration of the montane landscape; it represents a critical spatial transformation that fractures ecological connectivity between upstream-downstream continuum. From the perspective of coupled human and natural systems, ecological changes in Lore Lindu demonstrate that development pressures in the upstream region have cross-ecosystem impacts on coastal and marine systems, including increased erosion, sedimentation in the catchment, and changes in downstream water quality (Liu *et al*., 2007). These findings demonstrate that biodiversity degradation in the upstream catchment extends far beyond a localized forest conservation issue; rather, it reflects macro-level regional transformations that reverberate across the entire SES of Central Sulawesi. These conditions highlight the importance of the relational socio-ecological DPSIR Framework, which views ecological pressures as processes that move between places and ecoregions. These conditions demonstrate that ecological degradation is never entirely socially neutral; rather, it manifests as highly uneven socio-ecological pressures that disproportionately burden marginalized community groups reliant on localized natural resources (Schlosberg and Collins, 2014). In the Eastern Tomini Bay, ecological pressures are primarily driven by coastal urbanization, port infrastructure development, and chronic sedimentation from the upstream catchment area. The decline in coastal environmental quality is reflected in the reduction of seagrass cover to around 24% over the last two decades, which has been followed by a decline in coral reef quality and coastal fisheries productivity (CSPEA, 2022). In this context, coastal degradation cannot be treated as an isolated marine environmental issue; rather, it represents the structural manifestation of regional spatial transformation that links mountain systems, river catchments, coastlines, and marine environments into a singular, continuous ecological landscape. This perspective reinforces the landscape connectivity approach, which places ecological connectivity at the heart of efforts to safeguard regional sustainability (Newell *et al*., 2022). The degradation of tropical fish breeding habitats has contributed to lower catch yields for small-scale fishers. Concurrently, coastal women have experienced escalating economic vulnerability, driven by the progressive depletion of localized food sources and marine resources. A similar situation is also evident along the coast of Tolo Bay. The growing popularity of aquaculture and the expansion of coastal development have put enormous human strain on mangrove and coral reef ecosystems. Data show that over 1,600 hectares (ha) of mangroves have been converted into fish ponds and coastal

aquaculture areas over the past two decades (CSPEA, 2022). Within the framework of regional development, the coastal transformation occurring across Tolo Bay exemplifies a highly extractive paradigm, wherein littoral zones are strategically reconfigured as specialized frontiers for economic production and commodity expansion. Consequently, the ecological functions of mangroves as natural coastal defenses, habitats for marine life, and blue carbon sinks have declined significantly (Friess *et al*., 2019). From the perspective of ecological regional planning, this situation indicates that development that fails to consider socio-ecological connectivity risks increasing the vulnerability of coastal areas to erosion, tidal flooding, and declining fisheries productivity. In the Banggai Islands, localized environmental stressors elucidate a highly nuanced intersection between site-specific ecological vulnerability and macro-level global economic pressures. International market demand for tropical ornamental fish has led to the intensive exploitation of the Banggai cardinalfish, an endemic species with limited adaptive capacity (Jawad, 2012). Concurrently, anthropogenic coral reef degradation—driven by destructive fishing modalities—compounds the inherent ecological vulnerability of small island systems, characterized by restricted carrying capacities. According to relational SES, ecological pressures in Banggai are caused not only by local activities, but also by global economic and political interactions that influence patterns of marine resource exploitation in small island locations. These conditions illustrate that localized biodiversity remains highly susceptible to global economic forces that operate independently of regional ecological thresholds and socio-economic sustainability. Small-scale fishers, coastal women, and communities living on small islands are among the most vulnerable to these changes because their livelihoods depend heavily on marine resources. Overall, the biodiversity changes across the four ecoregions are closely linked to broader agromaritime development transformations in Central Sulawesi. These transformations are driven by interacting factors, including land-use change, economic pressures, ecological fragmentation, and socio-ecological inequality. These findings underscore that biodiversity should not be conceptualized as an isolated environmental component distinct from regional development; rather, it constitutes the foundational bedrock of the regional socio-ecological system. Consequently, biodiversity management requires a regional planning approach that is not only oriented toward economic growth, but is also capable of maintaining ecological connectivity, strengthening social resilience, and reducing ecological inequalities in a more inclusive and adaptive manner (Bennett *et al*., 2021; Porter *et al*., 2020).

Drivers and mechanisms of biodiversity degradation under agromaritime development

The results of the analysis using the cross-ecoregional socio-ecological DPSIR framework indicate that biodiversity degradation in Central Sulawesi does not occur in a linear and isolated manner, but is shaped by interconnected socio-ecological relationships between terrestrial, coastal and marine areas. Unlike the conventional DPSIR framework, which tends to be sectoral and state-centric, this study establishes that the linkages among drivers, pressures, changes in ecological conditions, social impacts, and governance responses are inherently relational, multi-scalar, and mediated by cross-ecoregional connectivity (Fan *et al*., 2024; Patrício *et al*., 2016). This perspective aligns with the SES approach, which views humans and the environment as systems that dynamically influence one another through constantly evolving ecological, social, and spatial relationships (Folke *et al*., 2021; Reyers and Selig, 2020). In the context of Central Sulawesi, the compounding pressures of agromaritime development transcend administrative boundaries, propagating through river basin networks, driving coastal sedimentation, and accelerating marine habitat degradation to generate acute socio-ecological vulnerabilities for coastal and small island communities (Mujio *et al*., 2026). The comparative relational DPSIR

characteristics of the four ecoregions are presented in Table 3. In the Lore Lindu Highlands, agricultural expansion, road construction and the growth of upstream settlements are driving deforestation and watershed degradation, which are weakening the ecological connectivity between the mainland and coastal areas. Primary forest cover in this area is recorded to have decreased by approximately 28,495 ha during the period 2001–2021 (Mujio *et al*., 2026). From a relational DPSIR perspective, upstream land-use changes transcend localized forestry concerns; instead, they propagate downstream as accelerated sedimentation and a decline in water quality degradation that ultimately impact coastal and marine ecosystems. This situation illustrates how cross-ecoregional ecological pressures are formed through interdependent upstream–downstream and land–sea relationships, as described in the landscape connectivity and regional ecological planning approaches (Langemeyer and Connolly, 2020; Mujio *et al*., 2026; Newell *et al*., 2022). The interconnected socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity mapping established throughout this research are visually conceptualized in Fig. 3. This relationship is most evident in the Eastern Tomini Bay, a coastal–marine transition zone. Seagrass beds and coral reefs are increasingly threatened by coastal urban growth, port development, and sediment runoff from nearby river basins. The area covered by seagrass has declined by around 24%, and fewer than 30% of coral reefs are considered healthy (Mujio *et al*., 2026). Rather than viewing coastal degradation merely as a standalone marine environmental problem, this analysis frames it as a consequence of broader regional spatial restructuring—one that functionally binds highlands, river basins, and the coastline within a unified, interconnected socio-ecological system. This perspective reinforces the argument that ecological pressures in agromaritime regions move across administrative boundaries through ecological connectivity and regional socio-economic flows (Folke *et al*., 2021; Mujio *et al*., 2026; Reyers and Selig, 2020). A similar pattern is found along the Tolo Bay coastline. Fish pond expansion, coastal development, and the exploitation of marine resources have resulted in the loss of almost 1,600 ha of mangrove forest and an increasing strain on coastal habitats (Mujio *et al*., 2026). In the DPSIR relational diagram, this area represents the intersection between land-based development pressures and the exploitation of marine ecosystems. Consequently, there has been a critical erosion of key coastal ecosystem services, severely compromising the shoreline's capacity to provide natural defense, sustain marine habitats, and serve as a socio-ecological buffer for local communities. This situation indicates that regional development still tends to treat coastal areas as spaces for economic production, rather than as part of an interconnected regional ecological system (Bennett *et al*., 2021; Langemeyer and Connolly, 2020). In the Banggai Islands, ecological pressures reveal a complex relationship between the global economy and local vulnerability. Driven by international market demands for tropical ornamental fish, the heavy exploitation of the endemic Banggai Cardinalfish (*Pterapogon kauderni*) has triggered a severe population decline of approximately 60%, a crisis exacerbated by its restricted ecological range and ongoinghabitat loss. (Mujio *et al*., 2026). From a relational DPSIR perspective, this situation demonstrates that the ecological vulnerability of small islands is produced not only by local activities but also by global economic relations that shape patterns of marine resource extraction in peripheral regions. This situation demonstrates how biodiversity transformation in coastal areas and small islands forms part of an uneven socio-ecological transformation process. The diagram ‘relational socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity’ also shows that ecological impacts are not experienced equally by all social groups. Degrading coastal environmental quality intensifies the livelihood precarity of small-scale artisanal fishers, compounds the gendered ecological burdens on

Table. 3: Comparative relational DPSIR across ecoregions

Ecoregion	Main drivers	Ecological pressures	Socio-ecological impacts	Governance responses
Lore Lindu Highlands	Agricultural expansion, road development	Deforestation, watershed degradation	Sedimentation, declining downstream water quality	Forest rehabilitation programmes
Eastern Tomini Bay	Coastal urbanization, port development	Coastal conversion, sedimentation	Coral decline, vulnerability of fisheries	Fragmented coastal governance
Tolo Bay Coast	Aquaculture expansion, growth in coastal settlements	Mangrove conversion, overfishing	Declining coastal resilience	Local mangrove restoration
Banggai Islands	Global ornamental fish trade	Overexploitation, coral degradation	Vulnerability of marine biodiversity	Weak species protection

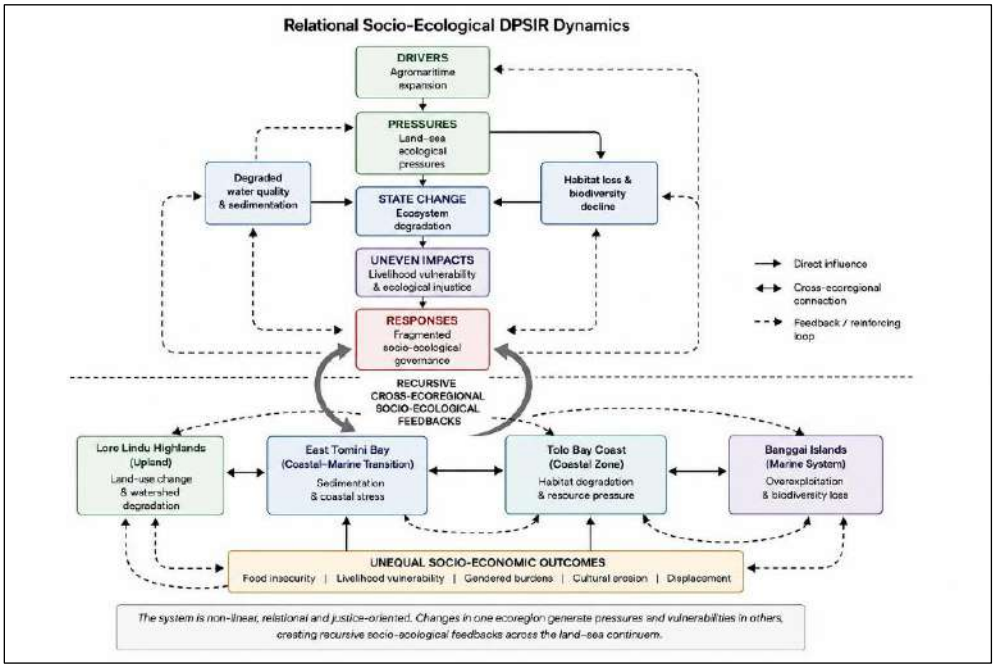

Fig. 3: Relational socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity

women in securing domestic water and food supplies, and encroaches upon the critical living space of resource-dependent indigenous and local communities. In this context, biodiversity degradation not only represents the loss of species and habitats, but also reveals a form of ecological injustice resulting from the unequal distribution of environmental impacts (Schlosberg and Collins, 2014). This perspective emphasizes that ecological change is always linked to power relations, access to resources, and communities' ability to defend their living spaces. This situation highlights the limitations of regional development and governance approaches, which remain dominated by sectoral and technocratic approaches, and are thus unable to adequately integrate the complexity of socio-ecological relationships into the regional planning process (Bennett *et al*., 2021; Porter *et al*., 2020). As illustrated by the DPSIR framework, the absence of integrated governance precipitates recurrent socio-ecological feedback loops that transcend ecoregional boundaries, progressively amplifying ecological pressures across diverse territories. Therefore, this study demonstrates that biodiversity transformation in Central Sulawesi cannot be understood solely as an environmental issue, but rather as a consequence of a regional development model that still fails to integrate ecological connectivity, socio-ecological justice,

and spatial sustainability. At the same time, existing governance responses remain largely piecemeal and fragmented. Terrestrial forest rehabilitation, mangrove restoration, and species conservation initiatives continue to be executed on a fragmented, sectoral basis, lacking substantive structural integration across the upstream-to-marine continuum (Mujio *et al*., 2026).

Cross-ecoregional connectivity and socio-ecological feedback mechanisms

The comparison of the four ecoregions shows that biodiversity change in Central Sulawesi cannot be explained by examining each ecosystem separately. Although each ecoregion experienced different pressures, changes in the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands were linked through ecological processes connecting upland, coastal, and marine environments. In upland areas, forest conversion and land-use change have degraded watershed integrity, generating cascading ecological effects beyond forest boundaries. Increased sediment movement, declining water quality, and reduced habitat connectivity have intensified pressures on coastal and marine ecosystems, including seagrass beds, coral reefs, and fisheries habitats (Sakti *et al.,* 2026). These findings demonstrate that biodiversity change in Central Sulawesi is driven by interactions among ecosystems rather than a single environmental pressure, underscoring the need for integrated ecosystem management and biodiversity governance (Almunawwaroh et al., 2026). This interpretation aligns with the SES perspective, which conceptualizes human activities and biophysical systems as inherently coupled and continuously co-evolving through dynamic feedback loops (Folke *et al*., 2005; Liu *et al*., 2007). From this perspective, biodiversity represents not only species and ecosystem conditions, but also the ability of landscapes to maintain ecological functions, support community resilience, and sustain local livelihoods. Understanding these relationships is important for regional ecological planning, particularly in areas where upstream, downstream, and marine systems are strongly connected (Cumming, 2011; Newell *et al*., 2022). Fig. 4 illustrates the movement of ecological pressures across the upland–coastal–marine continuum. Changes occurring in terrestrial landscapes influence downstream ecosystems through hydrological processes, sediment flows, and changes in habitat conditions. Simultaneously, escalating anthropogenic and environmental pressures on coastal and marine ecosystems directly undermine the resilience of local communities whose livelihoods are inextricably linked to natural resources. Within the relational socio-ecological DPSIR framework, these findings suggest that biodiversity transformation should be understood as part of broader interactions among development processes, ecosystem change, and human–environment relationships. Therefore, biodiversity governance within agromaritime regions necessitates frameworks that transcend rigid administrative jurisdictions, account for cross-scale ecological connectivity and integrate reciprocal landscape–seascape feedback dynamics.

Toward adaptive and just agromaritime governance

The socio-ecological changes observed across the four ecoregions indicate that biodiversity degradation extends beyond ecological impacts and influences the relationship between communities and their surrounding environments. Consequently, the impacts of these environmental shifts diverge among demographics, varying as a function of each group's reliance on natural capital, livelihood strategies, and adaptive capacity in the face of changing ecosystem conditions. In the Lore Lindu Highlands, forest degradation and watershed changes have affected communities whose livelihoods are closely connected to forest landscapes, water resources, and traditional production systems. Similarly,

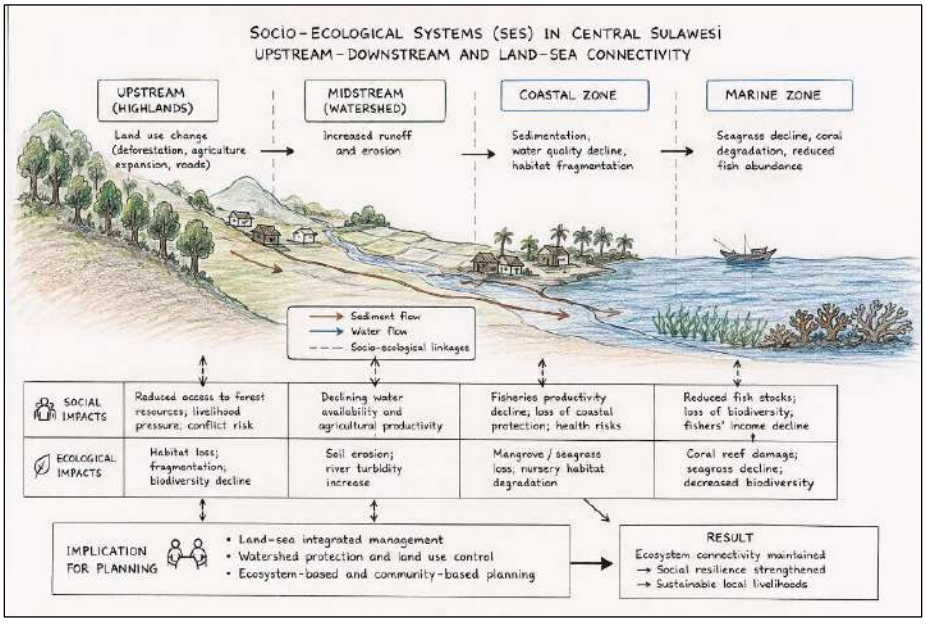

Fig. 4: Socio-ecological connectivity across upstream, watershed, coastal, and marine systems in Central Sulawesi

declining ecosystem conditions in Tomini Bay, Tolo Bay, and the Banggai Islands have created additional pressures for coastal and small island communities that depend on fisheries resources, mangroves, coral reefs, and marine biodiversity (Fadilah *et al.,* 2026). These transformations have progressively compromised community access to the ecological spaces and customary resources that have historically supported local livelihoods. These findings suggest that biodiversity transformation is closely related to broader questions of access, participation, and environmental justice (Almunawwaroh et al., 2026). Shifting environmental conditions can restructure local social systems, creating differentiated vulnerabilities among communities, particularly those that depend heavily on ecosystem services (Langemeyer and Connolly, 2020). From the perspective of ecological justice and FPE, environmental pressures should therefore be understood not only through ecological indicators but also through how benefits, risks, and decision-making opportunities are distributed among different social groups, including indigenous communities, small-scale fishers, coastal women, and small island communities (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Notwithstanding these interconnected socio-ecological challenges, biodiversity governance in Central Sulawesi continues to be dominated by fragmented, sector-specific frameworks that fail to account for systemic cross-scale dynamics. Forest rehabilitation, mangrove restoration, coastal management, and species conservation programs have contributed to ecosystem protection, but they are often implemented separately and have not fully incorporated ecological connectivity across upland, watershed, coastal, and marine systems (Mujio *et al*., 2026). Consequently, future agromaritime governance necessitates an institutional transition toward a more adaptive and integrated paradigm—one that seamlessly couples biodiversity conservation, spatial planning, and localized community participation across distinct ecoregional scales. Such an approach recognizes conservation not only as an effort to protect species and habitats but also as a process of maintaining socio-ecological resilience, ecological connectivity, and sustainable relationships between communities and nature (Bennett *et al*., 2021; Porter *et al*., 2020).

CONCLUSION

This study demonstrates that biodiversity transformation in Central Sulawesi is not merely an ecological phenomenon, but a socio-ecological process shaped by the continuous interaction between development dynamics, ecosystem changes, and community dependence on natural resources. The analysis of four ecoregions shows that the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands are connected through ecological processes that cross administrative boundaries. Environmental changes propagating across terrestrial landscapes fundamentally alter watershed functions, thereby driving cascading impacts through coastal ecosystems and marine habitats that ultimately threaten the livelihoods of resource-dependent communities. Applying the Cross-Ecoregional Socio-Ecological DPSIR Framework provides a broader understanding of how agromaritime development pressures move across land and sea systems. The findings indicate that agricultural expansion, infrastructure development, coastal transformation, and marine resource exploitation act as major development drivers that generate land conversion, habitat fragmentation, sedimentation, and coastal degradation. Rather than presenting as isolated environmental phenomena, these stressors operate as cumulative processes that fundamentally restructure regional resilience and transboundary ecological connectivity. Therefore, biodiversity management requires an integrated perspective that considers the relationships among ecosystems, human activities, and governance systems. This study also highlights the limitations of conventional approaches that view biodiversity primarily through ecological indicators or sectoral management. By synthesizing social-ecological systems thinking, ecological connectivity, and socio-ecological justice dimensions, the adapted DPSIR framework presented in this study offers a deeply relational ontology for understanding of biodiversity transformation. It emphasizes that environmental degradation affects communities differently, particularly small-scale fishers, women, indigenous groups, and coastal communities whose livelihoods are closely linked to ecosystem services. The empirical results suggest a necessary paradigm shift for future agromaritime strategies, moving away from merely trade-off compromises between ecological protection and economic expansion toward cultivating systemic adaptability and environmental justice at the society–nature interface. Strengthening land-seascape connectivity, protecting critical ecosystems, incorporating local knowledge, and transforming fragmented sectoral governance into integrated cross-ecoregional management are essential elements for maintaining biodiversity resilience. In this context, spatial planning must transcend its traditional regulatory role over terrestrial land and marine resources; instead, it should be operationalized as a strategic mechanism to orchestrate sustainable socio-ecological transformation. Overall, the experience of Central Sulawesi provides important lessons for tropical regions facing similar challenges between development and biodiversity conservation. The Cross-Ecoregional Socio-Ecological DPSIR Framework proposed in this study offers an integrated approach to support more sustainable, inclusive, and resilient agromaritime management in interconnected land-sea systems.

AUTHOR CONTRIBUTIONS

Mujio conceptualized the study, developed the socio-ecological framework, conducted data interpretation, and prepared the original manuscript draft. M. Natsir conducted ecological observations, biodiversity assessment, and environmental data validation. M. Ermyanyla carried out stakeholder interviews, socio-ecological analysis, and data curation. A. Yanuadi contributed to theoretical integration, relational planning analysis, manuscript review and editing, visualization, and final manuscript preparation. All authors read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of 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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During the preparation of this work, the authors used Artificial Intelligence (AI), specifically ChatGPT (OpenAI), as an AI-assisted tool to support language refinement, grammar checking, readability improvement, and editorial enhancement of selected sections of the manuscript. The AI tool was not used to generate research data, perform data analysis, develop scientific findings, or formulate conclusions. After using this tool, the authors carefully reviewed, verified, and edited all AI-assisted outputs to ensure scientific accuracy, originality, and consistency with the research objectives. The authors take full responsibility for the content and integrity of the final publication.

ABBREVIATIONS

%	Percent
CBD	Convention on Biological Diversity
DAS	River Basin (Daerah Aliran Sungai)
DLH	Environmental Agency (Dinas Lingkungan Hidup)
DPSIR	Drivers–pressures–state–impact–response
FAO	Food and Agriculture Organization
FPE	Feminist political ecology
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GmbH	Gesellschaft mit beschränkter Haftung
ha	Hectare
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
km	Kilometer
km²	Square kilometer
NGO	Non-governmental organization
SDGs	Sustainable Development Goals

SEPLS	Socio-ecological production landscapes and seascapes
SES	Socio-ecological systems
SOLUSI	Solutions for Integrated Land and Seascapes Management in Indonesia
UN	United Nations
UNEP	United Nations Environment Programme

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CASE STUDY

An integrated framework for sustainable natural resources management in freshwater lakes

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ABSTRACT

BACKGROUND AND OBJECTIVES: Freshwater lakes are increasingly threatened by environmental degradation, resource-use conflicts, climate change, and institutional fragmentation, particularly in arid and semi-arid regions where water resources are essential for sustainable development. Existing approaches, including driver–pressure–state–impact–response, integrated lake basin management, integrated water resources management, ecosystem-based management, and adaptive management, are typically operationalized in isolation rather than through an integrated approach. The study objectives were to construct an integrated framework that synthesizes these disparate approaches within a unified decision-support structure underpinned by environmental indicators, institutional governance assessment, and geographic information systems-based spatial analysis.

METHODS: A mixed-methods approach was adopted, integrating framework synthesis, comparative case studies, and institutional governance assessment alongside environmental indicators and geographic information system-based spatial analysis. The proposed framework is structured across five sequential phases: a baseline assessment, a causal diagnosis, a sustainability and carrying-capacity evaluation, planning and governance strategies, and an implementation stage paired with adaptive monitoring. The framework was applied to Lake Nasser, Egypt, and compared with the Great Lakes, Lake Biwa, and Lake Victoria.

FINDINGS: The proposed framework integrated environmental assessment, governance evaluation, spatial planning, and adaptive management within a single operational structure. Geographic information systems-based sensitivity analysis, supported by weighted overlay analysis, zonal statistics, area calculations, and consistency with ecological characteristics reported by the Egyptian Environmental Affairs Agency and previous studies, indicated that approximately 15–20 percent of the Lake Nasser region comprises very high sensitivity zones requiring strict protection, whereas 30–35 percent represents high-sensitivity areas requiring controlled management. Spatial suitability analysis indicated that nearly half of the lacustrine system necessitates either heightened conservation status or strictly regulated development frameworks. The integrated lake basin management-based assessment revealed institutional fragmentation, limited coordination, weak information systems, and insufficient stakeholder participation. The comparative evaluation highlights a triad of critical determinants for sustainable lacustrine governance: continuous environmental monitoring, adaptive management interventions, and robust stakeholder engagement.

CONCLUSION: This study introduces a pragmatic, adaptable framework that serves as a viable methodological tool for advancing sustainable natural resource management in freshwater lakes. By integrating driver–pressure–state–impact–response, integrated lake basin management, integrated water resources management, ecosystem-based management, adaptive management, environmental indicators, governance assessment, and geographic information systems -based spatial analysis, the framework strengthens environmental decision-making and planning implementation. Application to Lake Nasser demonstrates its potential to improve environmental protection, governance effectiveness, and long-term resource sustainability.

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91	6	10

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INTRODUCTION

Freshwater lakes are sensitive ecosystems critical to water security, biodiversity, economic activity, and regional development, particularly in arid and semi-arid environments. These systems face intensifying pressures from climate change, land-use transformation, development expansion, and institutional fragmentation, creating complex challenges for sustainable natural resource management (UNEP, 2019; OECD, 2006). Several environmental management approaches have been widely applied in lake management, including driver–pressure–state–impact–response (DPSIR), integrated lake basin management (ILBM), integrated water resources management (IWRM) (OECD, 2009), ecosystem-based management (EBM) (Imperial, 1999), and adaptive management (WCED, 1987; Giordano and Wolf, 2003). Historically, however, the majority of prior studies have implemented these paradigms in isolation or through fragmented combinations, with each individual framework addressing only a narrow dimension of lake management. DPSIR mainly supports causal environmental diagnosis, ILBM emphasizes governance and institutional coordination, IWRM focuses on integrated resource allocation, ecosystem-based management (EBM) addresses ecosystem integrity and services, whereas adaptive management provides mechanisms for monitoring and iterative learning. Consequently, important interactions among environmental assessment, governance evaluation, environmental indicators, stakeholder participation, spatial planning, and adaptive monitoring often remain fragmented within existing decision-support systems (EEA, 2018; GWP, 2000; Pahl-Wostl *et al.,* 2010). A critical methodological deficiency thus persists regarding an actionable framework capable of holistically embedding environmental, governance, and carrying-capacity assessments alongside spatial planning and adaptive monitoring within a unified structure tailored to complex freshwater lake dynamics (Long *et al.,* 2014; UNEP, 2021). Lake Nasser, formed following the completion of the Aswan High Dam in 1970, is one of the world's largest artificial freshwater reservoirs and a strategically vital water resource for Egypt and Sudan (Jønch-Clausen and Fugl, 2001). Despite its importance, the lake faces complex environmental challenges related to sedimentation, water-quality degradation, habitat fragmentation, and competing development pressures (El-Shabrawy, 2009; El-Shabrawy and Fishar, 2009; Abdel-Satar, 2005). Institutional governance remains highly fragmented across various ministries and administrative agencies, characterized by the absence of a formally adopted, unified management blueprint (Abdel-Satar *et al.,* 2017). Freshwater lake systems are increasingly exposed to emerging challenges associated with climate change, water scarcity, population growth, competing resource-use demands, land-use transformation, and institutional fragmentation. Such intersecting pressures give rise to multifaceted ecological and regulatory conflicts; resolving them requires the deployment of adaptive, integrated management frameworks designed to strike a balance between economic expansion priorities and systemic environmental conservation (UNEP, 2021; Hák *et al.,* 2016; Nakatsuka *et al.,* 2020; Nakamura, 2022). This research addresses this gap by developing and applying an integrated methodological framework that combines DPSIR, ILBM, IWRM, EBM, and Adaptive Management with environmental indicators and geographic information system (GIS)-based spatial analysis. The framework is applied to Lake Nasser and evaluated against international lake-management experiences from the Great Lakes (USA–Canada), Lake Biwa (Japan), and Lake Victoria (Africa) (EPA, 2019). The scientific contribution extends beyond the simple combination of existing approaches. Unlike previous studies that have generally focused on individual approaches or partial integrations, the proposed framework establishes

a unified operational workflow linking governance assessment, environmental indicators, GIS-based spatial analysis, carrying-capacity assessment, stakeholder participation, and adaptive monitoring within a single decision-support structure (Holling and Meffe, 1996; WCED, 1987; UNEP, 2019; Hák *et al.,* 2016; Svarstad *et al.,* 2008). Serving as a robust baseline for sustainable lacustrine governance, this unified architecture leverages a combination of environmental indicators and GIS-based spatial modeling to inform all phases of the proposed framework (Bertram, 1993; Botts and Muldoon, 2005; Pahl-Wostl *et al.,* 2010; Nakamura, 2022; Masese *et al.,* 2025). Lake Nasser was selected because it represents one of the world's largest artificial freshwater reservoirs and is characterized by complex environmental and governance challenges under arid climatic conditions. The selected lakes present highly contrasting environmental baselines and institutional structures, rendering them ideal candidates for a cross-comparative benchmarking analysis. Environmental, spatial, institutional, and socio-economic datasets were used to support framework development, application, and evaluation (Allan *et al.,* 2013). This study aims to: (1) develop an integrated methodological framework linking DPSIR, ILBM, IWRM, EBM, and adaptive management with environmental indicators and spatial analysis; (2) apply the framework to Lake Nasser; (3) compare international lake-management experiences; (4) evaluate governance using ILBM; and (5) provide recommendations and assess framework transferability. This study was conducted in the Lake Nasser region, southern Egypt, during 2024–2026.

MATERIALS AND METHODS

The study area

The study area is Lake Nasser, located in southern Egypt and extending into northern Sudan, where it is known as Lake Nubia (Fig. 1). Extending roughly 500 kilometers (km) southward from the Aswan High Dam, Lake Nasser represents one of the largest anthropogenic reservoirs globally, created upon the completion of the dam structure in 1970. Its total storage capacity is approximately 162 billion cubic meters (m^3), with a surface area exceeding 5,000 square kilometers (km^2) at maximum water level, a length of approximately 500 km, a maximum width of about 35 km, an average depth of 25–30 m, and a maximum depth exceeding 180 meters (m) near the dam. Geographically situated within a hyper-arid climatic zone, the reservoir system experiences extreme meteorological constraints, characterized by a negligible annual precipitation threshold of under 5 millimeters per year (mm/y) and substantial potential evaporation rates fluctuating between 2,500 and 3,000 mm/y.

The lake environmental conditions

The lake serves multiple critical functions: water storage (regulating Nile flow and ensuring water security for Egypt); hydroelectric power generation with an installed capacity of approximately 2,100 megawatts (MW); fisheries (annual production 20,000–30,000 tons); agriculture (potential irrigated expansion); tourism (recreational activities and cultural heritage); and navigation between Egypt and Sudan. Characterized by heterogeneous ecological zones, the basin integrates desert terrains, wetlands, fluvial islands, and coastal khors (embayment) that serve as vital breeding and foraging habitats for diverse fish, bird, and wildlife populations (El-Shabrawy and Fishar, 2009).

Environmental status and governance context

Lake Nasser is subject to a multitude of anthropogenic and environmental pressures. Key ecological concerns include accelerated sedimentation, localized water quality degradation within marginal zones, and the disruption of shoreline habitats. Furthermore, these challenges are compounded by a decline in

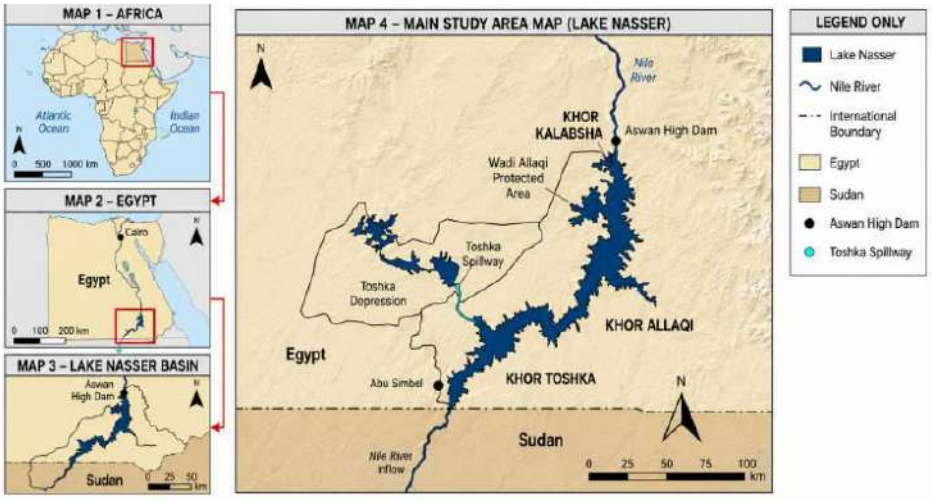

Fig. 1: Geographical location of the study area in Lake Nasser showing the lake's position in southern Egypt along the Egypt–Sudan border

fisheries productivity alongside escalating development demands driven by tourism, aquaculture, agriculture, and infrastructure expansion (Abdel-Aal *et al.,* 2023). These pressures are intensified by the absence of a unified lake-management plan and by fragmented institutional responsibilities among several governmental bodies, including the Ministry of Water Resources and Irrigation (MWRI), the Ministry of Environment, the Egyptian Environmental Affairs Agency (EEAA), the South Valley Development Authority, and the Nubia Development Authority (EEAA, 2019). Current environmental monitoring frameworks fail to align with the significant spatial scale and strategic importance of Lake Nasser. Rectifying this deficit requires a multi-dimensional, integrated approach capable of synthesizing environmental metrics, governance evaluations, and spatial planning into a cohesive, adaptive monitoring paradigm (MWRI, 2005; MWRI, 2021).

Data collection and sources

Data were collected from multiple spatial, environmental, institutional, and socio-economic sources to support framework development, GIS-based spatial analysis, environmental sensitivity assessment, suitability analysis, and governance evaluation. Spatial datasets included Landsat and Sentinel satellite imagery for land-cover interpretation and change detection, digital elevation model (DEM) data derived from Shuttle Radar topography mission (SRTM) and advanced spaceborne thermal emission and reflection radiometer (ASTER) for terrain analysis, and available shoreline, hydrological, and accessibility layers. The environmental dataset synthesized institutional water-quality records from the EEAA, fisheries statistics from the general authority for fish resources development (GAFRD), and ecological data from peer-reviewed literature on Lake Nasser. Socio-economic and planning data were obtained from census records, national development plans, sectoral reports, and institutional documents. Governance data were extracted from national strategies, legislation, policy documents, institutional reports, and published studies. Field observations and stakeholder consultations were used to support interpretation and validation of the spatial and governance findings (GAFRD, 2020; Malczewski, 1999).

Research design and framework development

This study employed a mixed-methods design integrating framework synthesis, GIS-based

spatial analysis, environmental-indicator assessment, semi-quantitative governance evaluation, and comparative case-study analysis. The methodological process proceeded through six sequential steps: 1) a systematic review to identify the analytical strengths and limitations of existing lake-management frameworks; 2) integration of DPSIR, ILBM, IWRM, EBM, and adaptive management into a unified five-phase framework; 3) selection and operationalization of environmental, spatial, socio-economic, and governance indicators; 4) development of GIS-based methodologies for sensitivity mapping, suitability analysis, and spatial conflict identification; 5) application of the framework to Lake Nasser; and 6) validation and benchmarking through comparison with international lake-management experiences from the Great Lakes, Lake Biwa, and Lake Victoria (Entz, 1976; Lindenmayer and Likens, 2010; Malczewski, 2006). Operating as a sequential decision-support system, the framework utilizes complementary analytical functions across each step. DPSIR supports causal diagnosis of drivers, pressures, environmental states, impacts, and responses; ILBM provides the governance and institutional assessment structure; IWRM supports integrated resource coordination; EBM strengthens ecosystem-based assessment and conservation priorities; and adaptive management provides monitoring, feedback, and iterative policy adjustment. Throughout all framework stages, environmental indicators and GIS-based spatial analysis function as cross-cutting elements linking empirical evidence directly to governance and planning decisions (Borja *et al.,* 2006; Medema *et al.,* 2008; Pahl-Wostl *et al.,* 2010). The relationships among these components and their integration within the proposed methodological structure are illustrated in (Fig. 2).

Operational application of the framework to Lake Nasser

The proposed framework was empirically validated through its application to Lake Nasser across a five-phase methodological sequence. Phase 1 involved baseline assessment through the collection and integration of environmental, hydrological, ecological, spatial, institutional, and socio-economic data using GIS, remote sensing (RS), field observations, and environmental indicators. In Phase 2, a causal diagnosis was executed via the DPSIR framework to map the interconnected drivers, pressures, states, impacts, and responses defining the lake's environmental profile. Phase 3 addressed sustainability assessment by evaluating environmental sensitivity, spatial suitability, sustainability indicators, and carrying-capacity constraints. Strategy formulation and governance planning were executed in Phase 4 using the ILBM framework, which encompassed stakeholder participation, institutional assessments, and scenario development. Phase 5 addressed implementation, monitoring, evaluation, and adaptive management through environmental indicators, performance assessment, reporting mechanisms, and feedback procedures. This sequence functioned as an operational framework to systematically link environmental assessment, governance appraisal, spatial planning, and adaptive management within the Lake Nasser case study, ensuring integrated sustainable decision-making processes (Goher *et al.,* 2021; Borja *et al.,* 2006; Medema *et al.,* 2008; Pahl-Wostl *et al.,* 2010; Nakamura, 2022). The operational application of the framework to Lake Nasser is summarized in Table 1.

The study questions

Research question 1 (RQ1): How can the functional integration of DPSIR, ILBM, IWRM, EBM, and adaptive management within a unified five-phase framework improve the comprehensiveness and effectiveness of freshwater lake management assessment?

Research question 2 (RQ2): How do the spatial configurations of environmental sensitivity and development suitability in Lake Nasser delineate pathways for sustainable land-use planning?

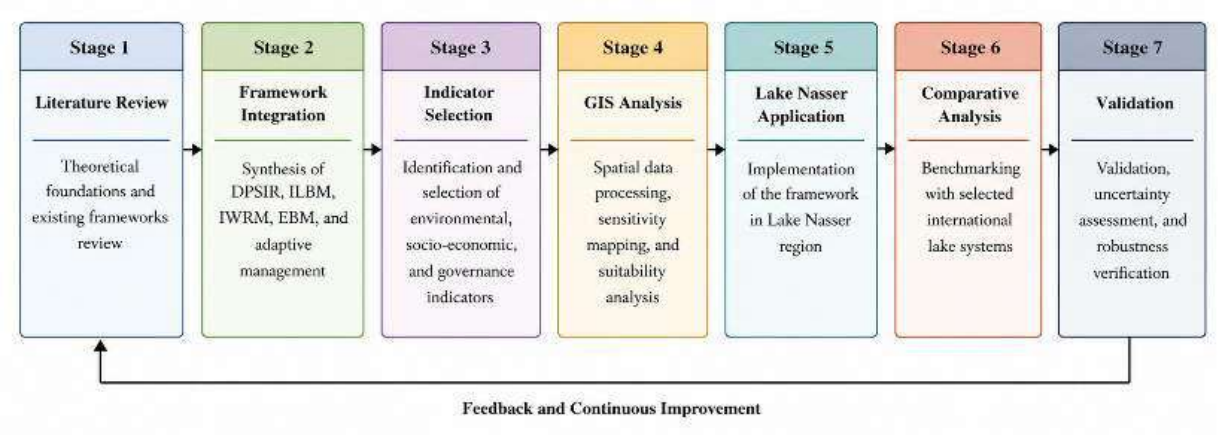

Fig. 2: Logical sequence of research methodology stages, from theoretical review to integrated framework

Table 1: Operational application of the proposed framework to Lake Nasser

Phase	Main analytical procedures	Analytical and implementation mechanisms	Key outputs and planning implications
Phase 1: Baseline survey and existing conditions assessment	Collection and integration of environmental, hydrological, ecological, spatial, institutional, and socio-economic data using GIS and RS, field observations, and environmental indicators	Spatial database development, data harmonization, institutional data integration, and stakeholder identification	Baseline environmental database, existing-condition maps, and characterization of environmental and socio-economic conditions
Phase 2: Integrated analysis, diagnosis, and scoping	Identification of environmental pressures, hotspot areas, governance gaps, spatial conflicts, and environmental risks using DPSIR and GIS-based analysis	Environmental diagnosis, inter-agency coordination, risk identification, and scoping mechanisms	Pressure maps, hotspot identification, conflict zones, and governance-gap assessment
Phase 3: Sustainability, suitability, and carrying-capacity assessment	Assessment of environmental sensitivity, spatial suitability, sustainability indicators, and carrying-capacity constraints using multi-criteria analysis	Environmental zoning, development-control measures, sustainability assessment, and prioritization mechanisms	Sensitivity maps, suitability maps, sustainability indicators, carrying-capacity thresholds, and environmental zoning priorities
Phase 4: Planning, governance, and strategy development	Development of planning alternatives, governance structures, stakeholder engagement mechanisms, and sustainable development scenarios based on ILBM principles	Strategic planning, stakeholder participation, governance integration, policy coordination, and scenario evaluation	Sustainable development scenarios, integrated management strategies, governance recommendations, and implementation priorities
Phase 5: Implementation, monitoring, evaluation, and adaptive management	Implementation of management programs, KPI evaluation, environmental monitoring, and adaptive policy adjustment	Monitoring systems, reporting mechanisms, institutional review procedures, and adaptive-management mechanisms	Monitoring reports, performance evaluation outputs, adaptive-management mechanisms, and updated planning policies

Research Question 3 (RQ3): How does the institutional management capacity of Lake Nasser align with international benchmarks established by the Great Lakes, Lake Biwa, and Lake Victoria?

Research Question 4 (RQ4): What governance, institutional, and policy reforms are required to align Lake Nasser's management strategy with the proposed integrated framework?

Justification for framework selection

The frameworks—DPSIR, ILBM, IWRM, EBM, and adaptive management—were selected based on four methodological criteria: 1) demonstrated applicability to freshwater lake and water-resource management; 2) complementary analytical scope covering causal diagnosis, governance integration, resource coordination,

ecosystem protection, and adaptive response; 3) availability of established conceptual or operational protocols in environmental-management literature; and 4) compatibility with environmental indicators and GIS-based spatial analysis. Alternative frameworks, including Ostrom's social-ecological systems framework, the water–energy–food nexus approach, and the planetary boundaries framework, were evaluated but ultimately excluded as core components. This decision was based on their lack of operational spatial protocols at the localized lake scale, their primary focus on cross-sectoral linkages at the expense of granular governance appraisals, or their tendency to function at regional or global scales rather than site-specific lake-management contexts (Ostrom, 2009; Grafton *et al.,* 2019). The selected combination was therefore considered suitable for developing an operational and transferable lake-management framework that remains applicable under data and institutional constraints.

The DPSIR framework

The DPSIR framework, developed by the European Environment Agency (EEA), provides a causal analytical structure linking human activities to environmental change and policy responses (GWP, 2000). The widespread adoption of the DPSIR framework in environmental assessments stems from its utility in structuring intricate ecological dynamics, thereby fostering effective communication among scientific, planning, and policy stakeholders (Kristensen, 2004; Gari *et al.,* 2015; Atkins *et al.,* 2011).

ILBM

ILBM, developed by International Lake Environment Committee Foundation (ILEC) and United Nations Environmental Program (UNEP), is one of the most comprehensive governance-oriented approaches for lake management (Nakamura and Rast, 2014). In contrast to traditional frameworks that prioritize ecological evaluation, the ILBM approach underscores the institutional and governance frameworks critical to achieving enduring lake sustainability. The framework facilitates multidimensional integration across sectoral, spatial, institutional, temporal, and scientific domains. It operates on the premise that comprehensive resource management hinges on systemic coordination among environmental protection, resource exploitation, stakeholder engagement, and policy execution (Nakamura, 2022; Reed, 2008; Jørgensen *et al.,* 2010).

IWRM

IWRM is defined as a coordinated approach for managing water, land, and related resources to maximize economic and social benefits while maintaining ecosystem sustainability (Long *et al.,* 2014). As a leading paradigm in water resource governance, IWRM connects hydrological systems with overarching environmental and socio-economic developmental processes (GWP, 2004; Biswas, 2004).

EBM

EBM evaluates the intricate dynamics between ecological components, anthropogenic activities, and environmental functions within a holistic framework (Arkema *et al.,* 2006). The approach emphasizes ecosystem integrity, resilience, cumulative environmental impacts, and the relationship between ecosystem services and human well-being. EBM has been increasingly applied in freshwater management because of its ability to support long-term sustainability while accommodating development activities (Slocombe, 1998; Grumbine, 1994; Long *et al.,* 2015).

Adaptive management

As an iterative framework for decision-making, adaptive management is structured to mitigate uncertainty within complex ecological systems by deploying a continuous cycle of monitoring, evaluation, and policy refinement (Holling, 1978). Particularly relevant to freshwater lake systems

because of climatic variability, hydrological uncertainty, and changing development pressures (Walters and Holling, 1990), successful implementation depends on long-term monitoring systems (Williams *et al.,* 2009; Halls *et al.,* 2013), institutional flexibility, and the capacity to integrate feedback into planning processes (Allen and Gunderson, 2011).

Environmental indicators and spatial analysis

Environmental indicators provide measurable information about environmental conditions, pressures, and responses, supporting evidence-based decision-making (OECD, 1993; Niemeijer and de Groot, 2008). GIS and spatial analysis technologies serve as foundational instruments in lake management, facilitating the visualization, assessment, and modeling of spatial configurations and environmental degradation or change patterns (Longley *et al.,* 2011). Applications include sensitivity mapping, suitability analysis, land-use monitoring, pollution tracking, habitat assessment, and planning support (GWP, 2004; EEA, 2018). The integration of environmental indicators with GIS-based analysis enhances the ability to identify sensitive areas, evaluate cumulative impacts, and support planning decisions (Malczewski, 2006; Jankowski, 1995).

Justification for framework integration

A critical synthesis of the selected frameworks reveals important complementarities: DPSIR provides causal analytical structure but lacks a governance integration mechanism; ILBM provides governance architecture but does not specify causal analysis protocols; IWRM addresses water allocation and cross-sectoral coordination but does not incorporate ecosystem service valuation; EBM provides the ecosystem service and biodiversity conservation dimension but lacks spatial planning tools; and adaptive management provides the feedback and learning mechanism but requires an operational monitoring system. The proposed synthesis overcomes these discrete limitations by designating a distinct functional role for each framework within a five-phase planning architecture. This methodology responds directly to contemporary scholarly advocacy for 'framework pluralism' in environmental governance (Pahl-Wostl *et al.,* 2010; Grafton *et al.,* 2019) and responds to documented failures of single-framework approaches in complex, multi-use lake systems (Masese *et al.,* 2025; Ostrom, 2009).

Conceptual synthesis and research gap

Environmental indicators and GIS-based spatial analysis have frequently been used as supporting assessment tools rather than being systematically embedded within an integrated management framework (Shalaby and Tateishi, 2007). Consequently, causal environmental assessment, governance evaluation, ecosystem management, spatial planning, and adaptive monitoring frequently operate as isolated elements rather than cohesive mechanisms within environmental decision-making frameworks. A methodological gap persists regarding the development of a unified operational framework capable of integrating these dimensions within a single decision-support structure (Young, 2010). Resolving this empirical gap serves as the core motivation for the current study. Accordingly, the proposed integrated methodological framework is detailed in Fig. 3, which maps out its five-phase architecture, institutional governance components, environmental indicators, spatial analysis tools, implementation mechanisms, and adaptive feedback loops. Table 2 summarizes the primary datasets and information sources used for framework development, spatial analysis, environmental assessment, and governance evaluation.

Environmental indicators

To ensure methodological rigor, environmental indicators were evaluated against four core criteria: their applicability to freshwater lake management, quantifiable measurability, data availability, and compatibility with the integrated framework. The selection process was based on an

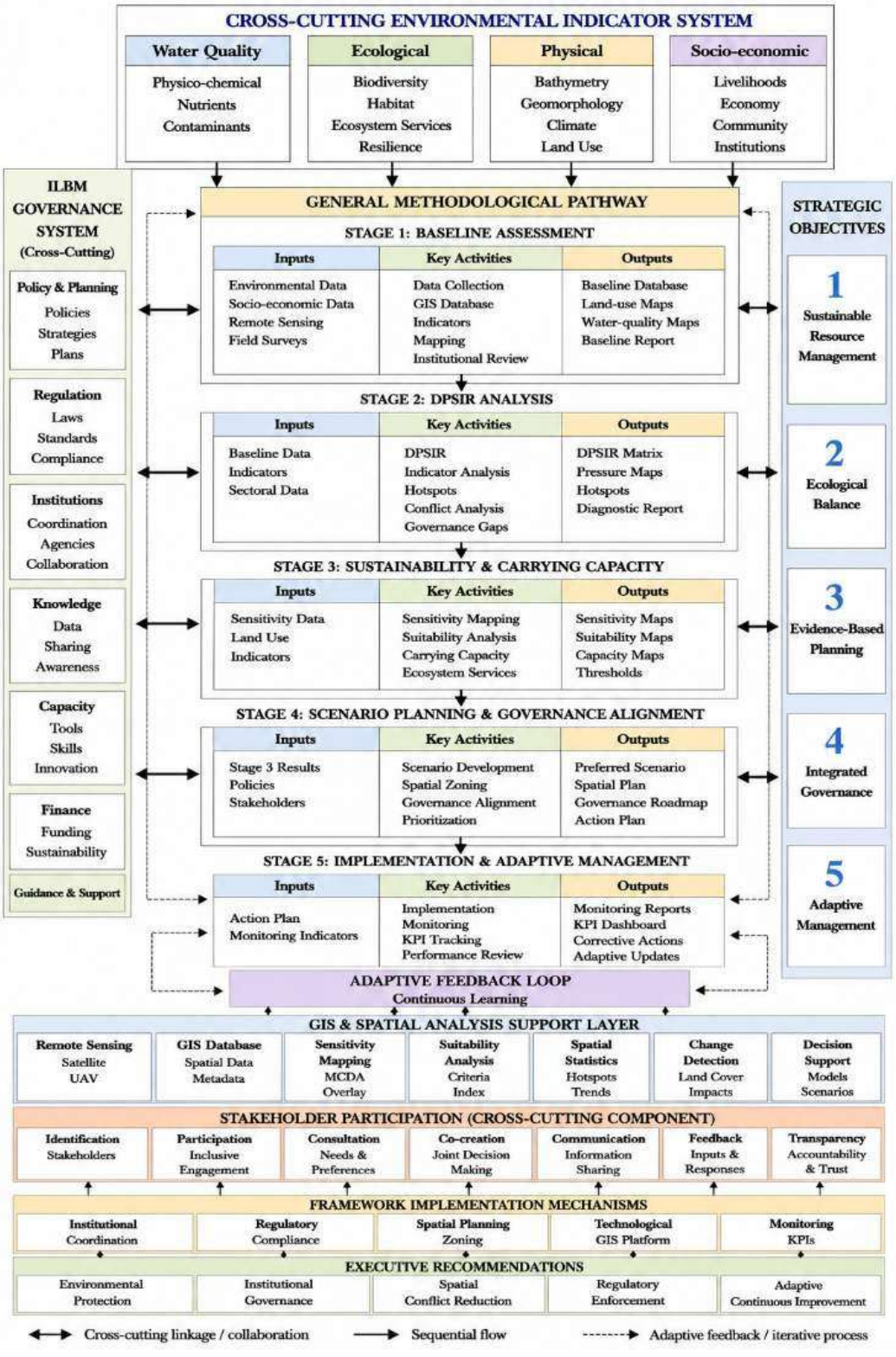

Fig. 3: The proposed integrated methodological framework for sustainable management of natural resources in freshwater lake areas

Table 2: Data sources used for spatial, environmental, socio-economic, and governance assessment

Data category	Main source	Spatial/temporal scale	Purpose in the study
Satellite imagery	Landsat 8/9 (USGS), Sentinel-2 (ESA)	10–30 m; 2020–2025	Land-cover mapping and spatial-change analysis
Topographic data	SRTM (NASA), ASTER GDEM	30 m; latest	Terrain and suitability analysis
Hydrological data	MWRI	2000–2025	Water levels and hydrological assessment
Water-quality data	EEAA, NIOF, published studies	2015–2025	Water-quality assessment and indicators
Fisheries data	GAFRD, published studies	2000–2025	Fisheries assessment and resource pressures
Ecological data	Studies and environmental reports	Various years	Habitat and sensitivity assessment
Socio-economic data	CAPMAS and development reports	2015–2025	Development pressures and socio-economic analysis
Policy and institutional documents	MWRI, EEAA, official reports	2005–2025	Governance and institutional assessment
Comparative case-study literature	Scientific and institutional literature	Various years	Benchmarking and best practices
Field observations and stakeholder consultations	Site visits and expert consultations	2024–2026	Validation and local knowledge integration

extensive review of previous freshwater lake management studies, environmental assessment frameworks, and internationally recognized indicator systems (OECD, 1993; Niemeijer and de Groot, 2008; EEA, 2018). The indicators were classified into six distinct categories: 1) water-quality indicators, including total dissolved solids, electrical conductivity, nutrients, chemical oxygen demand, and chlorophyll-a; 2) ecological indicators, including fish biomass, biodiversity, wetland extent, habitat condition, and ecosystem integrity; 3) hydrological indicators, including water-level fluctuation, inflow, outflow, evaporation, and residence time; 4) socio-economic indicators, including population pressure, fisheries production, tourism activity, agricultural expansion, and infrastructure accessibility; 5) governance indicators, including institutional capacity, policy implementation, enforcement, stakeholder participation, and information sharing; and 6) spatial indicators, including land-use change, shoreline modification, distance to infrastructure, habitat fragmentation, and land-use intensity. To facilitate cross-comparative analysis and subsequent aggregation, all indicators underwent normalization to a standardized scale ranging from 0 to 1. Indicator weights were assigned using a combination of literature-based evidence, expert judgment, and the Analytic Hierarchy Process (AHP), where sufficient expert knowledge and supporting information were available (Malczewski, 1999). To ensure the reliability of the pairwise comparisons, the consistency ratio (CR) was calculated, with a threshold below 0.10 established as acceptable. Indicator validation was performed using published studies, monitoring records, and field observations (Jørgensen *et al.,* 2010; Pahl-Wostl *et al.,* 2010; EEA, 2018).

GIS-based spatial analysis

All spatial analyses were conducted using ArcGIS 10.8 and QGIS 3.x. The spatial analysis workflow comprised six primary phases. First begin with the preprocessing of geospatial datasets. This initial stage involved geometric correction, projection into the WGS 1984 UTM Zone 36N coordinate system, and spatial resampling to a uniform 30 m resolution. Second, raster layers representing environmental, physical, socio-economic, and accessibility criteria were prepared. Third, all criteria were standardized to a common 1–5 scale, where 1 represented very low suitability or sensitivity and 5 represented very high suitability or sensitivity. Fourth, weighted overlay analysis based on the weighted linear combination (WLC) approach was applied. Fifth, buffer analysis was used to evaluate shoreline zones, protected areas, infrastructure corridors, settlements, and accessibility conditions. Ultimately, zonal statistics

and areal computations were executed to quantify and summarize the spatial distribution across the various sensitivity and suitability classes. Spatial outputs were checked against field observations, high-resolution satellite imagery, published maps, and available literature to improve interpretation reliability (Malczewski, 1999; Malczewski, 2006; Longley *et al.,* 2011; GAFRD, 2020). The overall workflow adopted for GIS-based spatial analysis, environmental sensitivity assessment, and suitability mapping is illustrated in (Fig. 4). The percentage ranges reported in the Results section were derived from the classified outputs generated through the GIS-based weighted overlay analysis, which is detailed in the subsequent sections. Relative areal proportions of sensitivity and suitability classes were quantified using zonal statistics and area calculations. To enhance interpretative reliability, these benchmark ranges were contextualized and cross-referenced with ecological characteristics documented by the EEAA, Ministry of Environment publications, and prior ecological literature.

Environmental sensitivity mapping

Environmental sensitivity mapping was deployed to delineate regions of significant ecological value or heightened vulnerability to anthropogenic disturbances and development pressures. Sensitivity criteria were grouped into three major categories. Ecological criteria included biodiversity hotspots, wetlands, khors, spawning grounds, migratory routes, and critical habitats. Physical criteria included slope, soil erodibility, water depth, shoreline stability, and erosion susceptibility. Socio-economic criteria comprised traditional fishing areas, cultural heritage sites, settlements, and areas exposed to development pressure. Each criterion was standardized to a uniform five-level ordinal scale, where a value of 1 denoted exceptionally low sensitivity and a value of 5 signified exceptionally high sensitivity. Criteria weights were assigned based on literature review, expert judgment, and (AHP) where sufficient expert information was available. The environmental sensitivity index (ESI) was calculated using the weighted linear combination (WLC) approach, which is widely applied in GIS-based multi-criteria decision analysis, using Eq. 1 (Malczewski, 1999; Malczewski, 2006):

$$ESI = \Sigma(Wi \times Xi) \quad (1)$$

Where: ESI represents the environmental sensitivity index, Wi denotes the relative weight assigned to criterion i, Xi represents the standardized score of criterion i, and n is the total number of criteria considered.

The resulting index values were classified into five sensitivity classes (very high, high, moderate, low, and very low) using natural breaks classification combined with expert-based interpretation. This procedure provided a transparent basis for identifying protection priorities and development constraints (Bishai and Abu Gideiri, 1976; Malczewski, 1999; Long *et al.,* 2014). To estimate the relative spatial extent of each sensitivity class, zonal statistics and area computations were executed. The percentage occupied by each class was calculated as the ratio between the area corresponding to the classified sensitivity zone and the total study-area extent, using Eq. 2 (Malczewski, 2006; Abdel-Satar *et al.,* 2017; Longley *et al.,* 2011):

$$Pi = (Ai / At) \times 100 \quad (2)$$

Where: Pi is the percentage occupied by sensitivity class i, Ai is the area corresponding to the classified sensitivity zone, and at is the total study-area extent. Rather than reflecting fixed ecological thresholds, these percentage intervals denote relative spatial proportions calculated directly from the classified GIS datasets. The resulting distributions were interpreted and cross-checked against known ecological characteristics

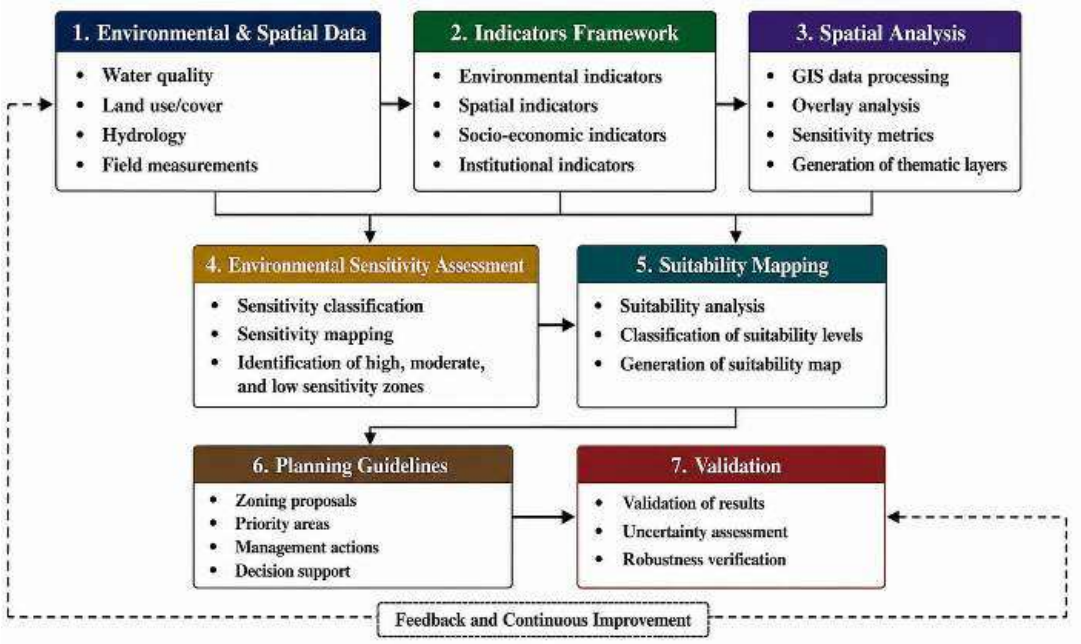

Fig. 4: GIS-based spatial analysis workflow from environmental and spatial data collection through indicators framework, spatial analysis, sensitivity mapping, suitability mapping, to planning

reported by the (EEAA), Ministry of Environment documents, high-resolution satellite imagery, and previous ecological studies on Lake Nasser ecosystems to improve interpretation reliability and ecological consistency (El-Shabrawy, 2009; El-Shabrawy and Fishar, 2009; Abdel-Satar *et al.,* 2017; Longley *et al.,* 2011). This spatial approach aligns with standard Egyptian methodologies, where GIS-based classification is routinely applied to environmental assessments and protected-area management.

Spatial suitability analysis

Suitability analysis was conducted to evaluate the appropriateness of different lake zones for sustainable fisheries, eco-tourism, agriculture, aquaculture, and conservation. Criteria varied according to each activity. Fisheries suitability considered water quality, water depth, ecological sensitivity, and accessibility. Tourism suitability considered scenic value, infrastructure, accessibility, and environmental sensitivity. Agricultural suitability considered water availability, slope, accessibility, and environmental constraints. Aquaculture suitability considered water quality, depth, infrastructure proximity, and ecological sensitivity (GWP, 2000; GWP, 2004; Malczewski, 2006; Arkema *et al.,* 2006; Long *et al.,* 2014; Nakamura and Rast, 2014). Conservation suitability considered biodiversity value, habitat importance, ecological connectivity, and ecosystem integrity. All criteria were standardized to a 1–5 scale and combined using weighted overlay analysis. Suitability outputs were classified into five classes: very suitable, suitable, moderately suitable, unsuitable, and very unsuitable. Highly environmentally sensitive areas were classified as development constraints, prioritizing them for conservation and restricted-use protocols. The suitability criteria varied according to the requirements and environmental characteristics of each development activity. The principal criteria considered for fisheries, eco-tourism, agriculture, aquaculture, and conservation suitability assessment are summarized in Table 3.

Table 3: Main criteria used for suitability assessment of different development activities

Criteria	Fisheries	Eco-tourism	Agriculture	Aquaculture	Conservation
Water quality	✓	✓	✓	✓	✓
Water depth	✓	-	-	✓	✓
Slope	-	✓	✓	-	-
Accessibility	✓	✓	✓	✓	-
Infrastructure availability	✓	✓	✓	✓	-
Environmental sensitivity	✓	✓	✓	✓	✓
Biodiversity importance	-	✓	-	-	✓
Habitat connectivity	-	-	-	-	✓
Scenic value	-	✓	-	-	-
Soil suitability	-	-	✓	-	-
Water exchange	-	-	-	✓	-
Protected areas and ecological constraints	-	✓	✓	✓	✓

Governance assessment using ILBM

Governance capacity was evaluated using the integrated Lake basin management framework, which assesses the system across eight distinct dimensions: 1) policies and planning; 2) legislation and regulatory enforcement; 3) institutional coordination and mandate clarity; 4) stakeholder participation; 5) information and knowledge systems; 6) technology and technical capacity; 7) financial mechanisms; and 8) governance transparency and accountability. Each dimension was evaluated using documentary evidence from national development plans, environmental policies, institutional reports, legislation, published studies, and stakeholder consultations. A semi-quantitative scoring system from 1 to 5 was applied, where 1 indicates very weak performance, 2 weak performance, 3 moderate performance, 4 strong performance, and 5 very strong performance. To generate a composite governance-performance score and pinpoint critical structural deficiencies, individual dimension scores were mathematically averaged. This procedure allowed comparison between Lake Nasser and international lake-management experiences while maintaining transparency in the scoring process, facilitating evidence-based policy formulation and long-term institutional capacity enhancement efforts. (ILEC, 2005; Jørgensen *et al.,* 2010; Nakamura and Rast, 2014; Nakamura, 2022). The main governance dimensions and their evaluation criteria are summarized in Table 4.

Comparative case study analysis

Comparative case-study analysis was used to benchmark Lake Nasser against selected international lake-management experiences. The Great Lakes, Lake Biwa, and Lake Victoria were selected because they represent different lake types, governance arrangements, socio-economic contexts, and management challenges. The Great Lakes represent an advanced binational governance and monitoring model; Lake Biwa represents a national and prefectural integrated lake-management model with strong community engagement; and Lake Victoria represents a developing-country transboundary lake system with complex institutional and resource-use pressures. The comparative analysis evaluated governance structures, legal and policy frameworks, monitoring protocols, and stakeholder engagement, alongside financing mechanisms, adaptive management practices, spatial planning instruments, and salient lessons applicable to Lake Nasser (EPA, 2019; Endoh *et al.,* 2005; Hecky *et al.,* 2010; IJC, 2012; IJC, 2023; Nakatsuka *et al.,* 2020; LVBC, 2021).

Statistical analysis

Statistical analysis was used to support environmental-indicator assessment, governance scoring, and spatial-analysis outputs. Descriptive statistics, including mean, range, standard deviation, and percentage distribution, were used to summarize environmental and socio-economic

Table 4: ILBM governance dimensions and evaluation criteria

Governance dimension	Assessment focus	Main evaluation criteria
Policies and planning	Strategic integration and policy coherence	Availability of integrated management plans, consistency of sectoral policies, long-term planning orientation
Legislation and regulatory framework	Regulatory adequacy and enforcement	Existence of legal framework, enforcement effectiveness, regulatory compliance
Institutions and coordination	Institutional responsibilities and coordination mechanisms	Clarity of mandates, inter-agency coordination, reduction of overlapping responsibilities
Stakeholder participation	Community and stakeholder engagement	Participation mechanisms, involvement of local communities, transparency of decision-making
Information and knowledge systems	Data availability and knowledge management	Monitoring programs, information accessibility, scientific support, data-sharing mechanisms
Technology and technical capacity	Monitoring and management capabilities	Availability of GIS, RS, technical expertise, environmental monitoring systems
Finance and economic sustainability	Financial support mechanisms	Budget availability, funding continuity, economic incentives, financial sustainability
Governance effectiveness and accountability	Transparency and institutional performance	Accountability, transparency, adaptive management capacity, implementation effectiveness

indicators. Weighted averages were used to aggregate environmental sensitivity, suitability, and governance scores. Where data availability permitted, correlation analysis was deployed to investigate the relationships existing between environmental pressures, specific indicators, and their corresponding spatial patterns. Sensitivity analysis was applied by varying selected indicator weights to evaluate the stability of the resulting sensitivity and suitability classifications. The consistency of expert-based weighting was assessed using the consistency ratio in the Analytic Hierarchy Process where applicable. Rather than establishing causal relationships from constrained datasets, these statistical procedures were implemented to maximize methodological transparency and reliability (Malczewski, 1999; Malczewski, 2006).

Framework validation and uncertainty analysis

Validation of the proposed framework was achieved via four complementary procedures: 1) internal consistency assessment evaluated the logical connectivity among the five framework phases and verified that the outputs of each phase effectively informed subsequent phases; 2) spatial validation, which compared sensitivity and suitability outputs with field observations, high-resolution imagery, published maps, and known ecological characteristics of Lake Nasser; 3) comparative validation, which benchmarked the framework against international lake-management experiences from the Great Lakes, Lake Biwa, and Lake Victoria; and 4) expert and stakeholder review, which substantiated the identification of governance gaps, spatial priorities, and implementation constraints. The principal validation dimensions, their application to Lake Nasser, and the corresponding findings are summarized in Table 5 (Goher *et al.,* 2021; Kayombo and Jørgensen, 2006; Kolding *et al.,* 2008; Krantzberg and de Boer, 2008). Uncertainty analysis considered limitations related to data availability, spatial resolution, temporal inconsistencies among datasets, subjectivity in indicator weighting, incomplete monitoring records, and uncertainty in governance scoring. To mitigate these uncertainties, the study integrated multiple data streams, cross-verification protocols, literature comparison, expert consultation, and sensitivity analysis of the selected weighting schema, to improve overall methodological robustness significantly**.** These procedures improved framework reliability. Table 5 also highlights the framework's theoretical, applied, spatial, institutional, decision-support, adaptive-management, and transferability validation dimensions (Lindenmayer and Likens, 2010; Malczewski, 2006; Allen and Gunderson, 2011; EEA, 2018).

Table 5: Framework validation and benchmarking dimensions

Validation dimension	Application to Lake Nasser	Main findings
Theoretical validation	Integration of DPSIR, ILBM, IWRM, EBM, Adaptive Management, and GIS-based analysis	Strong functional integration among framework components
Applied validation	Environmental sensitivity, spatial suitability, and governance assessment	Identification of priority conservation and development zones
Spatial validation	GIS-based sensitivity and suitability analysis	Strong correspondence with known environmental characteristics
Institutional validation	Governance-gap assessment and stakeholder coordination	Identification of institutional weaknesses and coordination priorities
Decision-support validation	Scenario evaluation and planning alternatives	Support for balanced and sustainability-oriented planning
Adaptive-management validation	Monitoring indicators and feedback mechanisms	Support for continuous monitoring and adaptive management
Comparative benchmarking	Comparison with Great Lakes, Lake Biwa, and Lake Victoria	High consistency with international best practices
Transferability assessment	Application to comparable environmental contexts	Potential adaptability to arid and freshwater lake systems

RESULTS AND DISCUSSION

Environmental sensitivity assessment of Lake Nasser

Environmental sensitivity assessment of Lake Nasser revealed considerable spatial variation in ecological vulnerability and environmental importance across the lake system. Very high sensitivity areas were mainly associated with khors, wetland habitats, shoreline ecosystems, spawning grounds, islands, and ecologically connected zones. Owing to their critical role in biodiversity conservation, fish reproduction, and ecosystem stability, these regions were designated as priority conservation zones necessitating strict protection or restricted-use management. High sensitivity areas were generally concentrated around ecologically valuable habitats and transitional zones exposed to development pressures (OECD, 2006; GWP, 2000; Pahl-Wostl *et al.,* 2010; Nakamura and Rast, 2014; Allen and Gunderson, 2011). Low-sensitivity zones exhibited greater resilience to anthropogenic disturbances. Environmental sensitivity patterns identified in this study are consistent with previous investigations highlighting the ecological significance of khors, wetlands, spawning grounds, and shoreline habitats within Lake Nasser (El-Shabrawy, 2009; El-Shabrawy and Fishar, 2009; Abdel-Satar *et al.,* 2017). The resulting protection-priority zoning and environmentally sensitive areas delineated by the proposed framework are illustrated in Fig. 5. A detailed comparison contrasting the proposed framework with alternative management approaches is delineated in Table 6.

Spatial suitability analysis for development activities

Spatial suitability analysis was conducted to evaluate the appropriateness of different zones for sustainable fisheries, eco-tourism, agricultural development, aquaculture, conservation, and integrated development. Suitability criteria varied according to the activity being assessed. Fisheries suitability considered water quality, water depth, spawning habitats, environmental sensitivity, and accessibility. Eco-tourism suitability considered scenic value, accessibility, proximity to cultural and natural attractions, infrastructure availability, and environmental sensitivity. Agricultural suitability considered soil suitability, slope, water availability, accessibility, and environmental constraints. Aquaculture suitability considered water depth, water quality, water exchange, accessibility, infrastructure proximity, and ecological sensitivity. The evaluation of conservation suitability integrated several criteria, including biodiversity value, habitat importance, ecological connectivity, ecosystem integrity, and the spatial distribution of wetlands and khors.

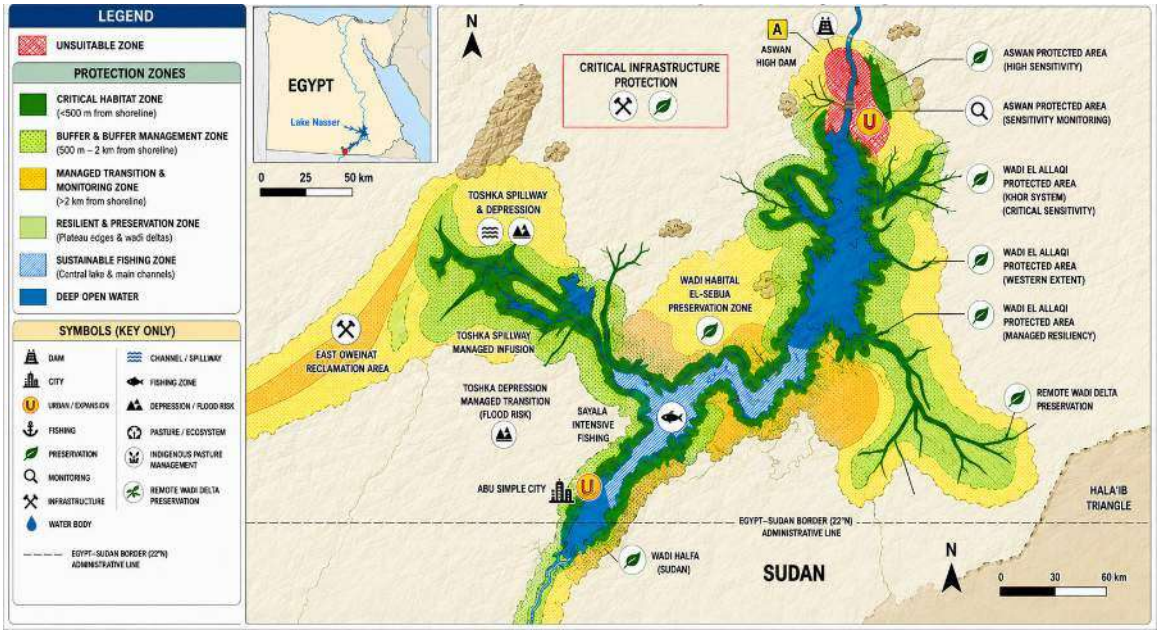

Fig. 5. Environmental sensitivity and protection-priority zoning of the Lake Nasser region, showing critical habitat zones, buffer areas, managed transition zones, and controlled-use areas.

Table 6: Comparative evaluation of the proposed framework and individual management approaches

Management component	Proposed framework	DPSIR	ILBM	IWRM	EBM	Adaptive management
Causal analysis of environmental pressures	✓	✓	–	–	–	–
Governance assessment	✓	–	✓	Partial	Partial	–
Environmental indicators	✓	Partial	Partial	Partial	✓	Partial
GIS-based spatial analysis	✓	–	–	Partial	Partial	–
Environmental sensitivity assessment	✓	–	–	–	✓	–
Suitability analysis and spatial planning	✓	–	Partial	✓	Partial	–
Carrying-capacity assessment	✓	–	Partial	✓	Partial	–
Stakeholder participation	✓	Partial	✓	✓	Partial	✓
Monitoring and feedback mechanisms	✓	Partial	Partial	Partial	Partial	✓
Decision-support capability	High	Moderate	Moderate	Moderate	Moderate	Moderate
Integration among environmental, spatial, and institutional dimensions	High	Low	Moderate	Moderate	Moderate	Low
Applicability to adaptive lake management	High	Moderate	High	Moderate	Moderate	High

Areas with very high environmental sensitivity were treated as constraints for intensive development and prioritized for conservation or restricted-use management. Based on environmental sensitivity and suitability assessment results, a balanced spatial development scenario was formulated for the Lake Nasser region, as delineated in Fig. 6, supporting sustainable resource allocation and minimizing ecological conflicts.

Ecological and socioeconomic implications of protection-priority zoning

Environmental sensitivity assessment indicates that a substantial proportion of the Lake Nasser system requires enhanced environmental protection or carefully managed development. From an ecological standpoint, delineating protection-priority zones fosters biodiversity conservation while safeguarding critical wetlands, khors, spawning grounds, and shoreline habitats—

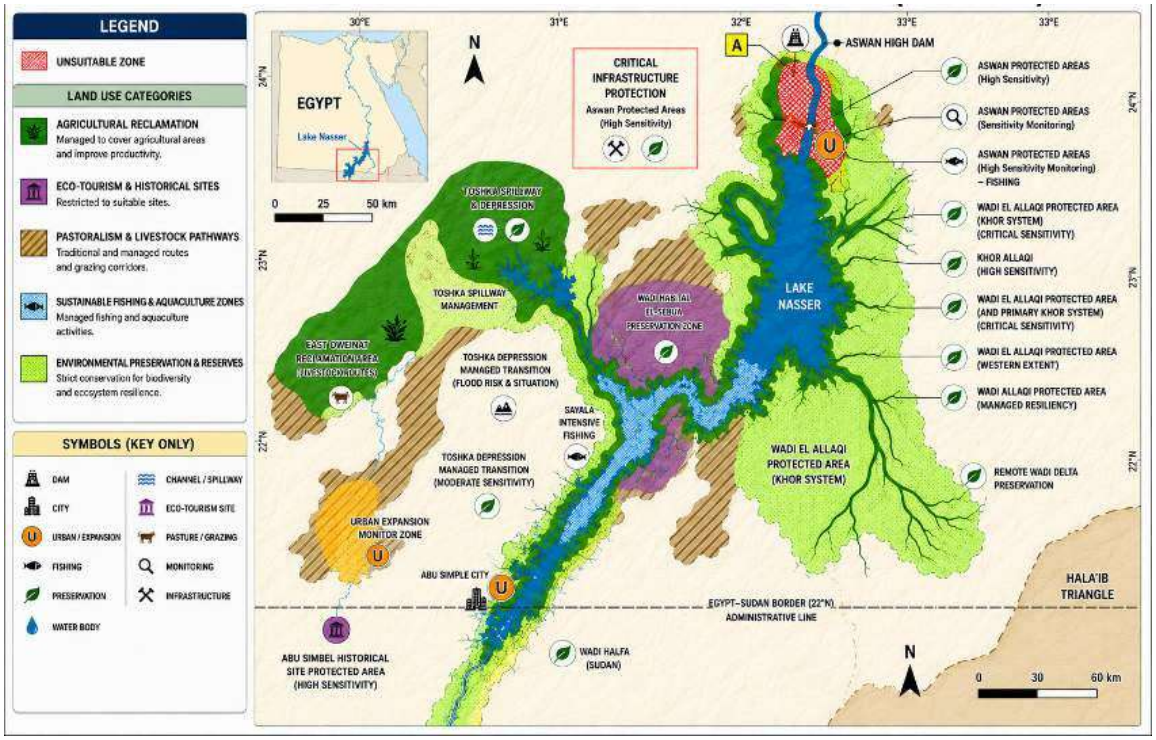

Fig. 6: Proposed balanced spatial distribution of land uses in the Lake Nasser region (2026–2035), showing the spatial framework for agricultural reclamation, eco-tourism, pastoralism, sustainable fishing, and environmental conservation

all of which are vital to sustaining ecosystem stability and resilience. Restricting intensive development within environmentally sensitive zones can reduce habitat degradation, minimize ecological pressures, and support long-term ecosystem sustainability (El-Shabrawy, 2009; El-Shabrawy and Fishar, 2009; Abdel-Satar *et al.,* 2017). From a socioeconomic perspective, protection-priority zoning provides a spatial basis for allocating development activities to environmentally suitable areas, thereby reducing conflicts among competing land and water uses (Folke *et al.,* 2005; Sayers *et al.,* 2021; Biswas and Tortajada, 2022). This approach supports sustainable development while improving resource-use efficiency.

Comparative analysis with global case studies

Comparative analysis revealed important lessons for Lake Nasser. The empirical evidence from the Great Lakes underscores the critical necessity of science-based management paradigms and sustained, long-term monitoring networks (IJC, 2012; IJC, 2023; Awange and Ong'ang'a, 2006). Lake Biwa represents a successful example of national-scale integrated lake management through the Lake Biwa Comprehensive Development Plan and the subsequent Mother Lake 21 Plan. Key success factors include continuous monitoring, community participation, and long-term ecosystem protection (Kumagai *et al.,* 2002; Kumagai *et al.,* 2003; Nakatsuka *et al.,* 2020). Due to its transboundary nature, competing development pressures, and institutional fragmentation, Lake Victoria presents a more intricate management paradigm. Implementation remains constrained by limited resources and institutional capacity (Njiru *et al.,* 2008). The Lake Victoria experience highlights the importance of regional cooperation (LVBC, 2021). The comparative assessment identified five critical determinants of successful lake management, namely long-term institutional commitment,

transparent legislative and governance frameworks, evidence-based monitoring coupled with adaptive management, robust stakeholder participation, and strong coordination mechanisms (Pahl-Wostl, 2009). The principal characteristics of the selected international case studies used for benchmarking are summarized in Table 7.

ILBM-based assessment of Lake Nasser

The ILBM-based governance assessment revealed significant weaknesses in institutional coordination, stakeholder participation, information systems, technical capacity, financial support, and governance transparency. The assessment indicated that management responsibilities remain distributed across a fragmented network of agencies, while existing monitoring systems and information-sharing protocols are inadequate to support integrated lake governance (Pahl-Wostl *et al.,* 2016; Kummu *et al.,* 2021). These governance constraints reduce the effectiveness of environmental planning and limit the ability to implement adaptive management strategies. Policy and planning remain largely sectoral, with the absence of a unified lake-management plan integrating environmental, spatial, and socio-economic dimensions. While a pertinent legislative foundation exists, the associated regulatory frameworks remain fragmented, and enforcement mechanisms lack sufficient efficacy. Institutional fragmentation and overlapping responsibilities among ministries and agencies represent major obstacles to coordinated management. Technical capacity is constrained by limited monitoring infrastructure and inadequate use of GIS and environmental information systems. Furthermore, longitudinal databases and data-sharing protocols remain underdeveloped, while stakeholder engagement and public participation in decision-making processes are currently constrained. Financial support for environmental monitoring and conservation programs also remains inadequate (ILEC, 2005; Jørgensen *et al.,* 2010; Nakamura and Rast, 2014; Nakamura, 2022). The principal governance gaps and priority improvement actions identified through the ILBM assessment are summarized in Table 8.

Critical analysis of Lake Nasser development strategy

When evaluated against the proposed integrated framework, the contemporary Lake Nasser development strategies articulated in national plans and sectoral programs reveal several structural deficiencies. Development activities are generally implemented through sector-based approaches with limited coordination among responsible institutions. Environmental considerations are often secondary to development objectives, while environmental impact assessment and mitigation measures remain insufficient. Furthermore, the absence of an integrated lake-management plan contributes to fragmented spatial planning and reduces opportunities for coordinated and sustainability-oriented development (Williams *et al.,* 2009; Gunderson and Light, 2006). A comparative analysis was performed to determine the degree to which the contemporary strategy aligns with the core tenets of integrated environmental management (Halls, 2004). The comparison revealed deficiencies in environmental indicators, spatial analysis, governance integration, monitoring systems, and stakeholder participation. The differences between the current strategy and the proposed framework are summarized in Table 9. To further examine the current strategy from a systems perspective, the DPSIR framework was applied to evaluate the relationships among drivers, pressures, environmental states, impacts, and responses. The analysis indicated that while development objectives and policy responses are clearly discernible, existing planning documents offer an incomplete representation of environmental pressures, state indicators, and causal impact linkages. The application of the DPSIR framework to the current Lake Nasser development strategy is summarized in Table 10, highlighting environmental priorities.

Table 7: Comparative characteristics of selected international lake-management case studies (Awange and Ong'ang'a, 2006; IJC, 2012; IJC, 2023; Kumagai *et al.,* 2002; Kumagai *et al.,* 2003; Nakatsuka *et al.,* 2020; Njiru *et al.,* 2008; LVBC, 2021; Pahl-Wostl, 2009)

Characteristic	Lake Nasser	Great Lakes	Lake Biwa	Lake Victoria
Type	Artificial reservoir	Natural glacial lakes	Natural tectonic lake	Natural tectonic lake
Surface area	~5,000 km²	~244,000 km²	~670 km²	~68,800 km²
Countries	Egypt, Sudan	USA, Canada	Japan	Kenya, Uganda, Tanzania
Climate	Hyper-arid	Temperate	Temperate	Tropical
Primary functions	Water storage, hydropower, fisheries	Navigation, fisheries, water supply, recreation	Water supply, fisheries, recreation	Fisheries, water supply, transport
Population in basin	~500,000	~30 million	~14 million	~40 million
Main pressures	Sedimentation, development, water allocation	Pollution, invasive species, climate change	Urbanization, pollution, eutrophication	Overfishing, pollution, invasive species, climate change
Governance structure	National agencies	Binational commission (IJC)	National and prefectural institutions	LVBC and national agencies
Management approach	Sectoral and developing integration	Integrated and ecosystem-based	Integrated and community-engaged	Developing integration and transboundary cooperation
Stakeholder participation	Limited	Strong	Strong	Moderate
Monitoring system	Developing	Comprehensive	Comprehensive	Moderate
Financial support	Limited	Strong and stable	Strong	Moderate
Adaptive management	Limited	Strong	Strong	Moderate

Table 8: Simplified ILBM-based assessment of Lake Nasser management system

Governance dimension	Main gaps	Priority actions
Policy and planning	Weak sectoral integration and limited spatial coordination	Develop an integrated lake-management plan and coordination mechanisms
Legislation	Fragmented regulations and overlapping institutional mandates	Harmonize legal frameworks and strengthen enforcement
Institutions	Limited coordination and technical capacity	Establish specialized lake-management units and joint technical teams
Technology and technical capacity	Limited GIS, monitoring, and modeling systems	Expand GIS, RS, and monitoring infrastructure
Information and knowledge systems	Weak long-term studies and limited data accessibility	Develop unified environmental databases and support applied research
Stakeholder participation	Limited stakeholder representation and participation mechanisms	Establish participatory platforms and awareness programs
Finance and economic sustainability	Dependence on limited government funding	Diversify financing sources and strengthen partnerships
Governance effectiveness and transparency	Weak monitoring, evaluation, and transparency systems	Improve reporting, accountability, and feedback mechanisms

Table 9: Comparison between the current Lake Nasser development strategy and the proposed framework

Component	Current strategy	Proposed framework	Improvement achieved
Environmental indicators	Partial	Integrated and multi-dimensional	More comprehensive environmental assessment
Spatial analysis	Limited	Structural component of assessment	Improved spatial decision-making
Environmental sensitivity	Not central	Core planning component	Better protection prioritization
Spatial suitability	Limited	Multi-criteria assessment	Improved development allocation
DPSIR relationships	Incomplete	Fully integrated	Enhanced causal diagnosis
Governance dimension	General	ILBM-based governance	Stronger institutional coordination
Monitoring and evaluation	Limited	Adaptive management framework	Continuous feedback mechanisms
Decision support	Implicit	Explicit and indicator-based	Improved planning support
Stakeholder participation	Limited	Integrated component	Increased participation and transparency
Scenario development	Weak	Built into planning stage	Enhanced sustainability orientation

Table 10: Evaluation of the current Lake Nasser development strategy using the DPSIR framework

DPSIR component	Representation in the current strategy	Main observations
Drivers	Relatively clear	Reflected on development and economic objectives
Pressures	Partial	Environmental pressures require clearer identification and quantification
State	Limited	Lack of integrated environmental indicators and monitoring systems
Impacts	Partial	Weak linkage between activities and environmental consequences
Responses	Present at policy level	Need for stronger monitoring, evaluation, and adaptive implementation mechanisms

Limitations and challenges

Several limitations and uncertainties should be acknowledged. Data availability and quality constraints affected the comprehensiveness of environmental baseline information and spatial assessments. The sensitivity and suitability analyses were subject to additional uncertainty arising from variations in spatial resolution and temporal coverage across the utilized datasets. Furthermore, the governance assessment relied primarily on documentary evidence and published studies, with limited direct institutional consultation (IPCC, 2022). Although the selected three international case studies offer valuable representative insights, this restricted scope potentially limits the capacity to fully encompass the broad spectrum of freshwater lake-management approaches (Bai *et al.,* 2023). In addition, the present application was conducted at the strategic planning scale, and more detailed site-specific investigations would be required before implementation. While these limitations do not compromise the validity of the findings, they underscore the necessity for subsequent refinement, expanded stakeholder engagement, empirical field validation, and continuous monitoring to optimize the framework's robustness and external applicability (Grafton *et al.,* 2019; Masese *et al.,* 2025).

Sustainability implications of the proposed framework

The proposed integrated framework contributes to sustainable lake management across environmental, institutional, economic, and social dimensions. Environmentally, the integration of environmental assessment with GIS-based spatial analysis improves the analytical capacity available for decision-making and enables the identification of priority areas for conservation and development (Geneletti, 2010; OECD, 2006). From an institutional perspective, the framework bolsters governance effectiveness by incorporating enhanced coordination mechanisms and adaptive management processes, thereby optimizing operational efficiency and inter-agency collaboration (Sayers *et al.,* 2021; Biswas and Tortajada, 2022). Economically, the framework promotes efficient resource allocation through spatial planning and carrying-capacity considerations. Socially, stakeholder participation and collaborative governance mechanisms improve transparency and community engagement (Folke *et al.,* 2005). The adaptive management component further enhances long-term sustainability by promoting continuous learning and policy adjustment in response to environmental changes and management experience (McLeod and Leslie, 2009; Vörösmarty *et al.,* 2018; Wu *et al.,* 2025). Beyond its immediate application to Lake Nasser, the developed framework serves as a scalable model, providing practical benchmarks for environmental planners and policymakers striving to balance ecological protection against sustainable development demands.

CONCLUSION

This study developed and applied an integrated methodological framework for sustainable natural

resource management in freshwater lake systems, using Lake Nasser as a case study. The proposed framework combines DPSIR, ILBM, IWRM, EBM, and adaptive management with environmental indicators and GIS-based spatial analysis within a unified five-phase operational structure. By integrating environmental assessment, governance evaluation, spatial planning, stakeholder participation, and adaptive management, the framework addresses an important methodological gap in existing lake-management approaches. Empirical testing of the framework on Lake Nasser demonstrated that sustainable resource management relies heavily on integrated environmental sensitivity testing, spatial suitability mapping, institutional governance appraisals, and adaptive management protocols. The results revealed that institutional fragmentation, weak inter-agency coordination, limited information systems, and insufficient stakeholder participation remain major constraints to effective lake management. Comparative analysis with the Great Lakes, Lake Biwa, and Lake Victoria emphasized the importance of long-term institutional commitment, science-based monitoring, adaptive management, and stakeholder engagement for successful lake governance. This study provides five principal contributions. First, the study develops an integrated methodological framework designed to functionally consolidate five recognized environmental management modalities within a unified operational architecture. Second, it demonstrates the practical applicability of the framework through its implementation in Lake Nasser. Third, an extensive governance appraisal is executed using ILBM principles to evaluate multiple operational dimensions. Fourth, it introduces a comparative benchmarking approach that facilitates learning from international lake-management experiences. Fifth, it presents a flexible decision-support framework that can be adapted to other freshwater lakes, reservoirs, and transboundary water systems. Despite its significant contributions, the developed framework is intended to function as an adaptable decision-support system rather than a prescriptive, universally applicable model. Its transferability depends on local environmental conditions, governance arrangements, stakeholder capacities, and data availability. Therefore, adaptation and recalibration are required before implementation in different contexts. To advance this field, future investigations should focus on strengthening data infrastructure through improved environmental databases and long-term monitoring networks, while enhancing stakeholder participation and climate-impact modeling. Furthermore, subsequent studies should integrate ecosystem-services assessments, deploy emerging technologies (RS, drones, sensors, and artificial intelligence), and test the framework's scalability in diverse domestic and international lacustrine contexts. These efforts would further enhance the robustness, applicability, and long-term effectiveness of the proposed framework.

AUTHOR CONTRIBUTIONS

M.A.A. Shahat conceived the research idea, developed the methodological framework, conducted data collection, performed spatial and governance analyses, interpreted the results, prepared the figures and tables, and drafted the manuscript. D.S. Saleh co-supervised the research process, contributed to data interpretation, participated in academic writing, actively developed and upgraded the manuscript, and provided critical revisions and academic comments. M.M. Qorqor served as the principal supervisor, contributed to the study design, guided the research process, and reviewed the methodology and results. H.N. Abdel Hamed supervised the overall research, contributed to

the conceptual development of the study, critically reviewed the manuscript, and approved the final version for submission. All authors reviewed, approved, and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, 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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During the preparation of this manuscript, limited use of SciSpace and Google Gemini was made to assist with literature exploration, language refinement, and presentation enhancement. These tools were used solely as supportive aids and did not contribute to the scientific design, methodology, data collection, analysis, interpretation of results, reference selection, or conclusions of the study. All outputs generated with the assistance of these tools were critically reviewed, verified, and substantially edited by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the final manuscript and confirm that all scientific content, methodological development, analyses, results, discussions, references, and conclusions were conceived, validated, and approved exclusively by the authors.

ABBREVIATIONS

%	Percent
AI	Artificial intelligence
AHP	Analytic hierarchy process
ASTER	Advanced spaceborne thermal emission and reflection radiometer
CAPMAS	Central Agency for Public Mobilization and Statistics
DEM	Digital elevation model

DPSIR	Driver–pressure–state–impact–response
EBM	Ecosystem-based management
EEAA	Egyptian Environmental Affairs Agency
EEA	European Environment Agency
ESI	Environmental sensitivity index
GAFRD	General Authority for Fish Resources Development
GIS	Geographic information system
GWP	Global Water Partnership
IJC	International Joint Commission
ILEC	International Lake Environment Committee Foundation
ILBM	Integrated lake basin management
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IWRM	Integrated water resources management
KPI/KPIs	Key performance indicator(s)
km	Kilometer
km²	Square kilometer
LVBC	Lake Victoria Basin Commission
m	Meter
m³	Cubic meter
MCE	Multi-criteria evaluation
mm/y	Millimeters per year
MW	Megawatt
MWRI	Ministry of Water Resources and Irrigation
OECD	Organization for Economic Co-operation and Development
QGIS	Quantum geographic information system
RQ	Research question
RS	Remote sensing
SDGs	Sustainable development goals
SES	Social-ecological systems
SI	Suitability index
SRTM	Shuttle radar topography mission
tons/y	Tons per year
UNEP	United Nations Environment Programme
USA	United States of America
WCED	World Commission on Environment and Development
WLC	Weighted linear combination
WGS 84	World Geodetic System 1984

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CASE STUDY

Collaborative culture for carbon emission disclosure quality among electricity sectors

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ABSTRACT

BACKGROUND AND OBJECTIVES: Carbon emission disclosure is an important mechanism for environmental accountability. However, disclosure quality in Asia remains relatively low despite the region's large contribution to global carbon emissions. While extant literature has predominantly examined governance, regulation, and demographic characteristics, the critical role of organizational culture remains comparatively underexplored. The study objectives were to examine the association between collaborative culture and carbon emission disclosure quality in electricity companies operating in carbon-intensive Asian economies.

METHODS: This study analysed 210 firm-year observations from 45 publicly listed electricity companies in China, India, Indonesia, Japan, and South Korea during 2016–2023. Drawing upon the quality principles of the Global Reporting Initiative, a carbon emission disclosure quality index was constructed and subsequently validated via expert review, yielding a robust Cohen's kappa coefficient of 0.97. Collaborative culture was measured by sustainability collaboration activities. The analysis employed ordinary least squares, fixed-effects, cluster-robust, and two-stage least squares estimations.

FINDINGS: Collaborative culture shows a positive and statistically significant association with carbon emission disclosure quality across all estimation models. The coefficient of collaborative culture reaches 3.749 ($p < 0.01$) under ordinary least squares, 1.723 ($p < 0.05$) under fixed effects model, and 4.107 ($p < 0.01$) under two-stage least squares estimation. Under the fixed-effects model, sustainability reporting experience exerted a positive and statistically significant effect (2.241, $p < 0.05$), highlighting the critical role of accumulated reporting capabilities within firms. Institutional ownership, firm age, and financial performance do not show significant effects. Furthermore, robustness checks employing an alternative metric for disclosure quality corroborate both the direction and statistical significance of the primary empirical findings.

CONCLUSION: The findings indicate that collaborative culture contributes positively to carbon emission disclosure quality. This study contributes a context-specific disclosure quality index and extends empirical evidence on the role of organizational capital in enhancing environmental transparency. Higher disclosure quality, however, should not be interpreted as lower carbon emissions. Improving corporate reporting credibility and reducing greenwashing exposure necessitates regulatory intervention to strengthen disclosure quality, standardize science-based metrics, and formalize third-party assurance protocols.

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58	2	10

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INTRODUCTION

Carbon emissions disclosure is increasingly drawing public attention. Carbon emission transparency has increasingly emerged as a critical institutional imperative across multiple sectors, with escalating pressure directed toward private firms. Paris Agreement has established net-zero carbon emissions as a global priority. Asia leads the world in total carbon emissions. Electricity and heat generating had the largest 1.8% or 261 Mt rise in emissions in 2022. Global coal-fired electricity and heat generating emissions increased by 224 Mt or 2.1%, led by emerging Asian nations (IEA, 2023). Carbon accounting addresses the accountability aspects of carbon-intensive business operations. This involves identifying, assessing, and monitoring greenhouse gas emissions and their impact on ecosystems. Carbon accounting is essential for achieving net-zero emissions targets. While accurate emissions measurement is an essential precursor to developing robust decarbonization frameworks, empirical evidence highlights ongoing systemic challenges in carbon disclosure practices. Complexity of the information is a major barrier. Non-specialist users, including investors, often struggle to interpret carbon disclosure reports. Ineffective decision-making is a documented consequence of this knowledge gap. In 2023, the composite carbon emissions disclosure quality (CEDQ) score in Asia reached merely 47 out of 100, falling short of the global average (Bell and Lumsden, 2024). The Ernst and Young Global Climate Action Barometer confirms these findings. Readability scores for the five Asian economies with the highest carbon emissions, such as China, India, Indonesia, Japan, and South Korea, remained below 60 during the same period. This pattern persists despite Asia's status as the world's largest emitter. Asia is also characterized by rich ethnic and cultural diversity. Distinct communal traditions exert a quantifiable influence on institutional and organizational practices (Weiner, 2022). Dominating Asian societies, the clan culture archetype strongly emphasizes familial orientation, collective togetherness, and mutual solidarity. It actively fosters cooperation and collaboration among individuals (Xu and Yao, 2015; Cameron *et al.*, 2006). Clan culture significantly shapes corporate culture. Corporate culture encompasses a company's values, beliefs, and operational norms (Barney, 1986). Extant literature suggests that the cultural characteristics of the surrounding community serve as a primary foundational input for the construction of organizational culture (von Meding *et al*., 2013), which subsequently dictates external communication and corporate reporting paradigms (Chao *et al.*, 2023). Consequently, within highly cooperative societies, companies that embody collaborative values demonstrate stronger performance and higher-quality disclosures. Thus, a strong collaborative culture (COLLAB) plays a crucial role in corporate transparency and effective disclosure practices (Handoyo *et al.*, 2024; García-Sánchez *et al.*, 2020). Previous literature identifies inadequate internal skills and resources as the primary drivers of disclosure quality issues. Management teams frequently manifest resistance toward corporate reporting mandates, with fiscal pressures and temporal constraints emerging as the most prevalent institutional barriers (Safari and Areeb, 2020; Diouf and Boiral, 2017). Safari and Areeb (2020) demonstrate that inadequate internal processes hinder the quality and reliability of disclosures. Effective measurement and data collection systems are prerequisites for reliable reporting. Companies aligned with the global reporting initiative (GRI) criteria for sustainability reporting generally lack critical resources. Informed board directors and robust governance frameworks emerge as the primary resources that organizations most frequently fail to secure (Chairina and Tjahjadi, 2023; Bazhair *et al.*, 2022). Empirical studies on the CEDQ remain limited. Key contributions include Caby *et al.* (2024), He *et al.* (2021), Luo *et al.* (2023), Shen and Li (2022),

Perkins *et al.* (2022), Solikhah and Maulina (2021), and Tan *et al.* (2020). Caby *et al.* (2024) examined the impact of gender diversity on disclosure quality. Female board members exert a positive influence on voluntary carbon disclosure. This effect becomes significant at a 30% representation threshold. Prior empirical research indicates that while government regulations positively correlate with the quality of carbon disclosures, media coverage exerts no significant influence (He *et al.*, 2021). Luo *et al.* (2023) demonstrated a positive association between carbon guarantees and superior disclosure quality. This association is particularly strong in stakeholder-oriented national contexts. Shen and Li (2022) documented the effectiveness of the Carbon Information Disclosure System. State-owned enterprises derive the greatest benefits from this mechanism. Perkins *et al.* (2022) examined the influence of culture on the CEDQ. High levels of individualism and high power distance are negatively correlated with disclosure quality. Assertiveness scores show a positive relationship. Solikhah and Maulina (2021) found that performance-based incentives significantly improve the quality of environmental disclosure. Tan *et al.* (2020) demonstrated that both carbon trading systems and robust internal control frameworks exert positive effects on disclosure quality, an association that is particularly pronounced among Chinese state-owned enterprises. Previous studies have examined governance characteristics, the regulatory environment, and individual executive attributes as determinants of CEDQ (Li *et al.*, 2025; Wang and Wu, 2024; Braasch and Velte, 2023). While resource-Based View (RBV) theory has been extensively utilized to examine competitive strategy and financial performance, its application to environmental disclosure quality, particularly through the lens of organizational culture as organizational capital, remains underdeveloped (Bazhair *et al.*, 2022; Luo *et al.*, 2023). The theoretical novelty of this study comprises four dimensions. First, it synthesizes the RBV with organizational culture theory. COLLAB serves as a path-dependent, intangible subdimension of organizational capital that enables firms to yield higher-quality disclosures. Sustainability collaboration activities strengthen the CEDQ through three channels (Wang *et al.*, 2023): 1) Transparency: External sustainability partnerships increase the diversity and volume of carbon-related information flowing into the organization, thereby enriching the completeness and accuracy dimensions of disclosure; 2) Credibility: Cross-sector collaboration with third-party verifiers, including non-governmental organizations (NGOs) and certification bodies, yields independent emissions data verification, directly bolstering the CEDQ's Verification dimension; 3) Reporting practices: Companies that routinely collaborate on sustainability activities develop institutional routines for the collection and reporting of carbon data, thereby improving consistency and timeliness over time. This integration has not been applied to the CEDQ in previous literature. A COLLAB mitigates information asymmetry through three distinct mechanisms directly relevant to the CEDQ framework: 1) internally, by reducing barriers between operational and reporting units, ensuring that raw emissions data reaches the disclosure function accurately; 2) externally, by reducing asymmetry between the company and its stakeholders by increasing the frequency and depth of sustainability communication; 3) by creating transparency norms that reduce incentives for selective or misleading disclosure. Second, previous studies have relied on national-level cultural dimensions (Perkins *et al.*, 2022) or governance structures (Chairina and Tjahjadi, 2023). This study isolates firm-level collaborative practices to establish them as a direct antecedent to CEDQ. Organizations with a strong COLLAB demonstrate enhanced adaptability and resilience. They mobilize resources quickly and respond effectively to changing stakeholder demands (Chatterjee *et al.*, 2024). Third, the Asian electricity sector provides an ideal theoretical research context. Its collectivist cultural substrate makes COLLAB a highly relevant organizational

resource. Fourth, previous methodologies for evaluating CEDQ exhibit significant limitations, primarily because the metrics employed in prior studies lack comprehensiveness. Some studies rely on scores published by rating agencies such as the carbon disclosure project. Other studies develop independent item-scoring indices that assess only specific quality aspects. In response to these limitations, the present study develops a more comprehensive measurement instrument to evaluate CEDQ. This instrument assesses all quality aspects based on GRI quality principles. It is specifically calibrated for the context of carbon emissions disclosure. By addressing the limitations inherent in prior empirical metrics, this approach significantly advances the methodological boundaries of CEDQ research. Regression analysis was executed to evaluate the nuances of annual CEDQ variation alongside evolving firm conditions (Gujarati, 2012). Various estimation approaches were applied to ensure robustness. Pooled ordinary least squares (OLS), Fixed Effects Model with cluster-robust standard errors (SE), and two-stage least squares (2SLS) were used as complementary estimators. This study aims to examine the relationship between COLLAB and the CEDQ among publicly listed electric power companies in China, India, Indonesia, Japan, and South Korea during the 2016–2023.

MATERIALS AND METHODS

Population, sample, and data sources

A quantitative research design was employed using secondary data. Data were collected from company websites and financial databases. The target population consists of publicly listed electric power companies operating in carbon-intensive Asian countries, namely China, India, Indonesia, Japan, and South Korea. Purposive sampling was applied to a population of 126 companies to identify observation targets meeting the core research requirements (Sekaran and Bougie, 2016). The selection criteria are as follows: 1) the company was listed on a stock exchange during the years 2016–2023; 2) the company published an annual report containing the required data on CEDQ and COLLAB; 3) the annual report is available in English; and 4) financial information is reported in U.S. dollars. The conceptual framework is presented in Fig. 1. Utilizing the entire population as the target of observation yields a final sample of 210 observation units, the structural framework of which is delineated in Table 1.

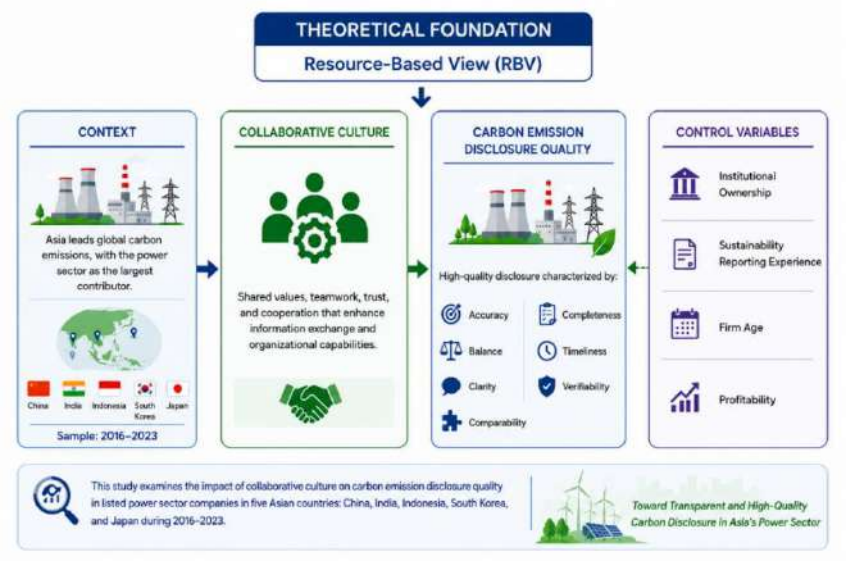

Fig. 1: The study conceptual framework

Table 1: Sample framework

Sample criteria	Number
Public companies in the electricity sector in China, India, Indonesia, Japan, and South Korea from 2016 to 2023	1008
Excluded: companies that do not publish annual reports in English	420
Minus: companies without research variable data	337
Minus: outlier data	41
Total observations (unbalanced)	210

The use of purposive sampling was necessary because the content analysis required comparable and publicly available disclosures across five countries. Firms that publish English-language disclosures may exhibit superior reporting capabilities and heightened exposure to international stakeholders, introducing a potential selection bias relative to excluded firms. Therefore, the findings should be interpreted within the context of firms that actively disclose sustainability information.

Variable measurement

Dependent variable

The dependent variable is CEDQ, defined as the degree of compliance with the principles of accuracy, balance, clarity, comparability, completeness, timeliness, and verification adopted from the GRI framework (Hahn *et al.*, 2015; Kolk, 2008). Table 2 provides an explanation of the GRI Reporting Quality Principles and Assessment Criteria. The index was constructed sequentially through the following phases: i) identification of candidate items from GRI quality principles; ii) expert review with carbon emissions specialists, sustainability reporting evaluators, government evaluators, certified practitioners (CSRS/CSRA), and academics with experience in disclosure indices; and iii) development of the final instrument. The final index consists of 50 items spread across seven quality dimensions. Table 2 provides a granular delineation of the specific items comprising the CEDQ Index (CEDQI). CEDQ variable is measured by calculating a CEDQI score consisting of 50 items. Each item criterion that is met is scored as 1, and conversely, if the item criterion is not met, it is scored as 0. The final index score is computed as the ratio of the cumulative score of items fulfilling the quality criteria to the aggregate number of applicable criteria. The same weighting is adopted following standard practices in sustainability disclosure indices (Pitrakkos and Maroun, 2019; Solikhah and Maulina, 2021; Tan *et al.*, 2020), consistent with the GRI Standards' position that the seven quality principles have equal normative weight. There is no theoretically justified hierarchy among the GRI principles; different weightings would introduce arbitrary subjectivity. To address subjective bias in the data collection process for the CDEQI score, this study employed a triangulation method involving two disclosure index raters (Ayton *et al*., 2023) and an inter-rater reliability test. The inter-rater reliability test utilized Cohen's Kappa as a method to minimize subjective bias during the disclosure index assessment process. This study does not use exploratory factor analysis (EFA) or confirmatory factor analysis (CFA) because the CEDQI is designed as a formative disclosure index, not as a reflective psychometric scale (Tome-Fernandez *et al.*, 2020; Shreedaran *et al.*, 2024). Unlike reflective measures, indicators within a formative index are not assumed to exhibit high multicollinearity; rather, each indicator captures a distinct, non-redundant, and complementary dimension of disclosure quality (Pribeanu, 2012). Therefore, theoretical validation, content validity, and coding reliability are considered more appropriate than factor testing. Based on this explanation, Table 3 summarizes the index development and processing, while maintaining attention to measurement validity and reliability, thereby ensuring methodological rigor, transparency, and consistency throughout index construction and empirical assessment.

Table 2: GRI Reporting Quality Principles, Assessment Criteria, and Carbon Emission Disclosure Quality Index (CEDQI) (GRI, 2021)

Principle	Description	Assessment Criteria	CEDQI items
Accuracy	The organization shall report information that is correct and sufficiently detailed to enable an assessment of its impacts.	1. Reports qualitative information consistent with available evidence and other disclosed information. 2. Indicates which data have been measured. 3. Adequately describes measurement methods, calculation bases, and procedures to allow replication. 4. Ensures that margins of error do not materially affect users' conclusions or assessments. 5. Identifies estimated data and explains the assumptions, estimation techniques, and limitations used.	1. Disclosure includes quantitative carbon emission data. 2. Disclosure includes images or photographs. 3. Disclosure provides access to real-time carbon emission data. 4. Disclosure uses internationally recognized measurement metrics. 5. Disclosure explains the carbon emission calculation methodology. 6. Disclosure includes an environmental management system. 7. Disclosure includes a carbon information management system. 8. Disclosure indicates compliance with ISO 14064.
Balance	The organization shall present information in a neutral manner and provide a balanced representation of both positive and negative impacts.	1. Presents information that enables users to identify both positive and negative impact trends over time. 2. Clearly distinguishes facts from the organization's interpretations. 3. Does not omit relevant information regarding negative impacts. 4. Does not place undue emphasis on positive impacts or achievements. 6. Avoids presenting information in a misleading manner that could influence users' judgments.	1. Disclosure presents carbon performance trends over multiple years. 2. Disclosure does not contain opinion-based information. 3. Disclosure includes information on public complaints. 4. Disclosure includes information on carbon emission non-compliance incidents. 5. Disclosure includes follow-up actions taken regarding carbon emission non-compliance. 6. Disclosure includes corrective actions taken regarding violations. 7. Disclosure explains the negative impacts of carbon emissions over different time horizons. 8. Disclosure explains mitigation efforts addressing the negative impacts of carbon emissions over different time horizons. 9. Disclosure explains preventive measures for negative carbon emission impacts over different time horizons.
Clarity	The organization shall present information in a way that is accessible and understandable to stakeholders.	1. Takes into account the accessibility needs of users regarding language, ability, and technology. 2. Organizes information so users can locate desired information without excessive effort (e.g., through tables of contents, maps, or links). 3. Presents information that can be understood by users with a reasonable understanding of the organization and its activities. 4. Avoids unnecessary abbreviations, technical terms, or jargon, or provides explanations when such terms are used. 5. Reports information concisely without omitting necessary details.	1. Carbon emission disclosure is accessible online. 2. Carbon emission disclosure is presented in two languages (local and international language). 3. Disclosure includes an index related to carbon emission disclosure. 4. Disclosure includes a list of tables related to carbon emission disclosure. 5. Disclosure includes a list of figures related to carbon emission disclosure. 6. Disclosure uses hyperlinks within the document.

		6. Uses charts, graphs, and summary tables to improve accessibility and understanding.	7. Disclosure includes a carbon footprint roadmap for business processes. 8. Disclosure includes a glossary of foreign or technical terms. 9. The index accurately corresponds to the pages containing carbon emission disclosures. 10. Disclosure avoids repetition of similar information.
Comparability	The organization shall select, compile, and report information consistently to enable analysis of the imp s changes in impacts over time, and comparison with other organizations.	1. Presents information for the current reporting period and at least two previous periods, including targets and objectives. 2. Uses internationally accepted metrics, standard conversion factors, and reporting protocols where applicable. 3. Maintains consistency in measurement, calculation, and reporting methods. 4. Maintains consistency in the presentation format of information. 5. Reports both absolute and normalized data to facilitate comparison. 6. Provides contextual information (e.g., organizational size, geographic location) to aid comparisons. 7. Presents current disclosures alongside restated historical data when changes have occurred. 8. Explains changes if historical data are not restated.	1. Disclosure provides carbon emission information for at least two previous reporting periods. 2. Disclosure uses internationally standardized metric units. 3. Disclosure provides information on internationally recognized emission factors or conversion factors. 4. Disclosure applies a consistent carbon emission measurement methodology. 5. Disclosure maintains consistency in the number of figures, tables, and graphs reported across years. 6. Disclosure consistently reports carbon performance ratios across years. 7. Disclosure explains the calculation of carbon performance ratios. 8. Disclosure provides information on the scope of carbon emissions included in the calculation. 9. Disclosure provides information on the scope of carbon emissions excluded from the calculation. 10. Disclosure explains any changes resulting from restatements. 11. Disclosure explains changes resulting from revisions to carbon emission calculation methods.
Completeness	The organization shall provide sufficient information to enable an assessment of its impacts during the reporting period.	1. Reports activities, events, and impacts occurring during the reporting period, including impacts that may be insignificant in the short term but substantial in the long term. 2. Does not omit information necessary for understanding the organization's impacts.	1. Disclosure provides information on direct emissions generated from business operations. 2. Disclosure provides information on indirect emissions generated from business operations. 3. Disclosure provides information on carbon emissions generated by business partners throughout the supply chain. 4. Disclosure provides carbon intensity performance ratios. 5. Disclosure links carbon performance to national targets. 6. Disclosure links carbon performance to global targets.
Timeliness	The organization shall report information regularly and make it available in time for	1. Balances the need for timely reporting with the need to ensure information quality. 2. Maintains consistency in reporting periods.	1. Carbon disclosure is reported in a timely manner. 2. Disclosure is reported consistently within the same reporting timeframe.

	stakeholders to make informed decisions.	3. Clearly indicates the reporting period covered by the disclosed information.	3. Disclosure explains the reporting period boundaries used in carbon performance calculations.
Verifiability	The organization shall collect, record, compile, and analyze information in a manner that allows for an assessment of its quality.	1. Establishes internal controls and documentation procedures that enable review by parties other than the report preparers. 2. Documents the decision-making processes underlying sustainability reporting, including materiality assessments. 3. Designs reporting systems to facilitate external assurance and verification. 4. Identifies original information sources and provides reliable evidence supporting assumptions and calculations. 5. Provides evidence confirming the accuracy of reported information within acceptable margins of error. 6. Avoids unsupported information unless necessary for understanding impacts. 7. Clearly discloses uncertainties associated with reported information.	1. Carbon emission disclosure is verified by an independent third party. 2. Disclosure indicates carbon reduction certification. 3. Disclosure demonstrates two-way communication with stakeholders regarding carbon emissions.

Table 3: Validity and reliability of the development of the disclosure quality index

Assessment dimensions	Definition	Evidence provided in the study
Construct validity	The extent to which an instrument truly measures the intended theoretical construct.	The CEDQI operationalizes disclosure quality as the degree of alignment with the seven disclosure quality principles established in the GRI Sustainability Reporting Standards, namely accuracy, balance, clarity, comparability, completeness , timeliness, and verifiability. Grounded in a robust theoretical foundation, these seven complementary dimensions collectively operationalize the construct of CEDQ. As *a formative disclosure index*, these indicators collectively form the CEDQ construct.
Content validity	The extent to which the indicators used are able to cover the entire domain of the concept being measured.	The CEDQI consists of 50 indicators developed based on the GRI's seven principles of disclosure quality. The indicator identification process was conducted systematically , integrating exhaustive literature reviews with expert consultations across five distinct stakeholder groups: carbon emissions specialists, sustainability evaluators, government experts, certified practitioners, and academics. This process ensures that the indicators used cover all key aspects of CEDQ.
Criterion validity	The extent to which an index correlates with other variables that are theoretically predicted to be related to the construct being measured.	COLLAB, as a variable theoretically predicted to influence CEDQI, was included in all estimation models (Pooled OLS, Fixed Effects, Cluster-Robust, and IV/2SLS). Furthermore, robustness testing using an alternative measure of CEDQ developed by Pitrakkos and Maroun (2019) is predicted to yield consistent relationship directions, thereby providing evidence of convergent validity.
Intercoder reliability	The level of consistency among raters in applying coding guidelines to disclosure items.	Coding is performed by two independent raters using the same assessment guidelines. Subsequently, a Cohen's Kappa test is conducted to demonstrate the level of consistency and reliability of the coding.

Independent variable

The primary independent variable examined in this empirical model is COLLAB. COLLAB is characterized by high levels of support and teamwork, as well as low levels of aggression and conflict (Graham *et al.*, 2022). COLLAB is operationalized by quantifying the total number of sustainability-focused collaborative activities. These activities serve as a behavioral proxy for an organization's COLLAB, capturing the degree to which firms externalize their strategic orientation through disclosed sustainability partnerships. This follows the tradition of content analysis in organizational culture research (Graham *et al.*, 2022; Giorgi *et al.*, 2020). Following Graham *et al.* (2022), the study adopts a revealed preferences approach, positing that companies whose cultures genuinely emphasize collaboration will

systematically engage in more sustainability partnerships, and these partnerships will be disclosed in annual reports. This approach is consistent with the archival research tradition in accounting, where direct measurement of organizational culture is generally unfeasible. Count-based behavioral proxies for culture are a well-established approach in large-scale archival research where direct measurement of culture via surveys is not feasible (Graham *et al.,* 2022). Specifically: 1) the content analysis of reported partnership activities is objective and replicable; 2) reported collaborative activities are verifiable manifestations of internal cooperation norms; organizations that do not embrace collaborative values internally tend not to consistently form and report sustainable external partnerships; 3) the measure varies significantly across companies, confirming that it captures genuine heterogeneity.

Control variable

This study also uses several control variables, including institutional ownership, sustainability reporting (sr) experience, firm age, and financial performance. Institutional ownership is measured by calculating the percentage of shares held by institutional shareholders (Bedi and Singh, 2025). Sustainability reporting experience is operationalized as the cumulative number of years a firm has actively engaged in sustainability reporting (Safari and Areeb, 2020; Truant *et al*., 2017; Park and Brorson, 2005). Firm age is measured by calculating the number of years the company has been in operation (Tommasetti *et al*., 2019). Financial performance is proxied by firm profitability, operationalized via the return on assets ratio (Rahman *et al*., 2025; Yulianti and Waworuntu, 2025). The definitions of each research variable and their measurements are summarized in Table 4.

Statistical analysis

This study utilizes a multi-pronged statistical approach, combining descriptive statistics to elucidate variable characteristics with regression analysis to test the primary hypotheses. The specific regression analysis method used is OLS regression, using Eq. 1 (Burton, 2021):

$$Qual_{t,i} = \alpha + \beta_1 Collab_{t,i} + \beta_2 Insti_{t,i} + \beta_3 Report_{t,i} + \beta_4 LnAge_{t,i} + \beta_5 ROA_{t,i} + e \quad (1)$$

Where:

α = Constant
β = Coefficient of the variable
$Qual_{t,i}$ = Carbon Emissions Disclosure Quality
$Collab_{t,i}$ = Collaborative Culture
$Insti_{t,i}$ = Institutional Ownership
$Report_{t,i}$ = SR Reporting Experience
$LnAge_{t,i}$ = Firm Age
$ROA_{t,i}$ = Financial Performance
e = error
i = company i
t = year t

To validate the research objectives, hypothesis testing was executed utilizing OLS panel regression as the primary empirical model. Pooled OLS treats all observations as independent and identically distributed (IID), assumes no within-firm correlation, maximizes efficiency if this assumption holds, but is inconsistent if firm-level fixed effects are correlated with predictors. OLS regression relies on the satisfaction of classical linear regression assumptions, specifically requiring residual normality, homoscedasticity, and the absence of both multicollinearity and autocorrelation. Conventional regression analysis may be biased because the research data is essentially panel data (Gujarati, 2012). Therefore, the SE robust regression model and panel data regression were used, controlling for country and year effects. OLS with cluster-robust SE relaxes the IID assumption by allowing for within-firm error correlation; coefficients are the same as OLS but inference is corrected. The FEM with cluster-robust SE is the most appropriate specification for this panel data, as its within-group transformation effectively eliminates all unobserved, time-invariant firm heterogeneity.

Table 4: Operational definitions and measurement of variables

Type	Variable	Definition	Measurement
Dependent	CEDQ	The degree of alignment between the disclosed carbon emissions information and the characteristics of CEDQ. The characteristics of disclosure quality include accuracy, balance, clarity, comparability, completeness, timeliness, and verifiability.	CEDQ is measured by calculating a disclosure quality index score consisting of 50 items. Each item that is met is given a score of 1, and conversely, if there is one item that is not met, it is given a score of 0. The index score is calculated by dividing the total score of met items by the total number of index items.
Independent	COLLAB	A culture of collaboration is one that is characterized by an orientation toward cooperation, mutual support, non-aggression, and minimized interpersonal or structural conflict.	Number of collaborative activities with partners in the field of sustainability.
Control	Firm Age	Firm Age is the number of years the company has been in operation since its establishment.	Firm Age is operationalized as the natural logarithm of the number of years since the company's inception.
Control	Sustainability Reporting Experience	Sustainability reporting experience is the number of sustainability reporting periods the company has conducted since the first report was published.	Sustainability reporting experience is measured by the number of years of the company's sustainability reporting periods.
Control	Institutional Ownership	Institutional ownership is measured as the percentage of shares held by Institutional shareholders	Institutional ownership is calculated by dividing the number of shares held by institutional shareholders by the company's total shares, multiplied by 100 percent
Control	Financial Performance	Financial performance is a concept that indicates a company's performance based on financial aspects	Financial performance is proxied by firm profitability, operationalized via the return on assets (ROA) ratio, which is calculated as net income divided by total assets.

Furthermore, this study addresses endogeneity bias in the form of reverse causality by using two-stage least squares estimation. 2SLS addresses endogeneity by instrumenting variable with its first lag, sacrifices some precision (lower N) for consistency under reverse causality. Following Wooldridge (2010) and Angrist and Pischke (2009), the lagged dependent variable as an instrument is relevant if the partial F-statistic exceeds 10 and meets the exclusion criterion when the previous year's activity does not directly determine the current year's disclosure quality except through its influence on the current year's COLLAB. To evaluate model robustness, this study employs alternative proxies for CEDQ and conducts sensitivity analyses under varying underlying assumptions across five distinct dimensions: accuracy, balance, clarity, comparability, completeness. Finally, to deepen the study's institutional insights, supplementary analyses utilizing a year- and country-matched control group design were executed, accounting for the inherent macro-level variances of this cross-country sample.

RESULTS AND DISCUSSION

Descriptive statistics

Descriptive statistical analysis was executed to evaluate baseline data patterns, the results of which are summarizedin Table 5. Table 5 presents the descriptive statistics for all examined variables, utilizing a final sample size of 210 observations. The results indicate that CEDQ remains relatively low, with an average score of 28.71 out of a maximum of 68 and a relatively homogeneous distribution across companies. COLLAB shows an average of 2.26 collaborative activities per year, suggesting a generally low level of collaboration, while the high standard deviation indicates considerable variation among firms.

Table 5: Descriptive statistics

Variable	Obs	Mean	SD	Min.	Max
QUAL	210	28.705	19.096	2.000	68.000
COLLAB	210	2.257	2.933	0.000	15.000
INSTI	210	15.127	17.033	0.000	71.910
REPORT	210	7.129	5.799	0.000	22.000
LNAGE	210	3.482	0.835	0.693	4.890
ROA	210	3.146	7.781	-30.221	66.360

Institutional ownership exhibits a mean value of 15.13%, accompanied by considerable cross-sectional variation across the sample observations. Sustainability reporting experience averages 7.13 years, indicating that most firms possess adequate experience in sustainability reporting, with relatively low variation. Company age averages 44.63 years, reflecting a mature sample of firms with fairly homogeneous characteristics. Financial performance, measured by ROA ratio, exhibits a sample mean of 3.15%; however, a comparatively high standard deviation indicates substantial cross-sectional variation in profitability across the observed firms. Overall, the descriptive statistics reveal substantial variability in governance and performance characteristics, while CEDQ remains relatively limited across the sampled firms. Based on Fig. 2, it can be concluded that CEDQ among electricity sector companies in Asia still exhibits considerable heterogeneity. Japan, Indonesia, and India demonstrate relatively higher levels of disclosure quality compared to China and South Korea. This variation indicates that CEDQ is driven not merely by national emission volumes, but by a complex interplay of macro-level institutional frameworks, governance structures, national sustainability reporting architectures, and firm-level carbon management capabilities.

Instrument validation results

Intercoder reliability

Data collection in this study, particularly for the CEDQ variable, utilized a triangulation method or a three-step data collection process: 1) Data collection by the first observer; 2) Data collection using a sample by the second observer; 3) Instrument reliability testing using the Cohen's Kappa analysis technique. The test results are summarized in Table 6. Intercoder reliability testing was conducted using Cohen's Kappa method to ensure the consistency and reliability of the disclosure index scoring process. The inter-coder reliability assessment yielded an observed agreement rate of 97.14%, demonstrating high baseline consistency between the two independent evaluators. Meanwhile, the expected agreement rate of 4.10% indicates that the likelihood of agreement occurring by chance is relatively very small. A Cohen's Kappa value of 0.9702 indicates a very high level of agreement, falling into the "almost perfect agreement" category according to the classification by Koch and Landis (1977). This value indicates that the content analysis process and the scoring of the disclosure index were conducted consistently and exhibit a very high level of reliability. Furthermore, a probability value of 0.00001 indicates that the level of agreement among coders is statistically significant. Consequently, these diagnostic results confirm that the underlying instruments and coding protocols exhibit robust measurement reliability, validating the disclosure index data for subsequent empirical estimation.

Correlation analysis

Correlation analysis was conducted to identify and measure the strength and direction of relationships between variables. This analysis is useful for detecting multicollinearity, which can

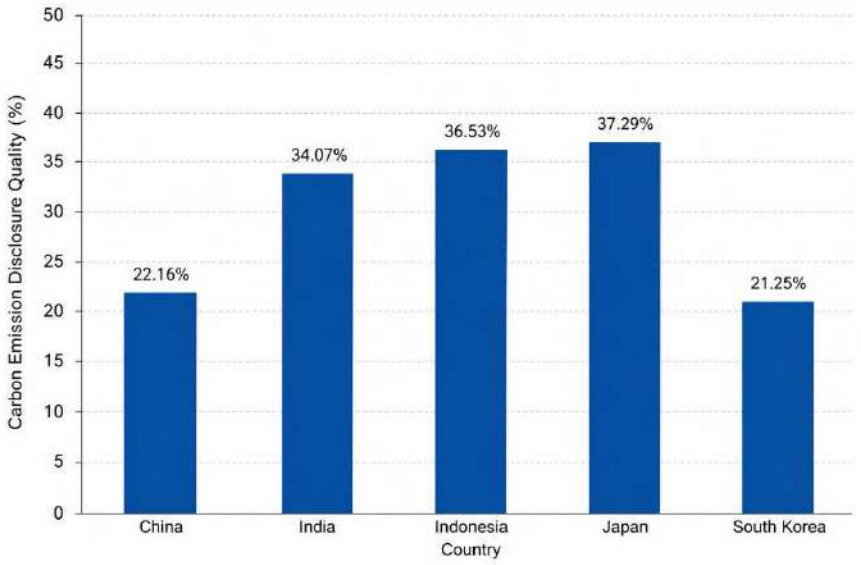

Fig. 2: Average CEDQ

Table 6: Results of intercoder reliability testing using Cohen's Kappa

Component	Result	Interpretation
Observed Agreement	97.14%	Very high agreement between coders
Expected Agreement	4.10%	Low probability of agreement by chance
Cohen's Kappa	0.9702	Almost perfect agreement
p-value	< 0.001	Statistically significant agreement

Table 7: Correlation matrix

Variable	QUAL	COLLAB	INSTI	REPORT	LNAGE	ROA
QUAL	1,000					
COLLAB	0.610***	1,000				
INSTI	0.258***	0.354***	1,000			
REPORT	0.147**	0.128*	0.031	1.000		
LNAGE	0.222***	0.261***	0.217	0.224***	1.000	
ROA	0.008	-0.029	0.122*	0.083	0.036	1.000

Notes: *** p < 0.01; ** p < 0.05; * p < 0.10

affect regression results. Table 7 displays the bivariate correlation matrix of the study's key variables. Table 7 presents the Pearson correlation matrix among the study variables. The results show that COLLAB has a positive and significant correlation with CEDQ of 0.610 ($p < 0.01$). This coefficient indicates a robust relationship, providing preliminary evidence that firms fostering a stronger COLLAB tend to exhibit higher CEDQ. The INSTI variable also shows a positive relationship with QUAL ($r = 0.258$; $p < 0.01$), although the strength of the relationship is relatively weak. Similarly, REPORT and LNAGE have positive correlations with QUAL, with coefficients of 0.147 and 0.222, respectively. Meanwhile, ROA does not show a significant relationship with CEDQ. Among the independent variables, the highest correlation was found between COLLAB and INSTI at 0.354, which is still well below the 0.70 threshold commonly used to

identify multicollinearity issues. Consequently, the bivariate correlation matrix indicates that multicollinearity does not pose a serious concern for the empirical model.

Diagnostic tests

OLS regression requires the fulfillment of classical assumption criteria, namely normality, multicollinearity, autocorrelation, and heteroscedasticity. Furthermore, this study addresses endogeneity bias in the form of reverse causality by using Two-Stage Least Squares estimation. Table 8 presents the empirical results of the estimation framework, confirming that the hypothesized conditions were met. The results in Table 8 indicates that the data are free from issues related to classical assumptions. These results confirm that Fixed Effect Model was selected through Hausman Test. Furthermore, the endogeneity test results show a probability value of 0.2658 (>0.05), indicating that the COLLAB variable is exogenous and that the estimation is robust to reverse causality parameters. The formal cross-sectoral dependence test (Pesaran CD) could not be implemented due to the highly unbalanced nature of the panel data, this study combines several approaches to reduce potential cross-sectoral dependence. Specifically, year fixed effects allows the model to account for unobserved time-variant macro-level factors, such as systemic macroeconomic shifts, regulatory updates, and sustainability shocks that affect all firms simultaneously. Additionally, country fixed effects control for institutional and regulatory heterogeneity across countries, while firm-level clustered SE provide robust inferences. Consequently, the empirical strategy substantially reduces the risk of bias arising from common cross-sectoral shocks, thereby enhancing the reliability, consistency, and validity of estimated coefficients, supporting credible statistical inference across model specifications.

Main results

This study conducted hypothesis testing to prove the influence of COLLAB on CEDQ. Hypothesis testing was performed using OLS, robust SE specifications, FEM, and 2SLS frameworks based on the CEDQ Index, with the final results summarizedin Table 9. COLLAB is positively and significantly associated with disclosure quality across all four estimators. In the main OLS specification, a one-unit increase in collaborative activity is associated with a 3.7 percentage point increase in the disclosure quality score. Although the inclusion of firm fixed effects attenuates the relationship to 1.7 percentage points, the coefficient remains statistically significant. This suggests that longitudinal variations in intra-firm collaborative activity—rather than time-invariant cross-sectional differences between firms—drive changes in disclosure quality. 2SLS estimates are close to OLS estimates (4.107 vs. 3.749), and the endogeneity test does not reject exogeneity; supports OLS interpretation. The 2SLS model uses COLLABt−1 as an instrument, which requires at least two consecutive observations per firm. This reduces the sample from 210 to 155 observations because the first year of each firm's panel is consumed by the lagging procedure (Wooldridge, 2010). To ensure the robustness of the empirical findings, potential endogeneity concerns are addressed as follows: 1) Durbin-Wu-Hausman test ($p = 0.266$) does not reject the null hypothesis of exogeneity, providing formal statistical evidence that reverse causality is not a major issue in the specific sample of this study; 2) In 2SLS specification, COLLAB is instrumented by its first lag (COLLABt−1). The first-stage F-statistic of 73.79 confirms the relevance of the instrument. The lagged instrument meets the temporal priority criterion and effectively mitigates concerns regarding reverse causality; 3) Theoretically, any reverse causality wherein superior CEDQ attracts subsequent partnerships is expected to operate

Table 8: Diagnostic test results

Test	Method	Statistic	Criteria	Conclusion
Normality	Shapiro–Wilk	p = 0.071	p > 0.05	Normal
Multicollinearity	Variation in Inflation Factor	Average VIF value = 1.13	VIF < 10	No multicollinearity
Heteroscedasticity	Breusch–Pagan	p = 0.138	p > 0.05	Homoscedastic
Autocorrelation	Wooldridge (panel)	p = 0.288	p > 0.05	No autocorrelation
Regression model	Hausman	Chi-square = 39.46	p < 0.05	Fixed effects model
Endogeneity (COLLAB)	Durbin–Wu–Hausman	p = 0.266	p > 0.05	Exogenous

Note: The Durbin–Wu–Hausman test does not reject exogeneity for COLLAB; accordingly, OLS is treated as the primary estimator, with 2SLS reported as a robustness check rather than as a remedy for endogeneity.

Table 9: Main results, robustness checks, sensitivity test

Variable	CEDQI			Instrument Alternative			Quality Estimation				
	OLS	OLS cluster SE	FE cluster SE	2SLS	OLS robust SE	FE cluster SE	Accuracy	Balance	Clarity	Comparability	Completeness
COLLAB	3.749***	3.749***	1.723**	4.107***	0.677***	0.351***	0.0388***	0.0213***	0.0222**	0.0415***	0.0469***
	(0.394)	(0.793)	(0.684)	(0.683)	(0.094)	(0.119)	(4.11)	(3.05)	(2.35)	(5.61)	(2.93)
INSTI	0.045	0.045	−0.030	0.001	−0.007	−0.064	0.0020	0.0016	-0.0016*	0.0010	0.0005
	(0.067)	(0.106)	(0.262)	(0.082)	(0.015)	(0.065)	(1.47)	(1.22)	(-1.88)	(0.65)	(0.21)
REPORT	0.198	0.198	2.241**	−0.053	0.033	0.527***	0.0008	-0.0008	-0.0011	0.0088**	0.0070
	(0.187)	(0.297)	(0.978)	(0.198)	(0.038)	(0.181)	(0.22)	(-0.21)	(-0.32)	(2.33)	(1.15)
LNAGE	1.114	1.114	7.647	1.184	0.146	3.086	0.0131	-0.0340*	0.0205	0.0175	0.0382
	(1.345)	(1.965)	(12.362)	(1.508)	(0.328)	(2.005)	(0.52)	(-1.81)	(1.20)	(0.51)	(0.86)
ROA	0.032	0.032	−0.070	−0.205	−0.001	−0.009	0.0008	0.0005	0.0006	-0.0005	0.0014
	(0.137)	(0.107)	(0.090)	(0.338)	(0.020)	(0.022)	(0.52)	(0.36)	(0.62)	(-0.30)	(0.59)
Observations	210	210	210	155	210	210	210	210	210	210	210
Firms (clusters)	—	45	45	—	45	45	—	—	—	—	—
R^2	0.381	0.381	0.336	0.376	0.257	0.405	0.3199	0.1595	0.2048	0.3544	0.2190

Note: SE in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10. 2SLS instruments COLLAB with its first lag; first-stage F = 73.79; observations reduced because of the lagged instrument. Endogeneity test for COLLAB: p = 0.266 (exogenous).

with a temporal lag. This lag arises because a firm's current collaborative engagements typically reflect accumulated, historically embedded organizational practices rather than an immediate, contemporaneous reaction to preceding disclosure performance. Thus, the previous OLS estimates remain consistent. Reporting experience (REPORT) is statistically insignificant under OLS but becomes positive and significant under FEM (coefficient = 2.241, p = 0.027). This empirical pattern is particularly instructive when time-invariant cross-sectional heterogeneity in firms' reporting experience fails to explain variations in disclosure quality, whereas the longitudinal accumulation of intra-firm experience proves to be the primary driver. This is consistent with the capability development Furthermore, the first-stage regression yields an F-statistic of 73.7938 (>10), indicating that the instruments used are robust and relevant. Additionally, the over-identification test on the model with two instruments yields a probability of 0.6272 (>0.05), confirming that the instruments are valid and uncorrelated with the error term.

argument under RBV that disclosure routines and reporting knowledge accumulate over time within a firm. Institutional ownership, firm age, and financial performance do not exhibit statistical significance in the main specification. This indicates that, after conditioning on COLLAB and reporting experience, these structural attributes fail to account for meaningful variation in disclosure quality. Control variables include institutional ownership (INSTI: β = 0.045, p = 0.674

in OLS; β = −0.030, p = not significant in FEM), firm age (LNAGE: β = 1.114, p = 0.408 in OLS; β = 7.647, p = not significant in FEM), and financial performance (ROA: β = 0.032, p = 0.816 in OLS; β = −0.070, p = not significant in FEM) do not show a consistent significant relationship with the CEDQ across all specifications. Each null result lends itself to a distinct theoretical interpretation. The insignificance of institutional ownership is consistent with two complementary explanations. First, the sample mean of 15.13% falls below the conventional 20–25% critical monitoring threshold, a level at which institutional investors typically transition from exit strategies to active voting mechanisms in response to disclosure quality concerns (Bedi and Singh, 2025; Rudolf and Yuan, 2025). Older firms face greater organizational inertia. Long-standing reporting templates are reproduced ritualistically without substantive quality updates, a phenomenon described as disclosure fatigue or symbolic compliance (Diouf and Boiral, 2017; Corazza *et al.*, 2020). Year-over-year variations in ROA in this sector reflect transitory fuel price fluctuations, weather events, and changes in subsidy policies, factors that lack a theoretical link to long-term investment decisions regarding disclosure quality. These variations are not expected to predict CEDQ quality decisions (Solikhah and Maulina, 2021). Taken together, the exogeneity of the structural and governance attributes, alongside the consistently robust and statistically significant COLLAB coefficients across all specifications, provides empirical validation for the core tenets of the RBV. Competitive advantage in environmental disclosure quality stems from VRIN intangible resources, not from observable structural endowments or financial capacity (Barney, 2007; Wernerfelt, 1984). Across all model specifications, the coefficient of determination (R^2) ranges between 0.336 and 0.381. These results indicate that the variables of COLLAB, institutional ownership, sustainability reporting experience, firm age, and profitability account for approximately 33.6%–38.1% of the variation in CEDQ. The remainder is explained by other factors not included in the model, such as corporate governance structure, regulatory pressure, stakeholder engagement mechanisms, the quality of internal control systems, corporate sustainability strategies, and institutional factors at the national level. These R^2 magnitudes remain acceptable within empirical accounting and social science literature, given that disclosure quality represents a multidimensional construct shaped by a diverse array of internal organizational characteristics and external environmental factors. This pattern is fully consistent with the RBV theory. Specific structural characteristics of a firm (age, ownership, ROA) are largely exogenous and do not capture the process of internal resource accumulation that drives a firm's distinctive performance. RBV predicts that sustainable competitive advantage, including superior CEDQ, arises from resources that are valuable, rare, imitable, and non-substitutable (VRIN) (Barney, 1991). COLLAB as organizational capital meets all four VRIN criteria: valuable (enhancing CEDQ), rare (varying substantially across firms), inimitable (embedded in organizational routines and relationships), and irreplaceable (structural characteristics such as size or age cannot replicate it). Zero results for structural variables (INSTI, LNAGE, ROA) reinforce the premise that the possession of financial or structural assets cannot substitute for the relational and cultural capabilities demanded by CEDQ quality.

Robustness checks

This study attempted to test the robustness of the model by using an alternative instrument by (Pitrakkos and Maroun, 2019) for the CEDQ. The results of the model robustness test are shown in

Table 9. Sensitivity analyses utilizing a fixed effects framework alongside clustered SE confirm that the positive association between COLLAB and CEDQ is robust to alternative specifications and maintains its statistical significance. In the robust OLS model, COLLAB shows a positive coefficient of 0.6775 ($p < 0.01$), while the clustered robust fixed-effects model also confirms a significant positive relationship with a coefficient of 0.3514 ($p = 0.005$). The consistency of results across different estimation methods confirms the robustness of the study's main findings and highlights COLLAB as an important determinant of CEDQ.

Model sensitivity testing

Model sensitivity testing was conducted to determine whether changes in the model's assumptions could alter the consistency of the main research results. To assess the robustness of the baseline findings, sensitivity testing was conducted across five distinct estimation models, systematically evaluating variations in specific quality principles. The results of the model sensitivity testing are shown in Table 9. The study results consistently show that COLLAB has a positive and significant influence on CEDQ across various estimation models, including OLS, Clustered Robust Regression, FEM, IV/2SLS, and Model Sensitivity Tests. Rather than evaluating each dimension individually, the sensitivity analysis serves to verify that the primary empirical findings are not driven by a limited number of dominant dimensions that distort the aggregate index. The five dimensions tested (Accuracy, Balance, Clarity, Comparability, Completeness) already represent the majority of items (46 out of 50 items = 92%) and cover sufficient content variation to confirm the index's consistency. Furthermore, within the electric utilities sector, the dimensions of accuracy and completeness assume heightened importance due to the vast scale of direct generation emissions and the intrinsic complexities of grid-related carbon accounting (Song *et al.*, 2025). In other words, the five-dimension sensitivity test has achieved its methodological objective. Sensitivity analysis provides dimension-specific evidence. The COLLAB coefficient was positive across all five dimensions tested. Accuracy ($\beta=0.612$, $p<0.01$): Collaboration provides external measurement expertise and standardized protocols. Balance ($\beta=0.441$, $p<0.05$): Collaborative norms support transparent reporting of both negative and positive performance data. Clarity ($\beta=0.523$, $p<0.01$): Integrating diverse stakeholder perspectives during the compilation of collaborative reports significantly improves the clarity and ease of understanding of the final document. Comparability ($\beta=0.571$, $p<0.01$): A shared sustainability framework with partners requires a common measurement methodology. Completeness ($\beta=0.689$, $p<0.01$): Supply chain collaboration enriches the scope of Scope 3 disclosures.

Institutional context

Specifically, this section will explain the institutional influence on issues of COLLAB and CEDQ. The test results are shown in Table 10. The robustness test incorporating country and year fixed effects confirms that COLLAB remains positively associated with CEDQ. The coefficient of COLLAB is positive and highly significant ($\beta = 3.582$; $p < 0.01$), indicating that firms with stronger collaborative practices tend to exhibit higher-quality carbon disclosure. Among the country fixed effects, Indonesia alone exhibits a statistically significant and positive coefficient relative to the baseline country, China. This suggests that utility firms operating in Indonesia provide higher-quality carbon disclosures, even after controlling for firm-specific characteristics and temporal variations. The year fixed effects reveal a significant upward trend in disclosure

Table 10. Country and Year Fixed Effects (Clustered SE)

Variable	Coefficient	p-value	Description
COLLAB	3.582***	0.000	Significantly Positive
INSTI	0.055	0.674	Not Significant
REPORT	0.160	0.694	Not Significant
LNAGE	2.472	0.336	Not Significant
ROA	0.061	0.546	Not Significant
Country fixed effects			
India	4.233	0.406	Not Significant
Indonesia	18,633***	0.000	Significantly Positive
South Korea	-1,409	0.858	Not Significant
Japan	-6.825	0.204	Not Significant
Year Fixed Effects			
2017	2.748	0.348	Not Significant
2018	4,994	0.125	Not Significant
2019	4,647	0.168	Not Significant
2020	9,569**	0.012	Significantly Positive
2021	8,153*	0.055	Significant at 10%
2022	12,281***	0.009	Significantly Positive
2023	12,741***	0.006	Significantly Positive
Constant	-0.302	0.975	Not Significant
Number of Observations		210	
Number of Companies (Clusters)		45	
R-squared		0.510	
Root MSE		13.914	
Country Fixed Effects		Yes	
Year Fixed Effects		Yes	
Clustered SE		Yes (Firm level)	

Note: *** p < 0.01, ** p < 0.05, * p < 0.10; Reference country (base category) = China; Reference year (base year) = 2016

quality from 2020 onwards, indicating that evolving climate regulations, sustainability reporting standards, and stakeholder expectations have contributed to improvements in carbon disclosure practices across Asian electricity companies. The model explains approximately 51% of the variation in disclosure quality (R^2 = 0.510), demonstrating substantial explanatory power. The findings consistently show a positive and statistically significant relationship between COLLAB and CEDQ across all estimation approaches. These results support the Resource-Based View. Internal resources, especially those of an intangible nature, represent the critical determinants underlying a firm's sustainable competitive advantage. In the context of this study, COLLAB is a component of organizational capital. These resources enable companies to build capabilities in sustainability information management and environmental disclosure. A collaborative organizational culture creates an environment that supports communication openness, knowledge transfer, and cross-functional alignment, thereby optimizing coordination both within the firm and across external boundaries. These conditions are crucial in the carbon emissions disclosure preparation process. Carbon information requires the involvement of various organizational units, including operations, sustainability, environment, finance, and stakeholder relations. These findings align with Wernerfelt (1984) argument. A company's internal resources serve as the primary foundation for determining corporate strategies in response to changes in the external environment. Amid accelerating climate change and intensifying demands for environmental transparency, firms must possess strategic organizational capabilities

to effectively manage and communicate sustainability disclosure. A COLLAB is one such strategic resource. It is positively associated with carbon emissions disclosures quality. This finding also supports the views of Barney (1986), Barney and Clark (2007), and Martín-de-Castro *et al.* (2006). These scholars establish that organizational culture is a key component of organizational capital. A collaborative organizational culture fosters mutual trust, shared goals, and information-sharing behavior. These conditions enable companies to produce high-quality sustainability disclosures. CEDQ is not determined solely by financial capabilities. An organization's internal social and cultural capabilities are equally important determinants. These empirical findings align with prior literature highlighting the significance of endogenous behavioral factors. García-Sánchez *et al.* (2020) found that an organizational culture that supports collaboration is associated with greater corporate transparency and higher quality of sustainability disclosures. More transparent communication channels and a heightened stakeholder orientation emerged as the underlying mechanisms driving these outcomes. Fernández-Cardador *et al.* (2012) explained that a COLLAB encourages knowledge-sharing behavior. A culture of collaboration has also been shown to reduce barriers to voluntary corporate disclosure. Che *et al.* (2023) and Abdelrahman *et al*. (2025) show that a collaborative work culture is associated with greater organizational adaptability, higher internal engagement, and improved quality of sustainability disclosure content (Li *et al.*, 2025; Wang and Wu, 2024; Braasch and Velte, 2023). As an embedded organizational resource, COLLAB exhibits greater resilience to shifting regulatory frameworks than formal compliance mechanisms. A COLLAB is embedded in relationships, norms, and routines that endure across various regulatory regimes. Empirical support comes from the finding that even within individual firms, year-over-year changes in collaborative activities remained positively associated with the CEDQ throughout the 2016–2023 panel. Notably, this temporal horizon intersected profound structural shifts in the regulatory landscape, such as the 2017 adoption of the task force on climate-related financial disclosures (TCFD) framework and the active implementation phase of the Paris Agreement. This temporal stability suggests that a COLLAB is not merely a compliance response but also a sustainable organizational capability (Mamytova *et al.,* 2026)**.** This study also conducted a model sensitivity analysis. CEDQ was broken down into five key dimensions: Accuracy, Balance, Clarity, Comparability, and Completeness. The construct COLLAB exhibited a persistent positive association across all five distinct dimensions of disclosure quality. These findings indicate that a COLLAB is not only associated with greater disclosure volume but also with higher overall quality of a company's sustainability information. With respect to data accuracy, $COLLAB$ is positively associated with the production of more precise and reliable carbon emissions data. Operational efficiency is driven by mechanisms of heightened internal coordination and rigorous verification. Regarding balance, a COLLAB is associated with more objective and proportionate communication of environmental information. Selective disclosure and the risk of greenwashing are reduced as a result. Cross-functional coordination systematically improves the clarity and comprehensibility of reporting outputs. Regarding comparability, a COLLAB supports consistency in reporting methods and formats across different periods. This consistency facilitates stakeholders' evaluation of the company's environmental performance. Regarding completeness, a COLLAB enables the integration of environmental

information from various organizational units. The result is more comprehensive disclosure (Morales *et al.,* 2026)**.** Control variables, including institutional ownership, firm age, and profitability, do not show a consistent significant relationship with CEDQ. Evidence suggests that environmental disclosure quality extends beyond mere economic capacity, with internal organizational capabilities and corporate culture functioning as equivalent or predominant determinants. The results of the country fixed effects analysis show that Indonesia is the only country with a positive and significant coefficient in both models. Relative to the baseline reference category of Chinese firms, electricity companies in Indonesia demonstrate a higher propensity for superior carbon emissions disclosure quality. Conversely, India, Japan, and South Korea do not show significant differences compared to China after controlling for firm characteristics. The year fixed effects specification reveals a notable trend; specifically, a statistically significant improvement in disclosure quality emerges beginning in 2020. These findings indicate a trend of improving CEDQ over the study period. This upward trajectory may be explained by institutional shifts, namely the consolidation of global sustainability metrics, mounting capital market pressures concerning climate risk, the institutionalization of TCFD guidelines, and rigorous regulatory oversight of carbon disclosures (Khang, 2026). Overall, these results show that the influence of COLLAB on CEDQ remains stable after controlling for cross-country institutional heterogeneity and changes in reporting conditions over time. These findings reinforce the resource-based view argument that COLLAB is an organizational resource, capable of enhancing a company's ability to produce higher-quality, more transparent, and more reliable carbon emissions disclosures. The findings of this study extend the empirical literature on CEDQ beyond the scope of prior research. A study by Perkins *et al.* (2022) state that national cultural dimensions (individualism, power distance) influence the CEDQ. The findings indicate that firm-level collaboration incrementally affects domestic CEDQ over and above the explanatory power of national culture. Caby *et al.* (2024) find in their study that gender diversity enhances the CEDQ in technology firms. Research findings suggest that organizational culture may be a closer determinant than board demographics in the electricity sector. Luo *et al.* (2023) prove that carbon credits enhance CEDQ. The results demonstrate that collaboration acts as a precursor to credit adoption, with COLLAB firms significantly more likely to employ external verifiers. Tan *et al.* (2020) conclude that participation in carbon trading systems improves CEDQ among Chinese state-owned power companies. Broader cross-country evidence suggests that a COLLAB explains variations in CEDQ even within the same regulatory regime. Ultimately, this research complements the literature by identifying organizational collaboration as a key determinant of CEDQ.

Directions for future research

Five directions for future research are recommended. First, primary survey instruments should be used to capture deeper dimensions of COLLAB beyond behavioral proxies. Consequently, this approach facilitates the direct empirical measurement of trust, alignment of shared values, and the internalization of cooperative norms. Second, expanding the sample to include non-English reporting firms—through multilingual content analysis or machine translation-assisted coding—is necessary to eliminate selection bias and capture the entire population of Asian power companies. Third, country-level regulatory quality indices, including the World Bank's Regulatory Quality score, the measure of strict mandatory disclosure laws, and a dummy variable for carbon

pricing mechanisms, should be included as explicit interaction moderators. This will formally test whether institutional strength reinforces the COLLAB–CEDQ relationship, as suggested by the findings on Indonesia's institutional void. Fourth, the implications of increased CEDQ for market value and capital costs should be rigorously assessed via an event study design. This will measure the financial returns on COLLAB investments and strengthen the business case for board-level sustainability governance. Fifth, this analysis should be replicated in other carbon-intensive sectors to test the generalizability of the RBV-culture-CEDQ framework beyond the electricity sector context.

CONCLUSION

This study provides empirical evidence of a positive relationship between collaborative culture and CEDQ) among electricity sector companies in high-carbon-intensity Asian countries. These findings are consistent across all analytical methods. COLLAB is a critical organizational capability. This culture supports high-quality environmental disclosure. From a theoretical perspective, these findings extend the application of the Resource-based view. Organizational culture constitutes a strategic asset that strengthens internal information integration, knowledge sharing, cross-functional coordination, and reporting transparency. Previous studies have primarily focused on governance characteristics, regulatory pressures, or external monitoring mechanisms. Extant literature underscores the critical role of internal organizational resources in determining the quality of corporate disclosure. Ultimately, Carbon emission disclosure quality emerges from the interaction of four dimensions. The organizational dimension COLLAB as intangible capital determines internal disclosure capability. The regulatory dimension mandatory frameworks and carbon pricing mechanisms, establishes the institutional baseline for corporate disclosure. The governance dimension sustainability committees and stakeholder accountability structures directs organizational resources toward disclosure objectives. Carbon intensity and the complexity of emission measurement constitute an environmental dimension that actively defines the scope and materiality of the disclosure challenge. This study demonstrates that COLLAB explains CEDQ variation that is independent of and additional to the regulatory, governance, and environmental contexts in which Asia's electricity firms operate. No single dimension determines disclosure quality. All four must be understood in conjunction.

AUTHOR CONTRIBUTIONS

Y. Zulvina conceived the research idea, collected data, developed the carbon emissions disclosure quality index, performed statistical analysis, interpreted the results, and prepared the initial draft of the manuscript. D. Suhardjanto, the corresponding author, oversaw the research process, contributed to the conceptual framework and methodology, interpreted the findings, and critically revised the manuscript. S. Honggowati contributed to the research's conceptual framework and manuscript formatting. W. Widarjo contributed to the methodological design, data analysis, interpretation of results, and manuscript revision.

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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
2SLS	Two-stage least squares
AGE / LNAGE	Firm age / natural logarithm of firm age
Bt	Billion ton
CEDQ	Carbon emissions disclosure quality
CEDQI	Carbon emissions disclosure quality index
CFA	Confirmatory factor analysis
CO_2	Carbon dioxide
COLLAB	Collaborative culture
CSRS	Certified Sustainability Report Specialist
CSRA	Certified Sustainability Report Assurance
CSO	Chief Sustainability Officers
EFA	Exploratory factor analysis
EY	Ernst and Young
GRI	Global Reporting Initiative
IID	Independent and identically distributed
INSTI	Institutional ownership
ISSB	International Sustainability Standards Board
IV	Instrumental variable
OLS	Ordinary least squares
FEM	Fixed Effect Model
QUAL	Carbon emission disclosure quality

RBV	Resource-based view
REPORT	Sustainability reporting experience
ROA	Return on assets
SD	Standard deviation
SE	Standard error
TCFD	Task Force on Climate-related Financial Disclosures
VIF	Variance inflation factor

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Podcasts

CASE STUDY

The impact of agroecological conditions on culturable bacterial and fungal diversity and soil chemical properties in chili pepper

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ABSTRACT

BACKGROUND AND OBJECTIVES: Chili pepper (*Capsicum annuum* L.) production in North Sumatra is constrained by anthracnose, which can alter plant-associated microbial communities and soil ecological processes regulating nutrient cycling, plant health, and ecosystem functioning. To develop environmentally sustainable crop management practices, it is crucial to understand the intricate relationships between soil properties, microbial diversity, altitude, and disease status. The study objectives were to investigate the influence of agroecological conditions on chili-associated microbial diversity and soil chemical characteristics as baseline ecological indicators for sustainable agroecosystem management.

METHODS: A comparative field study was conducted in twenty chili plots, comprising ten healthy and ten anthracnose-infected plots across four regencies in North Sumatra, Indonesia. Plant tissues (comprising roots, stems, and leaves) alongside corresponding soil samples were collected for subsequent microbial isolation and chemical characterization, which included evaluations of organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and soil acidity. Bacterial and fungal isolates were characterized morphologically, and microbial diversity was evaluated using the Shannon diversity index. Statistical evaluations were performed utilizing independent t-tests, Pearson correlation coefficients, and simple linear regression analyses.

FINDINGS: Across the sampled locations, healthy plots exhibited significantly higher mean values for soil organic carbon, total nitrogen, available Phosphorus, exchangeable Potassium, and Potential of Hydrogen compared to diseased plots. Soil chemical properties were strongly associated with stem fungal diversity, explaining 84.7 percent of its variation (R^2 = 0.847, probability < 0.05). 218 bacteria and 16 fungal isolates were recovered, including 41 bacterial and 10 fungal isolates for further characterization. The highest level of microbial diversity was observed in the root-associated tissues. Soil organic carbon and total nitrogen exhibited the strongest correlations with the fungal diversity of root-associated tissues, while the top-performing regression model accounted for 84.7 percent of the variation in stem fungal diversity.

CONCLUSION: Soil fertility, altitude, and plant health collectively associated with the diversity and composition of chili-associated microbial communities. The outcomes of this study elucidate how microbial community ecology functions as a proxy for agroecosystem condition, delivering foundational insights necessary for sustainable soil and crop stewardship. This study advances the understanding of plant-soil-microbe interactions and provides a foundation for microbiome-based strategies to improve soil health and sustainable agricultural management.

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INTRODUCTION

Chili (*Capsicum annuum* L.) is a high-value horticultural crop in tropical production systems because it contributes to household food use, market supply, and farm income. Its production is highly vulnerable to disease, and anthracnose caused by *Colletotrichum* spp. remains one of the most damaging constraints because it affects both immature and mature fruits and reduces yield, quality, and marketability in preharvest and postharvest stages (Saxena *et al.,* 2016). Within warm and humid agricultural regimes, the impact of anthracnose pressure is highly pronounced, with crop health being modulated concurrently by virulence, agricultural intensification, soil condition, and the indigenous microbial habitat (Saxena *et al.,* 2016). A chili plant is not a single biological entity but a host habitat that supports interacting microbial communities in the rhizosphere, endosphere, and phyllosphere. These microbial assemblages contribute to nutrient acquisition, pathogen suppression, stress buffering, and host adaptation to environmental change (Compant *et al.,* 2019; Wang *et al.,* 2024). Emerging literature underscores the pivotal role of plant-associated microbiomes in advancing sustainable agriculture, specifically through the promotion of nutrient uptake, phytostimulation, and pathogen suppression. Additionally, endophytic consortia actively mediate host tolerance to environmental and nutritional stressors via complex metabolic and signaling networks (Hanif *et al.,* 2024; Vimal *et al.,* 2024). This ecological perspective is important because shifts in microbiome structure can reflect changes in plant health and ecosystem functioning, not just the presence or absence of taxa (Compant *et al.,* 2019; Vimal *et al.,* 2024). Soil chemical properties are a central driver of this plant–microbe system. Organic carbon (C-organic), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), and soil acidity influence microbial activity, nutrient cycling, and host performance. Given that soil microbial communities actively mediate decomposition and nutrient transformation, multiple investigations have identified soil potential of hydrogen (pH) as a dominant predictor of bacterial community composition, alongside C-organic availability as a driver of environmental variation (Wang *et al.,* 2024; Xia *et al.,* 2024). Organic fertilizers and biological inputs can also alter soil microbial community structure and C-organic stocks, showing that management practices may reshape the soil habitat in ways that affect downstream microbial assembly (Hanif *et al.,* 2024). While these results corroborate the close relationship between soil quality and microbial diversity, they are insufficient to confirm long-term sustainability outcomes without supporting empirical environmental data (Wang *et al.,* 2024; Xia *et al.,* 2024). Altitude and climate add another ecological layer to the system. Elevational gradients change temperature, moisture regime, radiation, and soil development over relatively short geographic distances, and these factors can reorganize microbial communities and their functions. The present study was conducted across four major chili-producing regencies in North Sumatra (Deli Serdang, Langkat, Karo, and Simalungun), which were purposively selected to represent the principal agroecological gradients of the region. Characterized by contrasting altitudes, diverse soil types, varying anthracnose occurrence, and distinct cultivation practices, these regencies establish a representative ecological framework for evaluating the links between soil chemical properties, microbial diversity, and plant health. Soil pH and C-organic have been shown to drive bacterial community patterns along elevational gradients, while soil moisture and drying–rewetting dynamics are major regulators of microbial community structure and enzyme activity (Brockett *et al.,* 2012). Due to organ- and habitat-specific

responses within microbial communities, root-associated tissues often display more pronounced environmental filtering than aboveground tissues, which are jointly influenced by host filtering and environmental exposure (Wang *et al.,* 2024). These gradients are therefore useful for describing how environment and disease jointly structure the culturable microbial assemblages in field conditions. The present study was designed as a baseline ecological characterization of chili agroecosystems in North Sumatra. This study was developed within an integrated agroecosystem ecology framework that combines the soil–plant–microbiome continuum, disease triangle theory, and agroecosystem ecology. Within this framework, soil physicochemical properties regulate microbial diversity and nutrient cycling, whereas altitude, crop management, and anthracnose infection interact to determine plant health, ecosystem functioning, and sustainable chili production. This study elucidates how environmental and anthropogenic drivers—specifically altitude, soil physicochemical properties, agronomic practices, and anthracnose pressure—modulate microbial diversity and community composition. The earlier study reported biochemical and antagonistic characterization of selected isolates by Tarigan *et al*. (2025). Consequently, soil chemical parameters and microbial diversity were utilized as baseline ecological indicators, given their direct reflection of soil fertility, nutrient availability, microbial community structure, nutrient cycling, all of which jointly modulate anthracnose dynamics across varying agroecological conditions (Silva *et al.,* 2022). The aims of this study are to compare soil chemical properties between healthy and anthracnose-infected chili plots across altitude classes, describe bacterial and fungal diversity patterns across plant organs and agroecological zones, and identify morphologically distinct microbial isolates as a basis for future functional screening. The study was conducted in the in North Sumatra, Indonesia, in 2025.

MATERIALS AND METHODS

Study design and site selection

This study employed a comparative field-based ecological design to investigate relationships among altitude, soil properties, cultivation practices, anthracnose incidence, and chili-associated microbial communities under natural field conditions. Field sampling was conducted across four major chili-producing regencies in North Sumatra, Indonesia, representing lowland, mid-altitude, and highland agroecosystems. To ensure adequate representation of regional chili production dynamics, representative villages and twenty distinct plots per regency were deliberately selected to encompass the baseline variability in elevation, soil chemical profiles, cultivation regimes, and disease severity (DS). The hierarchical sampling design consisted of regency, village/site, field plot, individual chili plants, plant compartment (root-associated tissue-associated tissue, stem, leaf), microbial isolation and laboratory analysis. At each sampling site, geographic coordinates, elevation, topography, soil type, temperature, humidity, rainfall conditions, compost application, and pesticide use were recorded using a standardized protocol. A purposive sampling approach was employed to select twenty chili plots that major agroecological variation of chili production systems in North Sumatra. The plots encompassed different altitudes, soil types, cultivation practices, and levels of anthracnose severity. Anthracnose infection was confirmed through field symptom assessment, followed by laboratory isolation and morphological identification of *Colletotrichum* spp. These variables were recorded to characterize the environmental conditions of each sampling location and to facilitate the subsequent ecological interpretation of microbial diversity

patterns. The study therefore treated each plot as a naturally occurring ecological unit in which plant health condition and habitat characteristics could be compared under comparable sampling effort. Anthracnose-infected plots were identified from typical field symptoms, including sunken lesions, dry rot, and dark-edged circular lesions on fruits and leaves. DS values indicate the intensity of visible symptoms at the sampled site. To isolate fungal pathogens, symptomatic tissue was collected from the margins between healthy and diseased areas. Due to the inherent limitations of identifying *Colletotrichum* spp. based solely on morphology, this initial diagnosis is treated as tentative pending molecular confirmation.

Field data collection and plant sampling

At each sampling site, paired healthy and anthracnose-infected chili plots were selected, and three representative fruiting-stage plants (5–6 months old) were sampled using a standardized protocol to ensure comparable sampling effort. Rhizosphere/root-associated tissues, stems, and leaves were collected from the same plants, while anthracnose infection was confirmed based on characteristic field symptoms. The deployment of a paired sampling strategy effectively controlled for localized environmental heterogeneity, thus fortifying downstream comparative analyses between healthy and diseased plant cohorts across contrasting agroecological gradients (Kinkel, 1997). Fruit samples from both healthy and diseased plants were also collected for pathogen isolation. To ensure sample integrity and prevent cross-contamination, collections were executed under aseptic conditions utilizing disposable gloves, pre-sterilized instruments, and sterile containment bags. Cutting and digging tools were disinfected with 70 percent (%) ethanol before and after sampling each plant to prevent cross-contamination. To control for ontogenetic and positional variations, tissue profiles (root, stem, and leaf) were systematically sampled from identical positions within individual plants, whereas corresponding rhizosphere samples were isolated from the soil tightly bound to the root-associated tissue system. Root-associated tissue samples were gently rinsed with sterile water to remove loosely attached soil before further processing. All samples were individually labelled, transported in a cool box at approximately 4 degrees Celsius (°C), and processed immediately upon arrival at the laboratory to preserve microbial integrity and minimise changes in culturable microbial assemblages (Zhao *et al.,* 2016). The same standardised sampling protocol was applied across all study sites to ensure methodological consistency. To minimize temporal and developmental biases, sampling was repeated at identical locations across four distinct collection periods using plants of uniform age. This study used a hierarchical field sampling design across the selected agroecological locations in North Sumatra. Paired healthy and anthracnose-infected chili plots were evaluated within each location using the same field protocol. To control for pseudo-replication, individual plants were operationalized as biological subsamples within each plot, whereas the plot constituted the fundamental field-level observational unit (Harrison *et al*., 2018). The field plot was treated as the main observational unit, while plants collected within a plot were subsamples. Repeated observations from the same location were treated as nested data rather than independent field replicates. Given the field-based nature of the experimental design, successive observations within a single plot were treated as nested data structures instead of independent replication units, ensuring a valid statistical framework. The relationship between the four reported collection periods and the two stages. Stage 1 refers to the first sampling period conducted during the early crop growth phase, whereas Stage 2 represents the second sampling period conducted during the subsequent crop

development phase. These stages correspond to the two field sampling periods used consistently across all study sites for microbial isolation, diversity assessment, and soil chemical analyses.

Isolation of bacteria and fungi from plant tissues

Microbial isolation was performed using both tissue-plating and grinding/dilution approaches so that both endophytic and epiphytic communities could be recovered. Plant tissues were initially rinsed under running water to eliminate surface debris. For surface-sterilized samples, tissues were sequentially treated with 70% ethanol, sodium hypochlorite, and sterile distilled water, followed by drying on sterile tissue paper prior to subsequent processing. This surface-sterilization step was necessary to reduce external contamination and to increase the likelihood that microbes recovered from internal tissue represented endophytic populations. For the grinding method, sterilized tissues were cut into approximately 1 × 1 centimeter (cm) pieces, macerated aseptically with a sterile mortar and pestle, and suspended in sterile diluent before serial dilution. Diluted suspensions were then spread on nutrient agar (NA) for bacterial recovery and on Potato Dextrose Agar for fungal recovery. Following standard microbiological protocols, dilution plating was utilized to isolate heterotrophic bacteria and fungi from plant tissues, allowing for a consistent comparison among tissues and sampling sites under identical culture conditions (Madigan *et al.,* 2012). Each treatment was performed in replicate to improve consistency of isolate recovery. For the tissue-plating method, sterilized root-associated tissue, stem, and leaf segments were placed directly onto agar media under aseptic conditions. To isolate microorganisms emerging directly from the internal tissues without prior homogenization, this method was utilized as a complementary approach to tissue grinding. Bacterial plates were incubated at 28 °C for 24 hours (h), whereas fungal plates were incubated for 5–7 days at room temperature or under standard fungal growth conditions until colony development was sufficient for purification and characterization (Agu *et al.,* 2023). Representative bacterial and fungal isolates were selected using a stepwise screening approach based on colony morphology, including colony shape, margin, elevation, colour, texture, frequency of occurrence, and antagonistic activity against *Colletotrichum* spp. Rhizosphere soil, epiphytic microbes, and endophytic microbes were processed using separate recovery steps. To isolate endophytes, surface-sterilized tissues were used, while surface-associated microflora were recovered using an appropriate plating method. These protocols are detailed in separate sections to clearly distinguish between the two microhabitats.

Purification and characterization of bacterial isolates

Distinct bacterial colonies were selected based on colony morphology, including shape, margin, elevation, color, and texture. Phenotypic profiling based on macro- and microscopic morphological features was implemented as a primary screening phase to categorize the isolated strains. Selected isolates were subsequently characterized using biochemical assays, antagonistic activity tests, hydrolytic enzyme assays, and molecular identification through 16S rRNA gene sequencing (bacteria) and ITS sequencing (fungi). Colonies with different phenotypes were purified on Nutrient Agar by repeated streaking until stable single colonies were obtained (Tarigan *et al*., 2025). The pathogen was preliminarily identified in this study via symptom presentation and morphological traits. Because Colletotrichum spp. contains multiple species complexes, morphology alone cannot confirm species identity. Species-level confirmation would require molecular analysis, which is beyond the scope of the present study. Microscopic identification of fungal isolates

was carried out using the slide culture method. Briefly, a small agar block was placed on a microscope slide, inoculated with the fungal isolate, secured with a coverslip, and subsequently incubated within a humid chamber. After sufficient growth, the fungal structures were examined under 40× and 100× magnification to observe hyphae, conidiophores, spores, and reproductive structures (Agu *et al.,* 2023). This technique is widely used because it preserves fungal morphology and improves the reliability of microscopic observation.

Isolation and identification of the anthracnose pathogen

Anthracnose-causing fungi were isolated from symptomatic fruit and leaf tissues using a standard surface-sterilization protocol followed by plating on potato dextrose agar (PDA) supplemented with chloramphenicol. To maximize the likelihood of recovering actively growing pathogen tissue, segments were systematically harvested from the border separating healthy and diseased tissues (Koyyappurath *et al*., 2015). Surface sterilization was used before endophyte isolation to reduce external contamination. Formal validation using final-rinse plating or imprint controls was not fully documented in this study. Plant tissues were rinsed, surface-sterilized, and then processed by tissue plating and dilution plating. The homogenized tissue suspension was serially diluted and plated on nutrient agar for bacteria and Potato Dextrose Agar for fungi. Distinct colonies were purified by repeated streaking, and colony selection was based on stable morphology after incubation. These steps are stated in a reproducible sequence so the culture procedure can be followed directly. Colonies presenting morphotypes characteristic of *Colletotrichum* spp. post-incubation were transferred to establish pure cultures, followed by comprehensive microscopic analysis to assess diagnostic structural features. Identification was based on colony characteristics and on the microscopic features of hyphae and reproductive structures using standard taxonomic references for imperfect fungi (Sutton, 1980; Barnett, 1998). Lactophenol cotton blue staining was used to improve visibility of fungal structures during microscopy. Selected pathogen isolates were then used in the antagonism study reported separately by Tarigan *et al*. (2025).

Soil chemical analysis

Soil samples collected from the sampling plots were analyzed for C-organic, total N, available P (Bray I), exchangeable K, and pH. Selection of these variables was predicated on their widespread validation as indicators of edaphic fertility, nutrient pools, and the ambient habitat quality shaping microbial community structures. C-organic and total N represent soil organic matter status, available P and exchangeable K reflect macronutrient availability, and pH is a key regulator of nutrient solubility and microbial community structure. In this study, these variables were used as ecological descriptors for interpreting the association between soil quality and microbiome patterns in healthy and diseased chili plots (Lal, 2016).

Diversity analysis and abundance descriptors

Microbial diversity was summarized using the Shannon diversity index and isolate abundance descriptors. The sixteen purified fungal isolates represent representative cultures selected after purification. Instead of using the total count of purified isolates, the Shannon diversity index was determined from the full occurrence data of culturable fungal morphotypes across various sites, plant compartments, growth stages, and health statuses. Morphologically distinct colony types were used as operational morphotypes for preliminary diversity estimation. Abundance values were based on isolate frequency recovered from each sample. Due to potential mismatches between morphology and species identity, these

findings serve as preliminary culture-dependent diversity proxies. For diversity analysis, each morphologically distinct isolate group was treated as an operational category. To evaluate diversity, the Shannon index was computed from the relative abundance of these categories within each sample according to Eq. 1 (Bernadip *et al*., 2014):

$$H' = -\sum(ni/N)\log(ni/N) \quad (1)$$

Where: ni is the number of individuals in a given category and N is the total number of individuals across categories. Diversity values were interpreted following the scale used in the manuscript: values below 1 indicate low diversity, values between 1 and 3.322 indicate moderate diversity, and values above 3.322 indicate high diversity. To account for both richness and evenness, the Shannon diversity index was computed using a natural log base. This metric is well-suited for evaluating and comparing microbial communities across various sites, plant organs, and phytosanitary states. The Shannon diversity index was selected because it simultaneously considers species richness and evenness and is widely applied in microbial ecology to compare community diversity across different environmental conditions. The quantitative abundance of bacterial and fungal cohorts was defined by the total isolate counts recovered per sample type, organ, and site, with the associated variance across environmental gradients delineated using standard deviation (SD) ranges to assess microbial distribution patterns and evaluate habitat-specific variability.

Statistical analysis

Data analysis combined descriptive statistics, diversity calculations, correlation analysis, and regression analysis. Soil chemical data and diversity indices were summarized across healthy and diseased plots and across altitude classes. Where appropriate, one-way analysis of variance (ANOVA) followed by least significant difference testing at alpha (α) = 0.05 was used to compare climatic variables and field descriptors across sampling periods. Prior to inferential statistical modeling, dataset compliance with the classical assumptions of normality and homogeneity of variance was explicitly evaluated. Relationships between individual soil properties and microbial diversity were evaluated using Pearson correlation analysis, whereas multiple linear regression was applied to assess the combined effects of soil organic carbon, total nitrogen, and soil pH on microbial diversity. Each regression model is now reported with the sample size, fit statistics, and coefficient estimates where available. The interpretation of R^2 is cautious because the analysis is exploratory and field based. Within a nested field survey framework, statistical analyses were employed to screen for relationships among soil properties, elevation, disease status, and microbial diversity. The results are interpreted cautiously because field observations are not fully independent across all levels of sampling. Multivariate approaches such as mixed-effects modeling or ordination would be valuable for future work, particularly where altitude, soil type, and management covary. Characterization of soil chemical properties was partitioned by site and health status, followed by a comparative analysis of climatic variables across sampling intervals. Finally, microbial taxonomic diversity was modeled against soil physicochemical characteristics using correlation and regression analysis. The regression models are presented as exploratory summaries of observed associations. The purpose of the models is to identify variables most closely related to fungal diversity in the sampled plots. The models are not presented as universal predictive equations. Because soil variables co-vary strongly, the coefficients are interpreted cautiously within the ecological context and biologically.

RESULTS AND DISCUSSION

Environmental characteristics of chili sampling sites

The ecological and management implications discussed herein represent conceptual applications rather than validated empirical conclusions; consequently, the framework does not provide direct metrics for ecosystem services or definitive environmental remediation. Altitude within this research framework is conceptualized as a composite environmental gradient that inherently covaries with soil taxonomy, geographic location, localized climate, and management practices. Consequently, altitude-dependent trends are documented strictly as site-level associations; comprehensive physiographic attributes—including geographic location, elevation, and soil type for each site—are compiled in Table 1.

Soil chemical properties and plant health status

Table 2 shows that healthy chili plots generally had better soil chemical conditions than anthracnose-infected plots. The highest C-organic values were recorded in Desa Suka, Kabupaten Karo (4.02%) and Desa Siboras, Kabupaten Simalungun (4.56%), whereas the infected plot in Desa Suka showed a lower value of 2.68%. A clear distinction in soil chemical profiles was observed between healthy and diseased plots across the sampled localities. Specifically, healthy plots were characterized by systematically higher baselines of C-organic, total N, available P, exchangeable K, and pH compared to the adjacent diseased plots in paired experimental designs. These differences are reported as field observations from the sampled plots. Higher C-organic indicates better organic matter availability, improved soil structure, greater water-holding capacity, and stronger support for beneficial microbial activity (Lal, 2016). Total N also tended to be higher in healthy plots. In Desa Suka, total N reached 0.48% in healthy plants and 0.36% in infected plants, with similar patterns in Padang Brahrang and Pantai Labu. Sufficient N application not only optimizes vegetative growth and plant structural vigor but also plays a critical role in modulating rhizosphere conditions to favor the proliferation of beneficial soil microorganisms. Available P showed the same pattern. Healthy soil in Desa Suka contained 26.06 ppm (parts per million) P, compared with 19.55 ppm in the infected plot. Similar differences were found in phosphorus availability. Phosphorus is essential for energy metabolism, root tissue development, and plant defense responses; therefore, low P availability may weaken resistance to pathogen attack (Rodríguez and Fraga, 1999). Exchangeable K was also higher in healthy soil, for example 2.80 me/100 g in Desa Suka compared with 1.95 milliequivalents per 100 gram (me/100 g) in the infected plot. K is important for osmotic regulation, photosynthate transport, and tolerance to biotic stress, including fungal infection (Wang *et al.*, 2021). Collectively, these empirical insights indicate that significantly higher soil fertility in healthy chili fields acted as a catalyst for enhanced nutrient cycling, microbial activity, and nutrient availability, mechanisms that directly augmented plant nutrient assimilation and sustained crop health. Enhanced soil fertility also promoted more stable microbial communities that contribute to natural disease suppression and greater resilience against anthracnose infection. These beneficial microbial interactions improved soil biological activity, nutrient availability, and ecosystem functioning. Conversely, lower soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and less favorable soil pH were observed in infected fields. These conditions were associated with reduced microbial stability, impaired nutrient cycling, increased disease susceptibility, and lower productivity.

Table 1: Position, altitude, and soil type of chili sampling sites

No.	Regency	Subdistrict – village	Plant condition	Sampling location (Coordinates)	Elevation	Soil type
1	Deli Serdang Regency	Beringin Subdistrict – Beringin Village	Healthy plants	3°36'28.019466" N, 98°52'42.13326" E	3.1 m a.s.l. (Meters above sea level)	Latosol
		Beringin Subdistrict – Beringin Village	Diseased plants (DS > 50%)	3°36'28.102271" N, 98°52'43.22228" E	3.19 m a.s.l.	Latosol
		Pantai Labu Subdistrict – Pantai Labu Village	Healthy plants	3°36'22.194621" N, 98°53'44.13228" E	2.3 m a.s.l.	Latosol
		Pantai Labu Subdistrict – Pantai Labu Village	Diseased plants (DS > 50%)	3°36'22.201325" N, 98°53'46.152019" E	2.16 m a.s.l.	Latosol
		Tanjung Muda Hulu Subdistrict – Bah Bah Buntu Village	Healthy plants	3°17'8.10466" N, 98°67'9.24587" E	601.3 m a.s.l.	Alluvial
		Tanjung Muda Hulu Subdistrict – Bah Bah Buntu Village	Diseased plants (DS = 65%)	3°17'7.98709" N, 98°67'8.16124" E	628.7 m a.s.l.	Alluvial
2	Langkat Regency	Stabat Subdistrict – Kwala Bingai Village	Healthy plants	3°44'20.23832" N, 98°25'34.35938" E	3.71 m a.s.l.	Alluvial
		Stabat Subdistrict – Kwala Bingai Village	Diseased plants (DS > 50%)	3°44'21.19021" N, 98°25'34.42156" E	3.79 m a.s.l.	Alluvial
		Selesai Subdistrict – Padang Brahrang Village	Healthy plants	3°35'24.75683" N, 98°25'59.47756" E	3.37 m a.s.l.	Alluvial
		Selesai Subdistrict – Padang Brahrang Village	Diseased plants	3°35'21.45656" N, 98°25'52.96818" E	3.31 m a.s.l.	Alluvial
3	Karo Regency	Tiga Panah Subdistrict – Suka Village	Healthy plants	3°05'00.77845" N, 98°53'05.69477" E	1,200 m a.s.l.	Andisol
		Tiga Panah Subdistrict – Suka Village	Diseased plants (DS = 55%)	3°05'08.0547" N, 98°53'05.68382" E	1,210 m a.s.l.	Andisol
		Merek Subdistrict – Negeri Tongging Village	Healthy plants	2°93'6.59787" N, 98°53'6.59775" E	1,280 m a.s.l.	Andisol
		Merek Subdistrict – Negeri Tongging Village	Diseased plants	2°93'6.54073" N, 98°53'64.6849" E	1,295 m a.s.l.	Andisol
4	Simalungun Regency	Silimakuta Subdistrict – Seribu Dolok Village	Healthy plants	2°09'19.20063" N, 98°63'13.7705" E	1,380.5 m a.s.l.	Andisol
		Silimakuta Subdistrict – Seribu Dolok Village	Diseased plants (DS = 65%)	2°09'20.10112" N, 98°63'15.2028" E	1,405 m a.s.l.	Andisol
		Pematang Silimahuta Subdistrict – Siboras Village	Healthy plants	2°93'8.48416" N, 98°58'75.57335" E	1,411.5 m a.s.l.	Andisol
		Pematang Silimahuta Subdistrict – Siboras Village	Diseased plants (DS = 50%)	2°93'8.490716" N, 98°58'76.0698" E	1,420 m a.s.l.	Andisol

Table 2: Soil chemical properties of chili plots based on C-organic, total Nitrogen (N-total), available P (P-Bray I), exchangeable K (K-dd), and pH

No.	Study Location	Organic C (%)	Total N (%)	Bray I P (ppm P)	Exchangeable K (Milliequivalents per 100 gram Soil, me/100 g)	pH
1	Healthy Plant – Beringin Village	1.22	0.12	12.50	1.06	5.75
2	Diseased Plant – Beringin Village	1.06	0.09	10.81	1.01	5.70
3	Healthy Plant – Pantai Labu Village	1.82	0.22	16.75	1.43	6.08
4	Diseased Plant – Pantai Labu Village	1.78	0.18	15.01	1.23	5.58
5	Healthy Plant – Kwala Bingai Village	0.72	0.11	17.69	1.53	6.59
6	Diseased Plant – Kwala Bingai Village	0.62	0.11	15.88	1.25	6.29
7	Healthy Plant – Padang Brahrang Village	1.51	0.21	15.19	1.37	7.27
8	Diseased Plant – Padang Brahrang Village	1.05	0.14	12.81	1.22	6.72
9	Healthy Plant – Bah-bah Buntu Village	2.34	0.23	19.60	1.37	5.71
10	Diseased Plant – Bah-bah Buntu Village	2.10	0.25	18.89	1.21	5.70
11	Healthy Plant – Suka Village	4.02	0.48	26.06	2.80	6.68
12	Diseased Plant – Suka Village	2.68	0.36	19.55	1.95	5.80
13	Healthy Plant – Negeri Tongging Village	2.21	0.28	15.62	1.42	7.13
14	Diseased Plant – Negeri Tongging Village	2.19	0.27	15.05	1.40	7.10
15	Healthy Plant – Seribu Dolok Village	2.21	0.28	15.62	1.42	7.13
16	Diseased Plant – Seribu Dolok Village	2.19	0.27	15.05	1.40	7.10
17	Healthy Plant – Siboras Village	4.56	0.46	20.87	1.05	6.43
18	Diseased Plant – Siboras Village	4.03	0.40	16.37	0.91	6.03

Agroclimatic conditions at the sampling locations

Agroclimatic conditions remained generally moderate throughout the study period, but it's still showed seasonal variation that is ecologically relevant for soil and plant-associated microbes. Temperature ranged narrowly from 18.13 °C to 18.55 °C, indicating that the sampling period was not characterized by extreme thermal stress. Nevertheless, a significant monthly effect was observed, with October showing distinct differences compared to the remaining months ($F(5,175) = 3.02$, $p = 0.012$). Although the absolute temperature difference was small, such variation can still influence microbial metabolism, enzyme activity, and decomposition rates, particularly in tropical agroecosystems where microbial processes are highly responsive to microclimatic change. Consequently, temperature functions as a critical environmental filter shaping community assembly, with the capacity to modulate taxonomic turnover and competitive dynamics among microbial communities, aligning with observations by Koyama *et al*. (2018) and Cregger *et al*. (2012). Humidity showed a stronger temporal pattern than temperature. The humidity indicator derived from paired dry-bulb and wet-bulb readings varied significantly across months ($F(6,208) = 73.49$, $p < 0.001$), with December showing the highest value and August the lowest. The degrees of freedom in the F-tests reflect the number of observations and group levels used in the climate analysis. This seasonal heterogeneity plays a pivotal role, since humidity levels govern leaf wetness, microbial persistence, and soil moisture retention, thereby shaping organismal survival across the rhizosphere-phyllosphere continuum. Higher humidity generally favors fungal growth, sporulation, and colonization, whereas lower humidity may reduce microbial abundance or shift communities toward more stress-tolerant taxa. Rainfall also fluctuated across the sampling period, although the variation was not statistically significant ($F(4,52) = 0.64$, $p = 0.637$). Rather than demonstrating that precipitation is negligible to the soil microbiome, this non-significant correlation underscores the resolution boundaries of the current site dataset (Cregger *et al*., 2012; Jiang *et al.,* 2024).

Environmental control of bacterial abundance and diversity

Table 3 shows that bacterial abundance was influenced by altitude, plant health status, and cultivation practice. Bacterial diversity in healthy plants exhibited greater heterogeneity across lowland and highland gradients, particularly within root-associated tissues, which suggests that root-associated tissues, implying that the root microenvironment represents the most dynamic microbial habitat. Table 3 summarizes the variation in endophytic bacterial isolate recovery across distinct altitude, plant health status, and manure application rates. The presented values represent descriptive intervals derived from the observed isolate counts in each sampling category, where notation n refers to the number of isolate recovery observations contributing to each group summary. Importantly, this dataset is intended to illustrate the descriptive distribution of recovered isolates, rather than serving as a quantitative biological measure of absolute abundance. It should also be recognised that agricultural management practices, including fertiliser application, irrigation, pesticide use, crop management, seasonal climatic variation, and previous land-use history, may have associated soil properties and microbial diversity independently of anthracnose infection. Although sampling was restricted to prominent chili-producing regions characterized by largely comparable cultivation practices, confounding environmental variables could not be entirely controlled under field conditions. Consequently, the documented variations in microbial structures should be attributed to the synergistic influences of agroecological conditions, agricultural management, and plant phytosanitary status rather than being ascribed solely to anthracnose

Table 3: SD of endophytic bacterial abundance in root, stem, and leaf tissues by altitude, plant condition, and manure dose

Environmental factor	Root-associated tissue (95% confidence interval, CI)	n	Stem (95% CI)	n	Leaf (95% CI)	n
Altitude based on healthy chili plants						
0–500 m a.s.l.	-21.988 to 60.623	126	-9.324 to 45.006	132	-7.152 to 45.607	144
>500–800 m a.s.l.	-7.434 to 44.478	69	-6.090 to 39.510	69	-9.433 to 46.149	84
>1340 m a.s.l.	-24.834 to 64.404	135	-17.313 to 55.210	123	-20.362 to 59.075	129
Altitude based on diseased chili plants						
0–500 m a.s.l.	-11.177 to 45.539	207	-6.478 to 42.822	216	-4.409 to 47.122	195
>500–800 m a.s.l.	-3.318 to 41.984	87	-0.944 to 39.240	81	-1.341 to 42.255	81
>1340 m a.s.l.	-7.943 to 44.533	210	-1.727 to 40.633	201	-3.310 to 46.283	203
Chili plant health status						
Healthy plants	-20.471 to 57.990	380	-13.143 to 51.587	342	-13.203 to 51.099	348
Anthracnose-infected plants	-8.529 to 44.223	505	-3.729 to 41.267	490	-3.401 to 47.316	498
0–100 g plant	-10.739 to 45.222	120	-0.789 to 15.222	161	-9.005 to 39.816	210

infection. This is consistent with the view that root-associated tissue-associated communities are strongly associated by environmental filtering, root-associated tissue exudates, and soil properties. In infected plants, bacterial community variation remained high, but the spatial distribution shifted toward foliar and cauline tissues. This transition indicates that anthracnose infection fundamentally alters the internal host microenvironment, subsequently disrupting microbial equilibrium. Pathogen infection can disrupt host physiology and open space for opportunistic or antagonistic bacteria to colonize plant tissues (Compant *et al.,* 2019; Liu *et al.,* 2020). Differences in manure dose also affected bacterial variation, suggesting that organic inputs modified the habitat quality for microbial colonization, although the effect remained associated by local environmental conditions. In the present study, microbial abundance was operationalized as the total count of bacterial and fungal isolates successfully recovered across various plant organs, sampling locations, elevational classes, and host health statuses. Although culture-dependent methods recover only the culturable fraction of microbial communities, this approach provided an appropriate baseline ecological assessment for comparing microbial abundance and diversity across contrasting agroecological conditions and for selecting representative isolates for subsequent functional characterization and future microbiome-based applications.

Bacterial diversity in healthy chili plants

In healthy plants, bacterial endophytes showed low to moderate diversity (Table 4). The root-associated tissue compartment consistently showed the highest diversity, followed by leaves and stems. The highest values were found in the mid-altitude sites, particularly Bah-bah Buntu Kampung Baru and Bah-bah Buntu Kampung Lama. Reduced bacterial diversity was documented in lowland sites such as Pantai Labu. This spatial trend suggests that internal tissues act as a highly selective microhabitat, permitting only specific bacterial taxa to establish, whereas root-associated tissues remain the most hospitable niches for colonization (Xia *et al.,* 2024; Hardoim *et al.,* 2015). The greater bacterial diversity observed in root-associated tissue tissues reflects their ecological role as the primary interface between plants and soil, where root-associated tissue exudates provide a continuous supply of diverse carbon compounds and signalling molecules that stimulate microbial colonisation and community assembly. Furthermore, root-associated tissue-associated microbial communities are strongly associated by soil physicochemical properties, including organic carbon, nutrient availability, and pH, resulting in greater diversity than in stems and leaves, which

Table 4: Shannon diversity and abundance of endophytic bacteria in healthy chili plants on NA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	0.910	1.014	0.937	0.974	0.852	0.487
2	Negeri Tongging Village	0.833	0.910	0.861	0.789	1.051	0.835
3	Seribu Dolok Village	0.988	1.043	1.048	0.903	0.604	0.574
4	Siboras Village	0.930	0.924	0.974	0.759	0.874	0.816
5	Bahbuntu Kampung Baru Village	1.042	1.058	0.985	0.807	0.501	0.645
6	Bahbuntu Kampung Lama Village	0.910	1.036	0.855	0.770	0.776	0.823
7	Kwala Bingai Village	1.043	0.562	0.877	0.921	0.523	0.603
8	Padang Brahrang Village	0.886	0.664	0.645	0.493	0.717	0.488
9	Beringin Village	0.692	0.746	0.834	0.809	0.760	1.009
10	Pantai Labu Village	0.801	0.812	0.626	0.646	0.514	0.479

constitute more selective habitats with stronger host filtering. These results underscore the ecological significance of the root-associated microbiome in sustaining nutrient cycling, microbial homeostasis, and host fitness across divergent agroecological gradients. Epiphytic bacteria in healthy plants showed moderate diversity, with higher values in Beringin and Padang Brahrang, particularly in root-associated tissues and leaves (Table 5). This result suggests that the plant episphere hosts a more diverse bacterial community than the endosphere, particularly in niches characterized by heightened environmental exposure and nutrient availability. Synergistic microbial interactions on root-associated tissues foliar surfaces may enhance community stability, thereby bolstering host resilience against biotic and abiotic stressors. All data present the complete Shannon diversity dataset for bacterial and fungal communities across sampling locations, plant compartments, developmental stages, and plant health conditions. This presentation of results highlights primary ecological trends and statistically meaningful comparisons, while keeping the dataset accessible to ensure transparency, verification, reproducibility, and future comparative analyses.

Bacterial diversity in anthracnose-infected chili plants

In anthracnose-infected plants, bacterial endophyte diversity was generally higher in leaves, followed by stems and root-associated tissues (Table 6). The highest values were recorded in Negeri Tongging and Suka, with Shannon diversity in the range of 1.475–1.759 for leaves and 1.428–1.610 in Suka. Stem diversity was also elevated in Bah-bah Buntu. This shift implies that anthracnose-induced tissue modifications carve out new ecological niches, selectively facilitating the establishment of stress-tolerant and opportunistic bacteria. Epiphytic bacteria in infected plants also showed a distinct pattern (Table 7). The highest diversity was found in Kwala Bingai, especially in leaves, where Shannon values reached 1.531–1.567. These observations indicate that pathogenesis alters the phyllosphere microenvironment, subsequently facilitating colonization by stress-tolerant bacterial cohorts through changes in nutrient availability and host physiological responses under disease pressure**.** This aligns with prior studies on diseased plant systems, where pathogen-induced tissue degradation triggers a transition from a stable climax microbiome to a highly dynamic, opportunistic microbial community.

Fungal diversity in healthy chili plants

Fungal endophytes in healthy chili plants showed low to moderate diversity (Table 8). The highest values were found in the highland sites, especially Seribu Dolok, Siboras, and Negeri Tongging, where Shannon diversity exceeded 1.0 and, in some cases, reached above 2.0. In contrast, lowland sites such as Kwala Bingai and Padang Brahrang

Table 5: Shannon diversity and abundance of epiphytic bacteria in healthy chili plants on NA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	0.816	0.868	0.549	0.602	0.740	0.759
2	Negeri Tongging Village	1.344	0.970	1.107	0.692	1.443	1.169
3	Seribu Dolok Village	1.163	1.211	1.061	1.144	0.803	0.796
4	Siboras Village	1.263	1.202	1.309	1.038	1.068	1.071
5	Bahbuntu Kampung Baru Village	1.103	0.957	0.936	0.686	1.116	0.759
6	Bahbuntu Kampung Lama Village	1.292	0.945	0.813	0.971	0.735	0.685
7	Kwala Bingai Village	1.254	1.384	1.124	1.172	1.252	1.288
8	Padang Brahrang Village	1.730	1.661	1.155	1.139	1.024	1.043
9	Beringin Village	1.567	2.017	1.740	1.646	1.004	0.913
10	Pantai Labu Village	0.988	0.994	0.799	0.708	1.055	0.731

Table 6: Shannon diversity and abundance of endophytic bacteria in anthracnose-infected chili plants on NA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	1.067	1.011	1.428	1.610	0.696	0.674
2	Negeri Tongging Village	0.984	0.826	1.759	1.475	1.271	1.137
3	Seribu Dolok Village	0.986	1.075	0.930	0.933	0.486	0.439
4	Siboras Village	1.162	0.923	0.956	0.920	1.161	1.132
5	Bahbuntu Kampung Baru Village	0.979	1.057	1.502	1.224	1.472	1.436
6	Bahbuntu Kampung Lama Village	1.089	1.614	0.776	1.204	1.236	0.801
7	Kwala Bingai Village	1.362	0.670	1.136	0.999	1.008	0.765
8	Padang Brahrang Village	1.607	0.922	1.177	0.606	1.283	0.588
9	Beringin Village	0.859	0.850	1.063	1.045	1.104	1.277
10	Pantai Labu Village	0.795	0.842	0.636	0.650	0.585	0.562

Table 7: Shannon diversity and abundance of epiphytic bacteria in anthracnose-infected chili plants on NA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	1.179	1.081	0.997	0.675	0.644	0.781
2	Negeri Tongging Village	1.108	0.908	1.160	0.774	0.950	1.146
3	Seribu Dolok Village	1.138	1.090	0.907	1.094	0.736	0.725
4	Siboras Village	0.967	1.079	0.999	1.145	0.980	1.079
5	Bahbuntu Kampung Baru Village	1.030	1.048	1.037	0.877	0.668	0.630
6	Bahbuntu Kampung Lama Village	0.943	0.883	0.932	0.776	0.806	0.901
7	Kwala Bingai Village	1.438	1.531	1.567	1.457	1.023	1.518
8	Padang Brahrang Village	1.148	1.649	0.869	1.422	1.235	1.281
9	Beringin Village	0.967	1.339	0.861	1.287	0.670	1.296
10	Pantai Labu Village	0.788	1.572	0.771	1.248	0.887	1.164

Table 8: Shannon diversity and abundance of endophytic fungi in healthy chili plants on PDA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	0.972	0.858	1.360	0.839	0.945	0.835
2	Negeri Tongging Village	1.586	1.165	1.440	1.159	2.051	1.158
3	Seribu Dolok Village	2.028	1.778	1.363	1.753	1.698	1.747
4	Siboras Village	1.791	1.686	1.575	1.688	1.642	1.688
5	Bahbuntu Kampung Baru Village	2.015	2.048	1.951	2.040	2.470	2.038
6	Bahbuntu Kampung Lama Village	0.970	0.942	1.207	0.946	1.285	0.947
7	Kwala Bingai Village	0.787	0.774	0.758	0.768	0.772	0.766
8	Padang Brahrang Village	0.479	0.651	0.476	0.658	0.673	0.659
9	Beringin Village	1.541	1.470	1.377	1.477	1.530	1.479
10	Pantai Labu Village	1.258	1.117	1.804	1.106	1.100	1.103

showed lower diversity. This pattern indicates that cooler and more stable highland habitats foster a more complex fungal community structure (Mendes *et al.,* 2013). Fungal epiphytes associated with healthy plants also exhibited low to moderate diversity (Table 9). Highland locations generally supported greater taxonomic richness than lowland locations, suggesting that climatic and elevational gradients shape fungal community assembly on both the episphere and within endophytic tissues. Environmental conditions such as humidity, temperature, and host physiological status are known to influence fungal colonization and community balance in the phyllosphere.

Relationship between soil chemistry and microbial diversity

The correlation analysis showed that soil C-organic and total N were the strongest positive predictors of fungal diversity in the root-associated tissue compartment (Fig. 1). Positive correlations were observed between C-organic and fungal Shannon diversity (r = 0.48 in stage I and r = 0.41 in stage II), and between total N and fungal diversity (r = 0.47 in stage I and r = 0.31 in stage II) (Fig. 2). These findings indicate that elevated soil organic matter and better N availability sustained a highly diverse fungal community within the rhizosphere (Banerjee and van der Heijden, 2023). Collectively, these findings indicate that soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, soil pH, and altitude act as complementary ecological drivers regulating soil fertility and microbial community assembly across the investigated agroecosystems. Higher soil fertility enhanced nutrient bioavailability and sustained more diverse microbial communities, particularly root-associated tissue-associated fungi—whereas diminished soil fertility was correlated with altered culturable microbial assemblages and a higher incidence of anthracnose (Zhou *et al.,* 2021). These findings highlight soil fertility as a key ecological determinant of plant–soil–microbe interactions in chili production systems. Although the documented soil variations correlate with plant phytosanitary status, they do not establish a causal relationship between soil chemistry and susceptibility to anthracnose. Other factors such as location, cultivar, irrigation, fertilization, and local management may also influence the pattern (Sterrantino, 2024). Bacterial diversity showed a more mixed response to soil chemistry (Fig. 3). Soil organic carbon and total nitrogen exhibited a strong positive mutual correlation with each other and were positively associated with the diversity of root endophytic fungi; conversely, both biogeochemical parameters were negatively correlated with root endophytic bacterial diversity. Soil pH exhibited the strongest positive predictor of root endophytic fungal diversity, suggesting that soil physiochemical gradients exert distinct selective pressures on culturable bacterial and fungal communities (Fig. 4). The regression models showed positive relationships between soil chemical properties and fungal diversity, with the multivariable model providing a significantly stronger fit (R^2 = 0.847) than the univariable model (R^2 = 0.461) overall. These results indicate that combined soil physicochemical properties accounted for a substantial proportion of the variance in stem endophytic fungal diversity (Fig. 5). These observations align with the well-documented sensitivity of soil bacterial communities to pH fluctuations (Jiao *et al.,* 2021). In the leaf compartment, bacterial diversity was positively associated with organic C, N, and P, especially in the second sampling stage. Fungal diversity was sensitive to soil pH and K availability, though the magnitude and polarity of these associations varied across developmental stages. These patterns suggest that soil chemistry directly modulates aboveground microbial communities, mediated by plant physiological responses and host filtering. Similar results have been reported in studies showing that microbiome assembly is

Table 9: Shannon diversity and abundance of epiphytic fungi in healthy chili plants on PDA

No.	Location/village	Root-associated tissue (Stage 1)	Root-associated tissue (Stage 2)	Leaf (Stage 1)	Leaf (Stage 2)	Stem (Stage 1)	Stem (Stage 2)
1	Suka Village	1.223	1.318	1.377	1.347	1.242	1.195
2	Negeri Tongging Village	1.397	1.439	1.431	1.382	1.285	1.268
3	Seribu Dolok Village	1.302	1.366	1.485	1.368	1.179	1.364
4	Siboras Village	1.376	1.500	1.363	1.316	1.257	1.226
5	Bahbuntu Kampung Baru Village	1.218	1.090	1.252	1.192	1.194	1.179
6	Bahbuntu Kampung Lama Village	1.285	1.317	1.232	1.259	1.163	1.106
7	Kwala Bingai Village	1.137	1.240	1.232	1.219	0.977	1.008
8	Padang Brahrang Village	1.166	1.242	1.212	1.225	1.123	1.177
9	Beringin Village	1.059	1.096	1.196	1.081	1.032	1.073
10	Pantai Labu Village	1.149	1.124	1.124	1.121	1.071	1.041

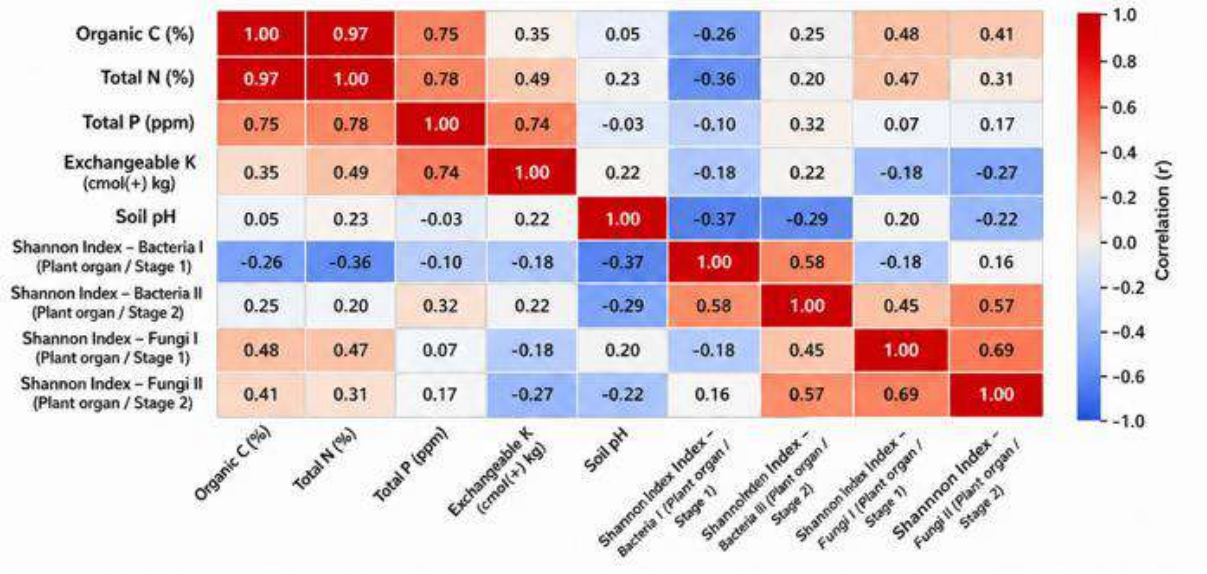

Fig. 1: Correlation matrix between soil chemical properties and microbial diversity in leaves of healthy chili plants

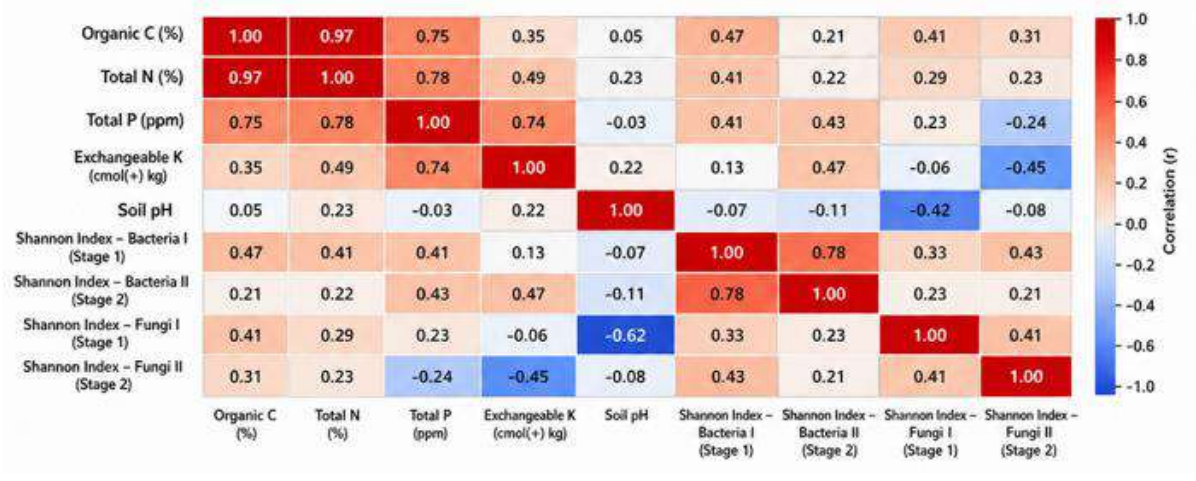

Fig. 2: Correlation matrix between soil chemical properties and microbial diversity in stems of healthy chili plants

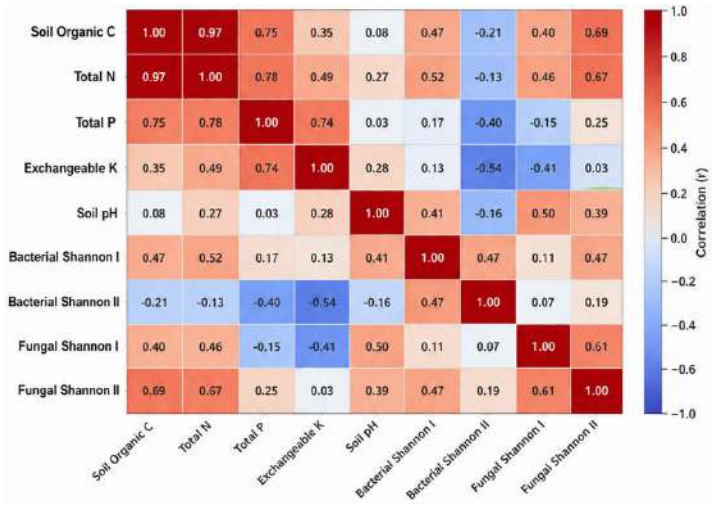

Fig. 3: Correlation matrix between soil chemical properties and microbial diversity in root-associated tissues of healthy chili plants

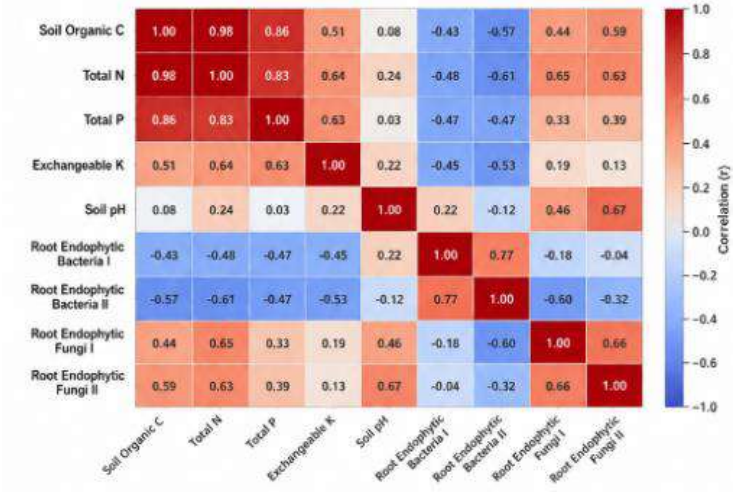

Fig. 4: Correlation matrix for fungal epiphyte diversity in root-associated tissues of healthy chili plants

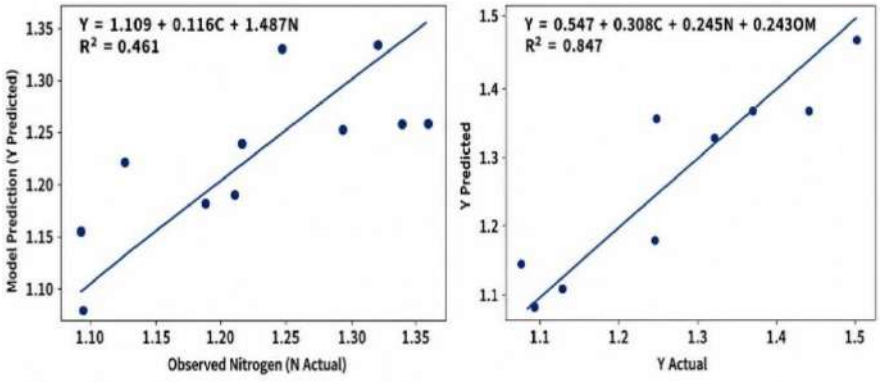

Fig. 5: Regression summaries for microbial diversity across plant compartments

controlled by soil nutrients, host traits, and microbial competition (Compant *et al.,* 2019; Liu *et al.,* 2020). In stems, C-organic and total N again showed the strongest relationships with fungal diversity. The regression analysis supported this pattern. In stage I, fungal diversity was modeled as Y = 1.109 + 0.116C + 1.487N (R^2 = 0.461). In stage II, the model improved substantially, with Y = −0.507 + 0.308(C-organic) − 2.405(N-total) + 0.262(pH), and R^2 = 0.847. Building upon the preliminary Pearson correlation analysis, multiple linear regression was employed to model the collective influence of soil physicochemical properties. The final model demonstrated that soil organic carbon, total nitrogen, and soil pH jointly accounted for a substantial proportion of the variation in fungal diversity, indicating that microbial community dynamics are shaped by synergistic interaction of among multiple soil properties rather than discrete variables. The high coefficient of determination (R^2 = 0.847) indicates that soil organic carbon, total nitrogen, and soil pH jointly explained a substantial proportion of the variation in stem fungal diversity. These variables collectively modulate nutrient availability, microbial proliferation, and habitat suitability, demonstrating that fungal community assembly is driven by the integrated effects of soil fertility rather than discrete, isolated soil properties. C-organic positively supported microbial diversity by providing an important energy source for microbial growth, whereas the negative coefficient of N during the second stage suggests that excessive N may reduce fungal evenness and diversity (Zhou *et al*., 2021; Li *et al.,* 2023). The ecological responses of bacterial and fungal communities were highly distinct: bacterial diversity was predominantly driven by soil pH, while fungal diversity correlated more strongly with overall soil fertility parameters (Jiao *et al.,* 2021). Higher soil fertility also promoted greater root-associated tissue microbial diversity, emphasizing the importance of the rhizosphere in regulating plant–microbe interactions through root exudates and soil physicochemical properties (Fitzpatrick *et al*., 2020). Subsequent regression modeling demonstrated that fungal diversity was governed by synergistic environmental interactions, with these associations becoming more pronounced during the second sampling stage—underscoring the combined role of seasonality and phenological crop development in shaping microbial community assembly (Liu *et al.,* 2020; Purohit *et al.,* 2024). These findings support the use of microbiome diversity as a biological indicator of soil quality, contributing to nutrient cycling, pathogen suppression, and ecosystem resilience in tropical chili production systems (Naylor and Coleman-Derr, 2018; Banerjee and van der Heijden, 2023).

Ecological interpretation of the microbial patterns

Altitude, soil chemical properties, plant health status, and cultivation practices collectively influenced the diversity of culturable microbial assemblages associated with chili plants. Root-associated tissues consistently supported the highest microbial diversity, while anthracnose infection restructured microbial composition in aboveground tissues, illustrating how environmental variables, host selection, and soil fertility interact to shape plant–microbe dynamics (Compant *et al.,* 2019; Jiao *et al.,* 2021; Liu *et al.,* 2020). The findings also show that high soil C-organic and N were associated with stronger fungal diversity, whereas bacterial communities were more sensitive to pH and to the balance among soil nutrients. These findings indicate that bacterial and fungal taxa exhibit divergent ecological responses to identical soil environment. These distinctions are significant, as soil microbiome structure typically reflects concurrent, multifaceted ecological pressures at the same time, rather than a single, dominant governing factor. The microbial communities identified in the present study comprised both beneficial and potentially opportunistic microorganisms. While beneficial microorganisms facilitate to nutrient cycling, nutrient acquisition, maintenance of soil biological stability, and the

biopriming or natural suppression of soil-borne pathogens, anthracnose-induced shifts in culturable microbial assemblages likely reflect ecological dysbiosis and a concomitant rise in colonization by opportunistic pathogens. Therefore, maintaining beneficial microbial communities through appropriate soil fertility and crop management practices represents an important strategy for improving soil health and promoting environmentally sustainable chili production. Finally, the recovery of 218 bacterial isolates and 16 fungal isolates, followed by the selection of 41 bacterial and 10 fungal isolates for further screening, establishes a valuable ecological repository for future functional characterizations of culturable microbial assemblages. The microbial consortia identified in this study establish a valuable biological foundation for the development of targeted microbiome-based disease management strategies. Representative antagonistic isolates may serve as candidate biological control agents against *Colletotrichum* spp., whereas maintaining diverse beneficial microbial communities through appropriate soil management may enhance natural disease suppression and reduce anthracnose incidence under field conditions. The ecological interpretation presented in this study was based on culture-dependent analyses, including microbial abundance, Shannon diversity, and their relationships with soil chemical properties across contrasting agroecological conditions. While these culture-dependent approaches yield crucial baseline ecological insights, incorporating high-throughput sequencing technologies in future studies will facilitate the detection of unculturable taxa, enhance taxonomic resolution, and offer a more holistic understanding of microbial community structure, ecological dynamics, and ecosystem functioning. The primary objective of the present study was to characterise culturable microbial diversity under contrasting agroecological conditions. Nevertheless, representative isolates recovered during this study were subsequently evaluated for antagonistic activity against *Colletotrichum* spp. as part of a separate investigation. Future evaluation of additional functional traits, including nutrient solubilisation, nitrogen fixation, siderophore production, and plant growth-promotion, would further strengthen the ecological interpretation and facilitate the development of microbiome-based biological control strategies. The subsequent biochemical and antagonistic screening of the selected isolates has been reported separately by Tarigan *et al*. (2025). Consequently, these findings establish a baseline characterization of how the field environment and host disease status interact to modulate microbial diversity in chili production systems. From an applied standpoint, these findings advocate for integrated soil and microbiome management strategies. Specifically, prioritizing the maintenance of soil organic matter, balanced fertilization regimes, preservation of beneficial microbial consortia, and minimized reliance on chemical fungicides is expected to enhance soil fertility, strengthen natural disease suppression, and sustainable chili cultivation.

CONCLUSION

This study demonstrates that agroecological conditions, particularly soil chemical properties, altitude, and plant health status, are important drivers of culturable microbial diversity associated with chili pepper. In contrast to anthracnose-infected areas, healthy fields exhibited significantly enhanced soil fertility, characterized by elevated levels of organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and near-neutral soil pH than anthracnose-infected fields. Root tissues consistently supported the greatest microbial diversity, highlighting their ecological importance in plant–soil interactions. While fungal diversity displayed more robust positive correlations with soil organic carbon and total nitrogen, bacterial diversity was predominantly driven by soil pH. These findings indicate that soil fertility plays a

central role in structuring culturable microbial assemblages under field conditions. Improving soil quality may therefore enhance microbial stability, plant health, and resilience against disease. In conclusion, this study establishes a vital ecological baseline that can guide the design of sustainable, microbiome-mediated soil and crop management strategies in chili production systems. A total of 218 bacterial isolates and 16 fungal isolates were recovered from healthy and anthracnose-infected chili plants, providing a valuable culture collection for future ecological and functional studies. Among these, 41 bacterial isolates and 10 fungal isolates were selected for further phenotypic profiling based on their distinctive morphological features. Although these findings are applicable to chili agroecosystems with environmental conditions similar to those investigated in North Sumatra, caution is required when extrapolating the results to regions with different climates, soil types, agricultural practices, or disease pressures. Further validation across diverse agroecosystems is recommended. This study establishes baseline data for long-term monitoring of soil fertility, microbial diversity, anthracnose incidence, and ecosystem functioning to evaluate temporal changes in agroecosystem sustainability. Future studies integrating high-throughput sequencing, metagenomics, functional diversity analyses, and ecosystem service assessments should complement the culture-dependent approach and provide a comprehensive understanding of plant–soil–microbe interactions. These findings provide a scientific basis for microbiome-based soil health assessment and sustainable disease management in chili production systems. They also support future research on beneficial plant-associated microorganisms to enhance crop resilience and promote sustainable agriculture. Differences in soil fertility between healthy and anthracnose-infected chili fields influence nutrient cycling, plant productivity, disease resistance, and agroecosystem sustainability. Healthy fields generally exhibited higher soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and a more favorable soil pH, providing conditions that enhance microbial activity, nutrient cycling, and plant nutrient uptake. These conditions support plant growth, improve resistance to *Colletotrichum* spp. infection, and maintain more stable microbial communities. In contrast, reduced soil fertility in infected fields is associated with poorer microbial habitats, increased disease susceptibility, and lower plant productivity. Therefore, the present study should be regarded as the ecological basis for functional investigations. From an environmental science and management perspective, this study provides baseline information on factors shaping chili-associated microbial communities. Soil properties, altitude, and plant health were associated with microbial diversity and community composition. The findings support microbiome-based management strategies that emphasize the conservation of beneficial microbial communities through maintenance of soil organic matter, balanced nutrient management, reduced dependence on chemical fertilizers and fungicides, and application of locally adapted beneficial microbial inoculants. These approaches may contribute to ecological restoration of agricultural soils, improved soil health, enhanced natural disease suppression, and sustainable chili production under diverse environmental conditions through integrated ecosystem-based agricultural management practices and interventions that strengthen ecosystem resilience while maintaining long-term agricultural productivity and environmental sustainability across regions. However, the observed soil differences are associated with disease status but do not prove that soil chemistry caused anthracnose susceptibility. Other factors such as location, cultivar, irrigation, fertilization, and local management may also influence the pattern. The results are presented as ecological patterns observed across sites, plots, and plant compartments. Any mechanistic explanation is framed as a hypothesis for future testing through controlled experimental validation studies.

AUTHOR CONTRIBUTIONS

R. Tarigan conceived the study, designed experiments, led fieldwork, interpreted data, and drafted the manuscript. Lisnawita supported study design, methodology contributed to data interpretation and manuscript revision. A.R. Tantawi participated in collecting data, conducting analytical procedures and assisted with manuscript refinement. C. Hermanto assisted with data interpretation and contributed to drafting figures and tables.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
α	Alpha
°C	Degree Celsius
ANOVA	Analysis of variance
DS	Disease severity
C-organic	Organic carbon
cm	Centimeter
G	Gram
GPS	Global positioning system
h	hour
H'	Shannon Diversity Index
K	Potassium
K-dd	Exchangeable Potassium
LSD	Least Significant Different

M	Meter
m.a.s.l.	Meters above sea level
Me	Milliequivalent
me/100 g	Milliequivalents per 100 g Soil
NA	Nutrient agar
n	Number sample
ni	Number of individuals in a given category
Ni	Total number of individuals across categories
N	Nitrogen
N-total	Total nitrogen
P	Phosphorus
PDA	Potato dextrose agar
pH	Potential of hydrogen
P-Bray I	Available P Determined by the Bray I Method
Ppm	Parts per million
SD	Standard deviation

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REVIEW ARTICLE

Key geographical indicators for environmental, social and economic sustainability of land use

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ABSTRACT

Sustainable land-use planning requires spatially explicit indicators capable of integrating environmental, social, and economic dimensions of territorial systems. Geo-indicators have been widely applied to assess land-use dynamics, environmental pressures, urban expansion, and spatial inequalities. Paradoxically, an integrated, the methodological and conceptual framework remains largely fragmented across the literature. The study objectives were to strengthen the conceptual and methodological basis for integrating geo-indicators into evidence-based land-use planning frameworks. To ensure methodological rigor, this study employed a systematic review and bibliometric analysis conforming to the preferred reporting items for systematic reviews and meta-analyses guidelines. Scientific records were retrieved from Scopus and Web of Science for the period 1998–2025. From an initial set of 497 records, 41 case-based studies were selected after duplicate removal, screening, and eligibility assessment. Bibliometric analysis was conducted utilizing RStudio (an integrated development environment for R programming), a bibliometric package (an R package designed for bibliometric analysis) and visualization of similarities viewer software. This analysis aimed to assess trends in scientific production, thematic structures, keyword co-occurrence, and international collaboration networks. The results indicate a significant increase in scientific production after 2018, reaching a peak in 2025, reflecting the growing relevance of geo-indicators in sustainability science. The thematic landscape resolved into three distinct clusters: environmental impacts and sustainability transitions, spatial modeling using geographic information systems coupled with multi-criteria decision analysis, and urban and territorial planning applications. Geographic information systems integrated with analytical hierarchy process, fuzzy logic, spatial modelling, and scenario simulation were identified as the most frequently applied methodological approaches. Environmental geo-indicators were found to dominate the literature, while social and economic dimensions remain underdeveloped and inconsistently integrated across studies. Such an asymmetry underscores a persistent disconnect in translating multidimensional sustainability frameworks into operational tools for territorial analysis. The main limitation identified is the absence of a standardized geo-indicator framework capable of integrating environmental, social, and economic dimensions across spatial and temporal scales. These findings demonstrate that while geo-indicators constitute powerful tools for land-use sustainability assessment, their ultimate utility depends on standardized methodologies, geospatial systems interoperability, and the incorporation of socioeconomic dimensions.

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INTRODUCTION

Sustainability in territorial planning involves the balanced management of natural resources to ensure environmental integrity, social equity, and economic development without compromising future generations (Elorrieta Sanz *et al.,* 2016; Smith *et al.,* 2023). In territorial planning, sustainability aims to balance socio-economic development with ecological constraints while ensuring responsible land and resource management (Global Forest Resources Assessment, 2020). Territorial planning policies should integrate environmental, social, and economic dimensions to balance development and conservation while maintaining life-support systems (UN-Habitat, 2020). In contemporary territorial planning, sustainability indicators serve as critical diagnostic tools to quantify and monitor progress toward sustainable development objectives (Tran *et al.,* 2024). Geo-indicators are spatially explicit measures that integrate environmental, social, and economic variables within geographic information systems (GIS) to support territorial analysis and decision-making. In contrast to conventional sustainability indicators, geo-indicators integrate explicit spatial dimensions and multidimensional sustainability criteria, allowing for a more granular evaluation of land-use dynamics. At the global scale, established frameworks such as the United Nations (UN) sustainable development goals (SDGs), the Driving Forces–Pressures–State–Impact–Response (DPSIR) framework, the Millennium Ecosystem Assessment (MA), and the System of Environmental-Economic Accounting (SEEA) enable integrated assessment of environmental, social, and economic territorial dimensions (Guo *et al.,* 2024; Mkhitaryan *et al.,* 2026). Rising pressure on natural systems—driven by the degradation of approximately 60 percent (%) of resources and a projected global population of 9.7 billion by 2050—emphasizes the need for robust, time-comparable spatial metrics to support territorial planning (United Nations, 2019). Consequently, sustainability indicators have emerged as institutionalized mechanisms to evaluate human-induced pressures on socio-ecological systems, thereby informing policy frameworks that foster equitable and resilient territorial development (Yang *et al.,* 2018). The transformation of sustainability indicators into geo-indicators incorporates the spatial dimension into sustainability assessment, allowing analysis of socio-economic and land-use dynamics linked to land use land cover (LULC). Unlike conventional indicators, this framework effectively delineates territorial gradients, critical vulnerabilities, and intricate spatial dynamics (Chaudhari *et al.,* 2024; Gioia *et al.,* 2024; Mathenge *et al.,* 2022). Advances in geotechnologies have enabled the integration and analysis of environmental, socioeconomic, and biophysical data, enhancing understanding of human–environment interactions across spatial scales (Académico *et al.,* 2025; Angelita, 2020). Since the 1980s, thematic mapping and geographic information systems (GIS) have supported environmental impact assessment, including LULC change, environmental degradation, urban expansion, and resource pressure (Handmer, 1980; Tsatsaris *et al.,* 2021). By endorsing geospatial methodologies and indicators for sustainable territorial and spatial planning, the 1992 Rio de Janeiro Earth Summit lent crucial institutional support to this approach (McCammon, 1992; Scott and Rajabifard, 2017). In the 21st century, the growing need to monitor climate change, assess progress on the SDGs, and anticipate future scenarios has solidified geo-indicators as tools for dynamically integrating the environmental, social, and economic dimensions of territories in a time-comparable manner (Márquez Delgado *et al.,* 2021; ONU, 2012). Cloud computing (e.g., Google Earth Engine (GEE)) and geospatial big data analysis have improved the processing of large territorial datasets, enabling real-time monitoring of land cover, vegetation productivity, water availability, and climate risks, and strengthening

geo-indicators in territorial planning (Gorelick *et al.,* 2017). Consequently, the integration of geo-indicators into territorial planning and management enhances decision-making frameworks by delivering spatially explicit evaluations, longitudinal assessments, and strategic guidance for sustainable development policies (Zhang *et al.,* 2024). The integration of spatial analysis and territorial modelling has enhanced sustainability assessment from a forward-looking, evidence-based perspective. Geostatistical techniques and spatial modelling enable geo-indicators to construct land-use change scenarios and anticipate the effects of planning decisions and policies (Bielecka, 2020; Smelror, 2020). Furthermore, integrating time-series analysis with dynamic modeling facilitates the evaluation of spatiotemporal variations in territorial systems, thereby enhancing the precision of multiscale assessments regarding anthropogenic impacts on ecosystems (Pricope *et al.,* 2019). These tools facilitate the identification of high-risk areas and change thresholds, supporting the implementation of territorial management strategies and the design of corrective measures at local and regional levels (Rezvani *et al.,* 2023). Systematic literature reviews in this field have been crucial in consolidating the available knowledge on geo-indicators applied to territorial planning (Argandoña-Castro and Peña-Cortés, 2025). While global efforts have extensively classified sustainability metrics—ranging from systematic dimensional analyses (Grassi et al., 2026; Parra-Pulido *et al.,* 2024) to screening frameworks designed to select representative indicator subsets (Behjat *et al.,* 2024); significant challenges remain. Chief among these are the persistent shortage of cohesive, integrative frameworks and the difficulty of adapting global metrics to localized contexts (Donatti *et al.,* 2020). Consequently, systematic reviews facilitate a rigorous synthesis of existing literature, establishing a robust foundation to guide future research while illuminating current knowledge gaps and methodological limitations (El Archi *et al.,* 2023). Some studies have applied geo-indicators to assess the impact of urban and rural dynamics on sustainability. In the Jakarta–Bandung Mega Urban Region (JBMUR), Indonesia, a local sustainability index (LSI) revealed spatial interdependence among local units, with many subdistricts showing low economic and social sustainability but moderate environmental performance (Pravitasari *et al.,* 2022). In Cuenca, Ecuador, a GIS-based approach was deployed to examine the relationship between urban fabric typologies and sustainability indicators, yielding critical insights for urban planning frameworks (Calderón *et al.,* 2024). Similarly, studies conducted in the Yangtze River Delta Basin in China and in Tanta, Egypt, highlight the roles of landscape characteristics and land use in rural and urban sustainability, using GIS and analytical hierarchical processes (AHP). These studies facilitated the identification of priority zones for urban densification and the preservation of agricultural land (Abdrabo *et al.,* 2021; Meng *et al.,* 2024). In Germany, spatial trade-offs in wind energy allocation are emphasized through participatory and transparent approaches balancing costs, ecological impacts, and interregional equity (Lehmann *et al.,* 2021). These empirical cases illustrate the capacity of geo-indicators to enhance assessment precision and optimize territorial management strategies. While the application of geo-indicators has expanded significantly, a standardized, multi-dimensional framework that seamlessly synthesizes environmental, social, and economic parameters remains absent. Existing studies remain fragmented, with a predominant focus on environmental indicators and limited methodological guidance for multidimensional integration across spatial scales. Geo-indicators contribute to sustainable land-use planning by enabling spatially explicit, multi-scale analysis of environmental and socio-economic processes, supporting evidence-based territorial management and decision-making. However, the

full utility of these metrics remains restricted by methodological discrepancies and an asymmetrical integration of sustainability dimensions. This review addresses these limitations by systematically synthesizing 41 Scopus- and Web of Science-indexed studies and combining bibliometric analysis with a systematic review approach. By analyzing methodological trends, spatial techniques, and dimensional integration patterns, this study introduces a structured framework designed to optimize geo-indicator operationalization in sustainable land-use planning. In this context, the study addresses two research questions: (i) what types of geo-indicators are used to assess land-use sustainability across environmental, social, and economic dimensions, and (ii) which spatial analysis methodologies are most frequently applied for their integration in sustainable territorial management. By systematically synthesizing spatial metrics and sustainability frameworks within territorial planning, this review offers a refined conceptual architecture for geo-indicators. Unlike previous reviews focused mainly on environmental indicators or regional applications, this study examines the integration of environmental, social, and economic dimensions using geospatial analytical approaches. Using bibliometric analysis and a systematic review, this study identifies methodological trends and emerging research areas, and highlights gaps in geo-indicator frameworks for sustainable territorial management. A systematic evaluation of literature indexed in Scopus and Web of Science (WoS) was conducted to characterize the geo-indicators and geospatial methodologies used in multi-dimensional land-use sustainability assessments. Based on this analysis, the study proposes a framework that integrates the main dimensions of sustainability with spatial analysis based on geo-indicators. This systematic review investigates the application of geo-indicators in evaluating land-use sustainability and highlights the spatial techniques that are most commonly employed to facilitate sustainable territorial management. The aims of this review study are to strengthen the conceptual and methodological basis for integrating geo-indicators into evidence-based land-use planning frameworks. This study has been carried out in ESPOL Polytechnic University, Guayaquil, Ecuador in 2026.

METHODOLOGY

The main purpose of the methodological base is to evaluate geo-indicators and demonstrate their strategic role in analyzing, monitoring and evaluating the sustainability of territories. This enables the spatial and temporal representation of changes induced by human activities on natural and socio-economic systems (Fig. 1). To address the stated objective, a comprehensive framework was established to synthesize the interactions among territorial systems, spatial indicators, and their corresponding geospatial evaluation tools. Fig. 2 illustrates this conceptual model, which informs the analytical structure of the study and demonstrates how geo-indicators can be incorporated into sustainable territorial planning processes. These conceptual frameworks (Figs. 1 and 2) were derived from the systematic synthesis of the reviewed literature and reflect the most frequently identified methodological patterns in geo-indicator research. Their conceptual architecture is derived from synthesizing bibliometric insights with the outcomes of a systematic literature review. This process combined a systematic review with a bibliometric analysis. The methodological process followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, which are divided into four key phases (Fig. 3). The Identification phase prioritizes the retrieval of records from comprehensive academic databases to guarantee an extensive compilation of relevant studies. In the Screening phase, the records are examined by reviewing titles and abstracts to determine their relevance to the research topic. Subsequently, during the Eligibility phase, full

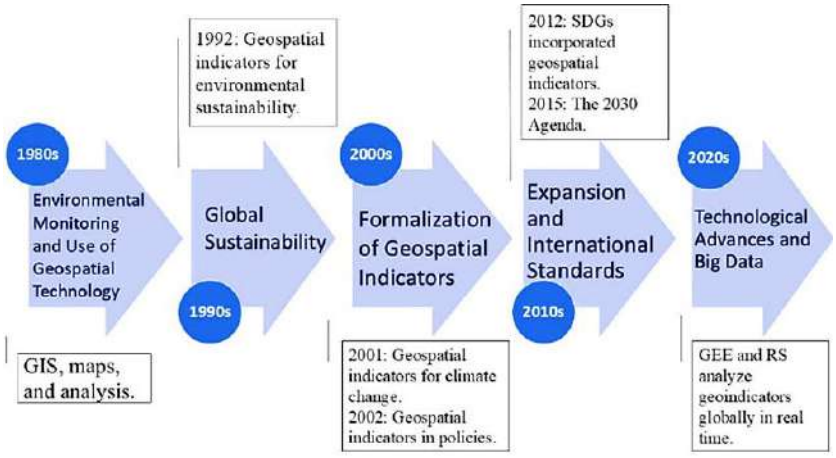

Fig. 1: Conceptual evolution of geo-indicators and their integration into spatial sustainability assessment frameworks

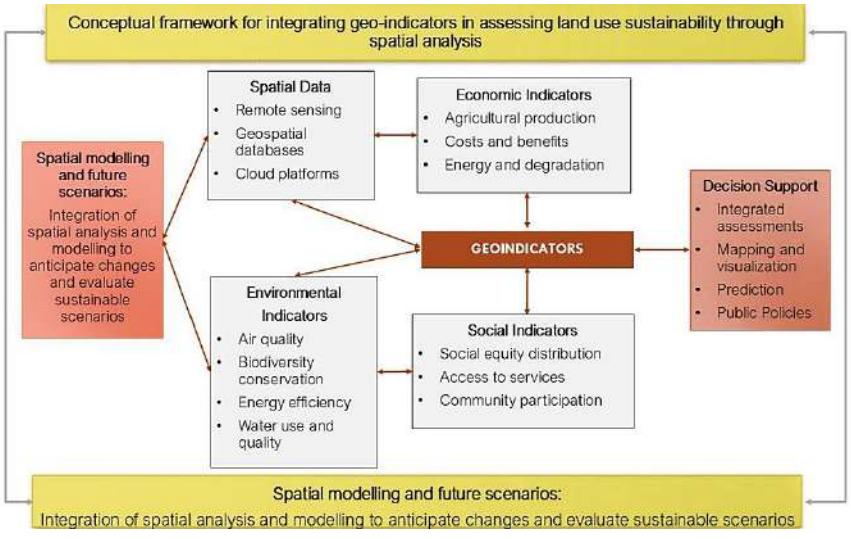

Fig. 2: Conceptual framework for the integration of geo-indicators in land use sustainability assessment through spatial analysis

articles are reviewed to assess their suitability against the established criteria. Ultimately, the inclusion phase guarantees that only studies satisfying the predefined eligibility criteria proceed to the final analysis, thereby facilitating a rigorous and consistent evaluation of the selected literature.

Identification

The search strategy was conducted using two major academic databases, Scopus and Web of Science (WoS). These databases were selected due to their broad multidisciplinary coverage, rigorous peer-review indexing standards, and extensive use in systematic reviews within environmental and spatial sciences. Deploying these methods in tandem guarantees methodological rigor, enhances data quality, and ensures the reproducibility of results—a dual approach heavily endorsed within bibliometric and systematic review literature (Pranckutė, 2021). This search focused on geo-indicators applied to the assessment of environmental, social, and economic sustainability, with the aim of identifying their applications in land use and land cover (LULC).

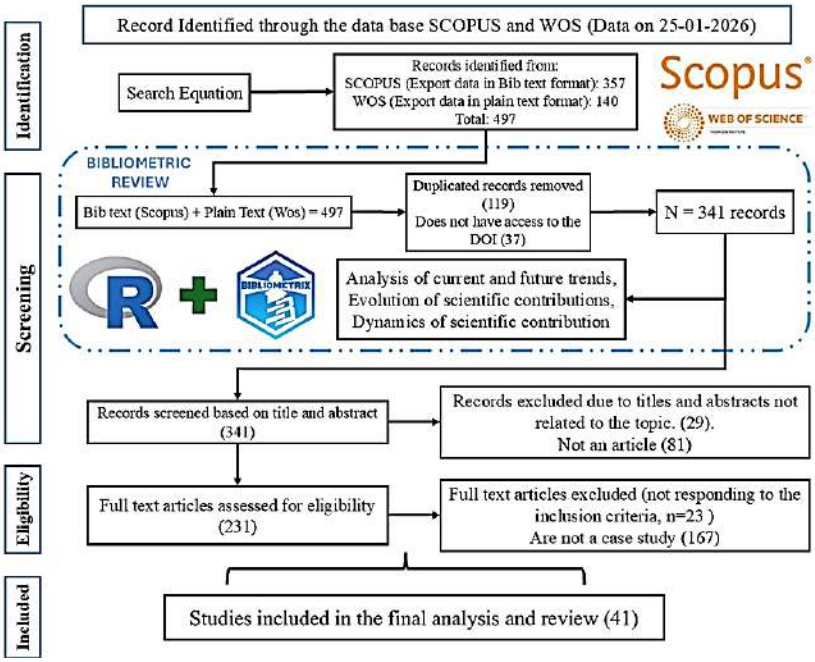

Fig. 3: Flowchart of the PRISMA-based methodology used for systematic review and bibliometric analysis

The search equations were structured using the keywords “sustainability indicators” and “spatial analysis,” along with their respective synonyms. To maximize the precision and relevance of the retrieved literature, Boolean logic was applied throughout the search strategy. Specifically, the Boolean operator OR was used to connect synonyms within each category, whereas the Boolean operator AND was used to intersect different search clusters (Table 1). The bibliographic search covered the period from 1998 to 2025, identifying early conceptual developments in spatial sustainability indicators and their methodological evolution, ensuring representation of both foundational and recent contributions. While omitting supplementary databases (e.g., Google Scholar, IEEE Xplore, and regional repositories) alongside grey literature may limit the review's overall comprehensiveness, this restriction was deliberately imposed to ensure methodological rigor, data quality, and study reproducibility. Additional keyword families were considered to enhance coverage, including geospatial indicators, land-use indicators, environmental indicators, spatial sustainability assessment, and territorial indicators. The literature search was executed across both databases on January 25, 2026, yielding a total of 497 articles (357 from Scopus and 140 from WoS). Subsequently, the retrieved records were exported in platform-compatible formats, utilizing BibTeX for Scopus and Plain Text for WoS (Yasin and Bacsi, 2025). Subsequently, these files were imported into RStudio, enabling efficient organisation and data cleaning for further bibliometric analysis (Yubo *et al.,* 2023). Data processing was carried out using a bibliometric approach that integrated RStudio, visualization of similarities viewer (VOSviewer), and Bibliometrix, enabling analysis of the dynamics of scientific production, the thematic structure of the literature, and emerging research trends in the field of geo-indicators. This procedure enabled the delineation of publication trends, thematic configurations, and epistemic networks, thereby offering a systematic view of the field's evolution and trajectory across diverse research domains over time (Kemeç *et al.,* 2023).

Table 1: Search strategy in Scopus and WoS for identifying articles related to spatial analysis and sustainability indicators

Search	Keywords and boolean operators
I. Spatial analysis	"GIS" OR "Spatial Analysis" OR "Geospatial Analysis" OR "Spatial Data Analysis" OR "Geographic Analysis" OR "Spatial Statistics" OR "Spatial Modeling" OR "Geographic Information Analysis" OR "Spatial Pattern Analysis" OR "Spatial Data Modeling" OR "Spatial Distribution Analysis" OR "Spatial Investigation" OR "Geostatistical Analysis" OR "Spatial Evaluation" OR "Spatial Examination" OR "Spatial Assessment" (The use of OR allows for including all possible synonyms for "Spatial Analysis")
II. Sustainability indicators	"sustainability indicators" OR "Sustainability metrics" OR "Sustainability measures" OR "Sustainability benchmarks" OR "Sustainability performance indicators" OR "Sustainability assessment criteria" OR "Sustainability evaluation indicators" OR "Sustainability indices" OR "Sustainability parameters" OR "Sustainability variables" OR "Sustainability criteria" OR "Sustainability standards" OR "Sustainability monitoring indicators" OR "Environmental performance indicators" OR "KPIs" OR " Key performance indicators " (The use of OR ensures the inclusion of various terms related to "Sustainability Indicators")
Final strategy	I and II (Combining both the spatial analysis and sustainability indicators searches for a comprehensive and precise search)

Screening

To ensure the relevance and methodological quality of the studies included in the review, inclusion and exclusion criteria were established (Costal *et al.,* 2021; Natvig *et al.,* 2025). The exclusion criteria comprised duplicate records, articles without digital object identifier (DOI) access, studies falling outside the designated timeframe, and non-peer-reviewed documents, such as technical reports or institutional publications. Additionally, works that did not address applied case studies or that did not meet the methodological requirements for territorial sustainability assessment were excluded. The initial screening process removed 119 duplicate records and 37 articles without a DOI, reducing the total to 341 articles. Subsequently, during the title and abstract screening phase, 29 articles were excluded due to a lack of direct relevance to geo-indicators in sustainability, while an additional 81 records were omitted because they did not constitute peer-reviewed academic research. Among the discarded articles were studies that, despite utilizing spatial analysis tools such as GIS, failed to explicitly address geo-indicators or their application in sustainability to territorial management. In general, these works focused on specific applications, such as optimizing logistics services or managing infrastructures through digital environments and three-dimensional visualization, without establishing clear links to sustainability assessment in its environmental, social, or economic dimensions (Alabbasi *et al.,* 2024; Labib and Watfa, 2023). Consequently, these studies were deemed to fall outside the thematic and methodological boundaries established for this review.

Eligibility

During the eligibility assessment phase, the remaining 231 articles were reviewed to ensure they met the previously established inclusion criteria. This stage entailed a critical evaluation of the full-text articles, prioritizing three analytical dimensions: the underlying methodology, the specific geo-indicators evaluated, and the geographical context of the studies. The methodology was assessed to ensure that the studies employed rigorous scientific approaches, while the geo-indicators were analyzed to ensure they were appropriate and aligned with the environmental, social, and economic dimensions of sustainability. To ensure practical relevance, the inclusion criteria mandated that the literature consist of applied research set within appropriate geographical contexts, spanning both urban and rural landscapes. The filtering process excluded 167 studies that did not use case studies, limiting their relevance to the practical approach of this review. This decision was made to ensure methodological comparability across empirical applications of geo-indicators in real-world land-use contexts. Furthermore, 23 articles were excluded on the basis that they failed to

adequately address the application of geo-indicators within a land-use sustainability framework. Finally, 41 articles were selected that met all the inclusion criteria. These studies were considered methodologically sound, as they provide relevant empirical evidence on the application of geo-indicators in sustainable territorial management. The exclusion process followed predefined PRISMA criteria to ensure methodological rigor, reproducibility, and relevance to the research objectives. To maintain a highly consistent and comparable dataset, strict exclusion criteria were applied; specifically, the review omitted theoretical papers without empirical applications, studies omitting GIS methodologies, and research failing to evaluate geo-indicators across environmental, social, or economic dimensions of sustainable land use.

Dataset design and methodological separation between bibliometric and systematic review analyses

The relationship between the datasets used in this study is clarified to ensure methodological transparency. A total of 497 records were initially retrieved from Scopus and Web of Science for bibliometric analysis. After data cleaning and preprocessing in RStudio, 421 publications were retained for bibliometric analysis to ensure data quality and consistency. From this same initial dataset, a PRISMA-based screening process was applied to identify relevant empirical studies, resulting in 41 articles selected for the systematic review. Consequently, the bibliometric analysis and systematic review serve as complementary yet distinct dimensions of this study: the bibliometric dataset elucidates macro-level publication trends and scientific mapping, while the systematic review dataset facilitates a granular, qualitative evaluation of geo-indicator applications in land-use sustainability.

Systematic review studies

Finally, 41 studies were included in the systematic review, selected after a rigorous evaluation to ensure they met all the established inclusion criteria. The included studies addressed the application of geo-indicators in assessing land-use sustainability across environmental, social, and economic dimensions. Furthermore, all selected articles utilized empirical case studies, thereby facilitating a comparative analysis of geo-indicator applications across diverse territorial contexts. This final sample provided a diverse and representative empirical basis, enabling a comprehensive analysis of the application of geo-indicators in sustainable territorial planning in a variety of contexts.

Analysis of the PRISMA systematic review

A methodological evaluation of the selected studies was conducted, considering the study design, the validity of the geo-indicators used, and the quality of the data employed. A qualitative quality assessment was applied to ensure methodological coherence, focusing on the robustness of study design, clarity in geo-indicator application, data quality, and relevance to land-use sustainability contexts. While a formal quantitative risk-of-bias scoring system was not deployed, study quality was rigorously appraised using uniform qualitative criteria to guarantee dataset reliability. This process helped identify potential selection and publication biases, while the information analysis was developed through a qualitative synthesis aimed at recognizing patterns in the use of geo-indicators to assess land-use sustainability across different territorial contexts. Additionally, several variables were analyzed to systematically characterize the reviewed studies. Specifically, the data extraction protocol captured the DOI to guarantee publication traceability, the country of origin to evaluate regional distribution, and the geographical scale of application—categorized into urban or rural environments. Furthermore, the studies were classified by the sustainability domains they addressed (environmental, social, and economic). On the methodological side, the spatial analysis methods and GIS tools used, such

as ArcGIS and QGIS, were examined to assess the precision of the construction of the geo-indicators. The degree of integration between GIS and sustainability indicators was analyzed, categorised into low, medium, or high levels, enabling evaluation of how spatial data is linked to sustainability metrics. By tracking these variables, this study establishes a rigorous literature profile that maps methodological configurations, regional approaches, and critical research gaps in the deployment of geo-indicators for sustainable territorial governance (Table 2). To address the predominantly descriptive nature of previous geo-indicator reviews, this study provides a structured quantitative synthesis of the literature. The bibliometric analysis quantifies scientific production trends over time, identifies thematic clusters based on keyword co-occurrence, and maps collaboration networks at the country level. In addition, geo-indicator applications were systematically classified according to sustainability dimensions (environmental, social, and economic), GIS methodologies, and spatial scales. Consequently, this integrated methodology transitions from a purely narrative synthesis to an objective, quantitative evaluation of geo-indicator research, enhancing the analytical rigor and reproducibility of the findings. Finally, the study selection process was represented using the PRISMA diagram, which transparently shows the different filtering stages and the 41 articles included in the review, ensuring the rigour, transparency, and reproducibility of the study.

Scientific contribution dynamics

Scientific production on geo-indicators applied to land-use sustainability shows a growth trend from 1998 to 2025, totalling 421 publications. As illustrated in Fig. 4, the temporal evolution of publication productivity follows an exponential trajectory (R^2 ~ 0.88). This strong coefficient of determination confirms the steady consolidation of the discipline and underscores its accelerating relevance within territorial sustainability and land-use planning across diverse contexts worldwide**.** The analysis identifies three evolutionary periods. The emergence period (1998–2008) is characterized by limited scientific production, averaging fewer than four articles per year and representing approximately 8% of total publications in isolated peaks. Although initially constrained in analytical scope, the early integration of GIS and multicriteria decision-making techniques in agricultural, forestry, and rural planning provided the foundational methodology for developing spatiotemporally comparable geo-indicators (Boers and Cottrell, 2007; Tiwari *et al*., 1999) (Graymore *et al.,* 2009; Sheppard, 2011). The consolidation period (2009–2017) shows sustained growth, with 8–18 publications per year (34% of total output), reflecting methodological and conceptual maturation. This stage is characterized by thematic diversification and the transition toward integrated approaches. In the environmental dimension, spatial modelling and territorial dynamics predominate, focusing on biomass estimation, bioenergy planning, and urban impact assessment (Sahoo *et al.,* 2016). In the social dimension, indicators of habitability and quality of life are incorporated into transport planning and residential design (Miller *et al.,* 2013). From an economic standpoint, these metrics serve to reconcile productive efficiency with territorial equity throughout both urban and rural frameworks (Xu and Coors, 2012). The expansion period (2018–2025) exhibits the highest scientific dynamism, with a marked increase since 2020 and a peak in 2025 (59 publications). This expansion is propelled by the global sustainability agenda, climate change imperatives, and territorial resilience demands, coupled with the burgeoning availability of multi-source geospatial datasets and advanced analytical technologies. Recent studies integrate environmental, social, and economic dimensions, extend temporal horizons, and develop geo-indicators for scenario analysis, water management, food security, urban sustainability, and climate risk assessment (Amini *et al.,* 2020; Duan *et al.,* 2021). This expansion is

Table 2: Analytical variables used for the systematic evaluation of geo-indicator studies

Variable	Operational description
DOI	Unique digital identifier of the analyzed article.
Country	Country or countries where the study was conducted.
Scale	Territorial level of the spatial analysis, such as local, municipal, regional, national, continental, or global.
Sustainability domain	Sustainability dimension addressed by the study: environmental, social, economic, or institutional.
Spatial analysis methods used	Spatial analysis methods applied in the study.
Sustainability indicator	Indicator, index, or metric used to assess sustainability.
GIS tools	GIS software, platform, or geospatial environment used.
GIS Integration–Indicators	Degree of integration between GIS and sustainability indicators: low, medium, or high.
Type of spatial data	Type of spatial data used, such as vector, raster, remote sensing (RS), census, administrative, or field data.
Temporal approach	Way in which the study incorporates the temporal dimension, such as cross-sectional, longitudinal, multitemporal, or time-series analysis.

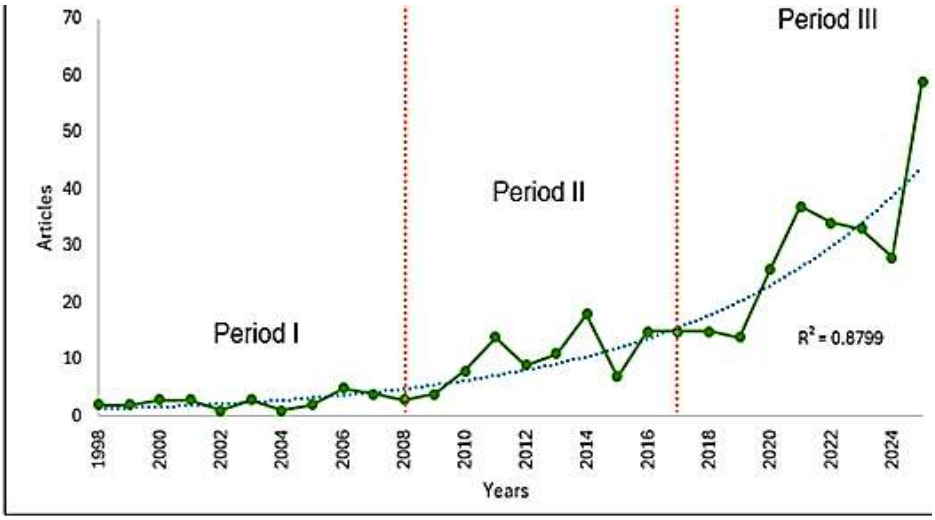

Fig. 4: Temporal dynamics of scientific production in studies of indicators for territorial management sustainability (1998 - 2025)

also supported by advances in geospatial computing, which have evolved significantly since the 1992 Rio Earth Summit and the subsequent adoption of the UN SDGs. Recent advancements in computational capacity for handling high-volume geospatial and socio-economic data have paved the way for more dynamic, multi-dimensional territorial assessments.

International scientific collaboration

The global scientific collaboration network (Fig. 5) shows that China (11.03%), the USA (10.06%), and Italy (7.63%) are the main centres of scientific production in land-use sustainability research. These countries serve as central nodes, underscoring their strategic importance in global knowledge production and international collaboration. Spain shows notable output but mainly regional collaboration within Europe. Australia and England function as bridges between Asia and North America, facilitating methodological and conceptual transfer in territorial monitoring. Egypt, Iran, and Canada show lower production but maintain collaboration mainly with the USA, indicating a dependent cooperation pattern. Overall, the research

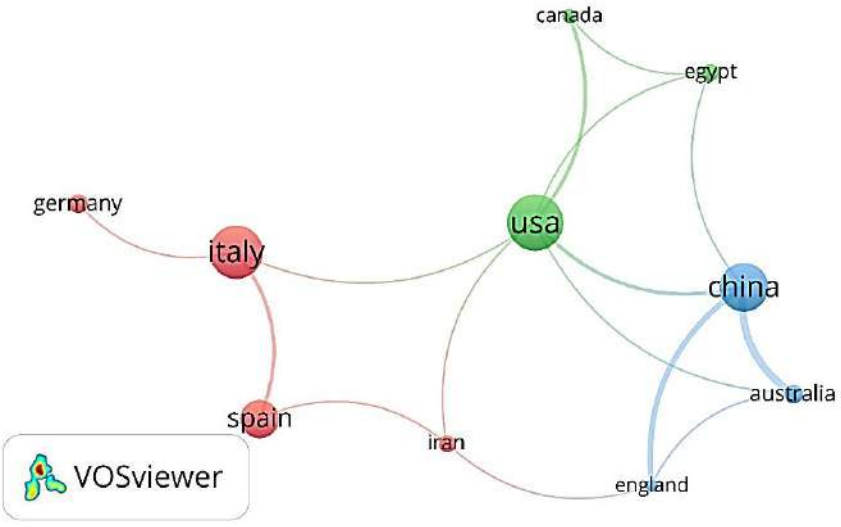

Fig. 5: Global scientific collaboration network in land use indicators and sustainability studies

network exhibits a pronounced dominance by the Global North, whereas developing nations remain significantly underrepresented within the literature on geo-indicator and territorial sustainability research.

Thematic structure and current orientation: current trends

The keyword co-occurrence analysis identifies three thematic clusters structuring scientific production on the environmental, social, and economic sustainability of land use. As illustrated in Fig. 6, the keyword co-occurrence network delineates the primary thematic trajectories and research trends dominating sustainable territorial management literature. The red cluster, associated with environmental impacts and sustainability, reflects a strong focus on the environmental dimensions of land use and energy transition. Keywords such as sustainability, biodiversity, landscape, challenges, and impacts highlight tensions between energy development and ecosystem conservation. Bioenergy has emerged as a prominent sector within renewable energy research, triggering critical debates regarding biodiversity depletion, landscape alteration, and multifaceted sustainability trade-offs. These findings emphasise the link between sustainable territorial management and the environmental and social impacts of energy systems. Characterized by its focus on methodologies and decision-support systems, the green cluster underscores the pivotal role of GIS in embedding spatial data within planning frameworks. The co-occurrence of model, optimisation, management, AHP, and renewable energy indicates a shift towards multicriteria and optimisation approaches in resource and energy management. GIS is no longer limited to cartographic representation but functions as an analytical tool for scenario evaluation and prioritisation of territorial alternatives. This underscores the imperative for robust geo-indicators to operationalize sustainability within public policy frameworks and localized initiatives. The blue cluster, linked to urban planning and sustainable development, includes terms such as urban planning, land use, and city, highlighting the practical application of sustainability in territorial planning. It reflects growing interest in how urbanisation, expansion, and land-use change affect territorial balance. The trend highlights the necessity of incorporating environmental, social, and economic indicators into urban planning to

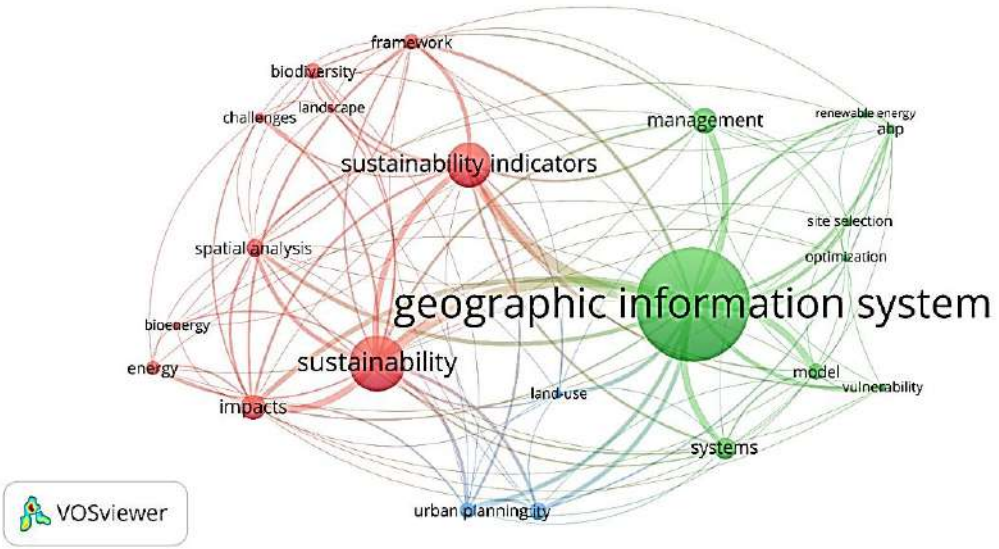

Fig. 6: Keyword co-occurrence map in the literature on sustainability and territorial management

foster more resilient cities, signifying a shift from theoretical development to practical application in territorial management through integrated, data-driven, and participatory approaches**.**

Conceptual evolution and emerging lines

The bibliometric thematic map reveals the conceptual structure of the research field on indicators and land use sustainability (Fig. 7). In the motor themes quadrant, renewable energy and land use planning emerge as pivotal driving forces, bridging environmental sustainability and territorial planning strategies. In the basic themes' quadrant, GIS analysis and multi-criteria methods emerge as structural elements in spatial modelling, scenario simulation, and sustainability assessment. Emerging computational frameworks artificial intelligence (AI), machine learning (ML), cloud computing platforms, and GEE significantly optimize geo-indicator-based sustainability assessments. By refining spatial pattern recognition and facilitating enabling large-scale remote sensing data processing, these technologies elevate the efficiency, scalability, and reproducibility of geospatial workflows beyond the capabilities of traditional GIS architectures. Their integration with GIS-based frameworks indicates a growing reliance on advanced computational methods and spatial data analytics for generating robust geo-indicators. These methodologies bolster the objectivity of territorial planning and facilitate a transition toward predictive modeling for sustainable land management. Niche topics, such as land-use monitoring and Bayesian networks, exhibit a high level of internal development, though they are less connected to the rest of the field. Their future evolution could focus on integrating probabilistic models and machine learning techniques to improve the predictive capabilities of territorial models and the accuracy of simulated land-use change scenarios. Finally, environmental indicators and climate adaptation within transition zones constitute burgeoning areas of academic inquiry. This trend anticipates the field's evolution toward integrating territorial planning, scenario analysis, and climate change adaptation, consolidating geo-indicators as key tools for sustainable territorial management and evidence-based decision-making through interdisciplinary collaboration, geospatial analytics, stakeholder engagement, policy integration, and monitoring frameworks across regions.

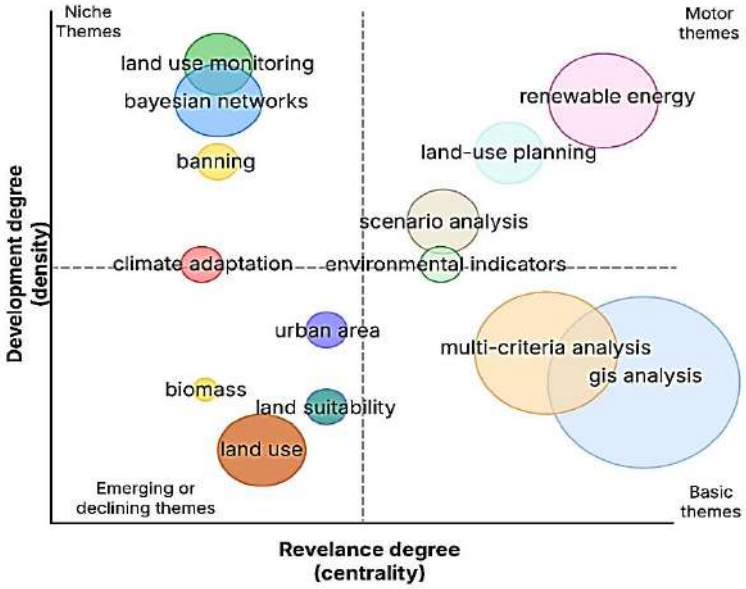

Fig. 7: Bibliometric thematic map of emerging research lines

Systematic review

The systematic review identified 41 studies on geo-indicators of environmental, social, and economic sustainability associated with LULC. These studies were developed across various geographical contexts, including Indonesia, Ecuador, Turkey, China, Egypt, Iran, and Mexico, and cover both urban and rural environments. To map the complexities of territorial sustainability, existing research deploys a broad spectrum of geo-indicators that targeted environmental quality, infrastructure layout, energy efficiency, and public service accessibility.

Prevalence of GIS methods in the study of sustainability geo-indicators

A principal finding of this review underscores the definitive prominence of GIS-based frameworks in synthesizing spatial datasets and executing geospatial analysis of geo-indicators (Fig. 8). In most case studies, these tools enable the integration of geographic information, socio-environmental data, and geoprocessing processes to assess territorial sustainability (Apostolopoulos and Nikolakopoulos, 2021). Among the platforms used, ArcGIS stands out as the most commonly employed tool, although other environments such as TerrSet were also identified, along with decision support methods, including the AHP and fuzzy logic (Chen *et al.,* 2025). Integrating geo-indicators into these platforms facilitates the detection of spatial configurations in land use, thereby aiding in the identification of priority zones for sustainable territorial planning (Jiménez-Espada *et al.,* 2023).

Integration of environmental, social, and economic geo-indicators in sustainable territorial planning

The analysis presented in Table 3 corroborates these findings, identifying critical geo-indicators that drive sustainable territorial management, specifically territorial expansion, biodiversity impacts, composite sustainability indices, and metrics governing agriculture, water, energy, and coastal systems. These indicators reflect the link between land-use planning and objectives such as social equity, balanced regional development, and

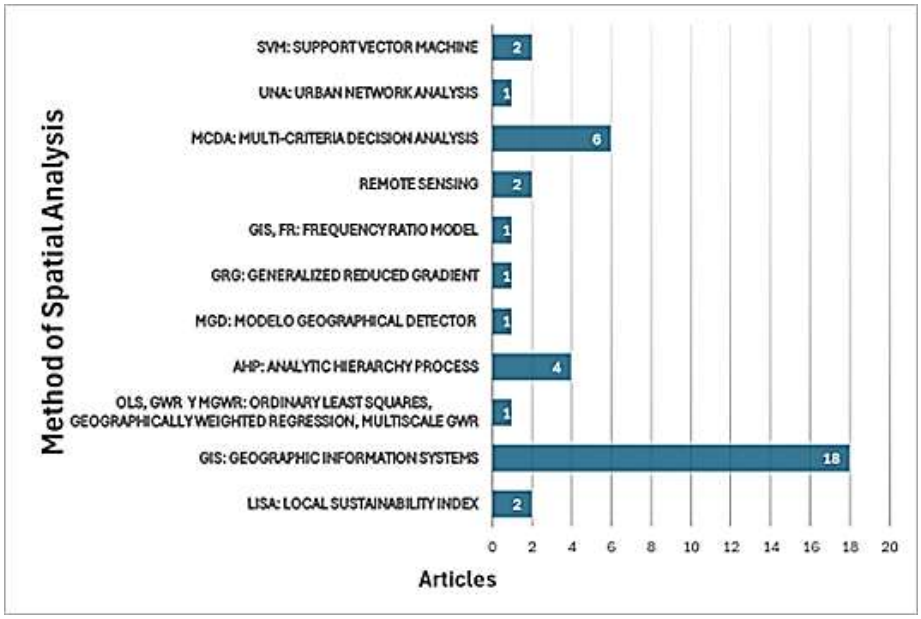

Fig. 8: Distribution of spatial analysis methods in sustainability geo-indicator studies (Analysis of published articles)

Table 3: Geo-indicators for land use sustainability: Impact on territorial management and case studies

Type of geo-indicator (Social = 1, Environmental = 2, Economic = 3)			
Geo-indicator	Impact on sustainable territorial management	Case study	Citation
Territorial expansion	Social equity[1,2]	Socio-spatial aspects and social sustainability	(Akcali and Ispalar Cahantimur, 2023)
	Regional development[3]	Sustainability and spatial heterogeneity in urban agglomerations	(Zhou *et al.*, 2021)
	Sustainable urban optimization[1]	Sustainable urban land-use optimization using multi-criteria decision making (MCDM)	(Arsanjani *et al.*, 2022)
	Expansion control[1]	Methodological approach to sustainable urban densification	(Abdrabo *et al.*, 2021)
	Urban renewal[1]	Analysis of urban spatial compactness and land use mix	(Liu *et al.*, 2023)
	Optimization of urban resources[2]	Spatial decision support for low-carbon cities	(Pignatelli *et al.*, 2023)
	Sustainable urban development[1]	Urban sustainability indicators based on urban grain	(Zhao *et al.*, 2023)
Impact on biodiversity	Interregional balance, social costs[1,2]	Managing spatial sustainability trade-offs in wind power	(Lehmann *et al.*, 2021)
Territorial sustainability index	Sustainable regional development[1,2]	Local sustainability and spatial interdependency	(Pravitasari *et al.*, 2022)
	Urban planning[1,2]	Urban sustainability and fabric typologies	(Calderón *et al.*, 2024)
	Improvement of environmental quality[2]	Optimal weights for urban sustainability	(Vyas *et al.*, 2022)
	Balanced development[1,2]	Spatial analysis of urban sustainability	(Shen and Guo, 2014)
	Sustainable urban development[1,2]	Integrating System Dynamics, GIS, and 3D in urban sustainability	(Xu and Coors, 2012)
	Urban design[1]	Spatial configuration's role in social sustainability and urban density	(Soltani *et al.*, 2022)
	Land use optimization[1,2]	Quantifying sustainability trade-offs in land use	(Bouman *et al.*, 1999)
Rural landscape	Improvement of rural sustainability[2]	Association between multichannel landscape features and rural sustainability	(Meng *et al.*, 2024)

Agricultural sustainability	Agricultural sustainability[2,3]	Energy analysis for sustainability of potato agroecosystems	(Shahhoseini *et al.,* 2022)
	Improves productivity[2]	Land suitability and agricultural sustainability assessment	(Amini *et al.,* 2020)
	Ecological conservation[2]	Geospatial analysis of the federal maritime zone	(Pérez Valdez *et al.,* 2021)
	Risk reduction[2]	GIS-based biomass assessment for sustainable biorefinery	(Sahoo *et al.,* 2016)
	Land management[1,2]	Sustainability indicators for agricultural land use	(Mohamed *et al.,* 2014)
	Food security and climate adaptation[2]	Economic evaluation of crop production in the Ganges region under climate change	(Singh and Dhadse, 2021)
	Land use optimization[1,2]	Framework for analyzing sugarcane agroindustry sustainability	(Aguilar-Rivera, 2019)
	Improvement of agricultural production[2]	Sustainability of wheat production in southwest Iran: Fuzzy-GIS evaluation	(Houshyar *et al.,* 2017)
Coastal sustainability	Territorial planning[2]	Sustainability index for urbanized coasts	(Martínez *et al.,* 2020)
	Risk reduction[1]	Coastal cities and sustainability	(Luengo, 2020)
	Coastal planning[1,2]	Ranking sustainable areas for tidal power plants	(Progênio *et al.,* 2020)
	Integrated coastal management[2]	Coastal sustainability analysis	(Tran *et al.,* 2024)
Infrastructure sustainability	Infrastructure optimization[1]	Automated sustainability assessment of infrastructure using GIS and RS	(Aguilar-Rivera, 2019)
	Road network optimization[1]	Sustainability evaluation of the forest road network using multi-criteria evaluation (MCE)	(Long *et al.,* 2023)
Resource sustainability	Resource optimization[2]	Resources time footprint analysis of wind turbines	(Huang *et al.,* 2023)
Ecological sustainability	Improvement in decision-making[1,2]	Sustainability criteria and cost-benefit analysis: a decision-making framework	(Tiwari, 2000)
Energy sustainability	Resource optimization[1,2]	GIS framework for optimal location and size of biomass energy plants	(Jayarathna *et al.,* 2020)
Water sustainability	Water sustainability[2]	Index-based groundwater sustainability assessment	(Majidipour *et al.,* 2021)
	Improvement of agriculture[2]	Environmental and institutional impacts of tidal river management	(Salam *et al.,* 2021)
	Water resource management[1,2]	Methodology for assessing aquifer sustainability	(Instituto Mexicano de Tecnología del Agua *et al.,* 2023)
	Space use optimization[1]	Geo-spatial multi-criteria evaluation of wave energy in a semi-enclosed sea	(Şan *et al.,* 2021)
	Water use efficiency[2]	Synthetic indicator for sustainability of water resources in agriculture	(Picone *et al.,* 2021)
	Water resource management[2]	Rural water sustainability index (RWSI): a multicriteria and participative approach	(Crispim *et al.,* 2021)

sustainable optimization of urban resources. Geo-indicators such as urban expansion control and renewal contribute to regional development and territorial planning. The use of GIS tools (e.g., ArcGIS and TerrSet) enables more accurate spatial analysis and supports evidence-based decision-making by adapting geo-indicators to specific territorial contexts. This underscores the imperative for unified methodological frameworks to bolster sustainability-oriented territorial management.

Global distribution of GIS tools and application contexts

Fig. 9 illustrates the geographical distribution of the studies included in this systematic review, alongside the specific GIS software platforms utilized across the respective studies. The results reveal that ArcGIS and TerrSet are the most commonly used platforms, although some studies incorporate specific spatial analysis methods, such as ordinary Kriging, and models, such as TRM (Taiwo *et al.,* 2023).

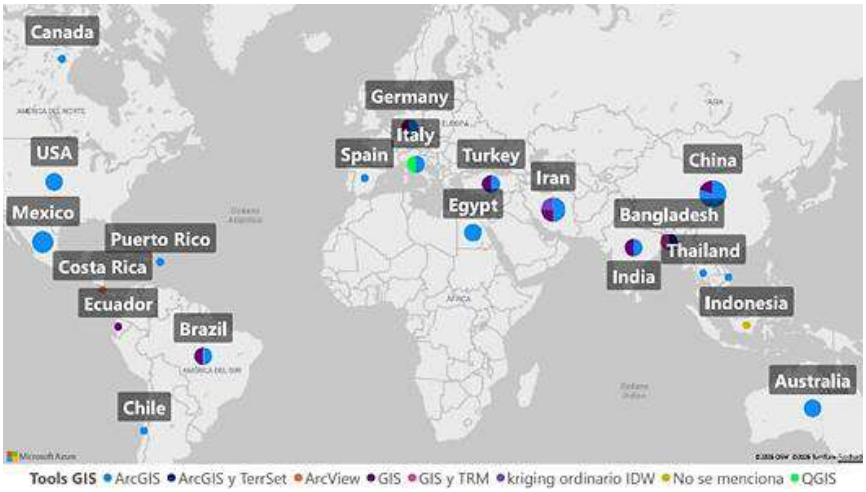

Fig. 9: Geographical distribution of studies on sustainability geo-indicators and the GIS tools used in land use management analysis

The analyzed cases cover a wide variety of territorial contexts, ranging from urban studies in countries such as Mexico, Ecuador, India, and Bangladesh to research conducted in rural areas of Iran and China. This methodological and geographical variations observed across the literature demonstrate that while analytical tools must remain sensitive to local contextual nuances, there is a critical need for unified frameworks capable of cross-referencing environmental, social, and economic geo-indicators (Nagavi *et al.,* 2024).

Identified gaps in literature

This review identifies the absence of a common conceptual framework integrating geo-indicators across environmental, social, and economic dimensions of sustainability. Most studies adopt partial approaches, limiting the understanding of interactions among territorial systems and revealing a significant gap in the literature. This highlights the need for holistic and interdisciplinary frameworks that unify geo-indicators for sustainable territorial planning. Data temporality is another key limitation, as standardized geo-indicator systems are constrained by geographic, institutional, and socioeconomic disparities. Discrepancies between contemporary and legacy datasets compromise the representativeness of geo-indicators, particularly in regions undergoing rapid territorial transformation and acute climate pressures (Mitrică *et al.,* 2021). This underscores the need for updated databases and continuous monitoring systems. Overall, integrated geo-indicator frameworks enable more robust and evidence-based territorial planning than fragmented approaches.

Comparative synthesis of geo-indicators in land use sustainability studies

Fig. 10a synthesizes the conceptual structure of the studies using spatial scale, sustainability domain, indicator type, and spatial data type. Most studies in industrialised countries (60–70%; USA, Canada, Australia, Spain, Germany) focus on national or regional scales, while nearly 50% of studies in middle- and low-income countries (Bangladesh, Iran, Egypt, Mexico) focus on local or urban scales. In terms of sustainability dimensions, about 65% of studies in developed countries integrate environmental, social, and

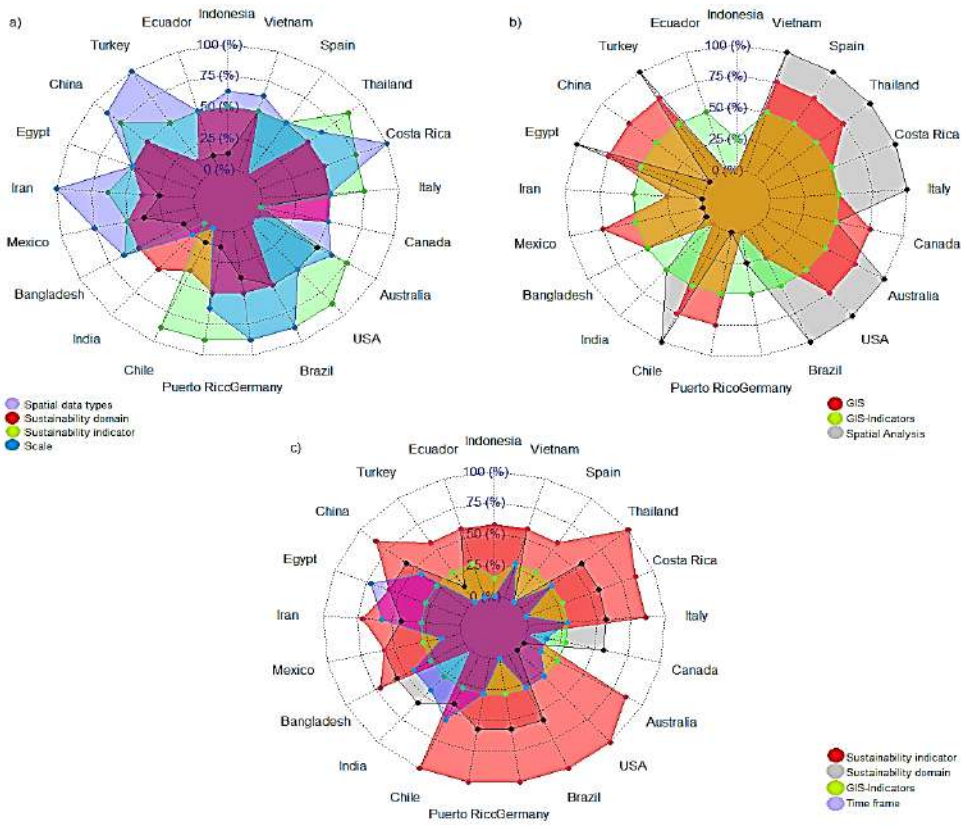

Fig. 10: Integrated Analysis of Indicator Studies. (a) General characterization of the studies, (b) application of spatial methods, and (c) impact and use of geo-indicators

economic aspects, whereas studies in China, Turkey, and Bangladesh are mainly environmental. A corresponding trend manifests across indicator categories, where integrated metrics predominate within developed frameworks (40–60%) whereas environmental or production-oriented indicators remain prevalent in other contexts. Multi-source spatial data is more frequently used in regions with advanced geospatial capacity (30–40%), while other contexts rely mainly on land-use, infrastructure, or RS data.

Fig. 10b reveals significant differences in methodological development based on GIS use, GIS–indicator integration, and spatial analysis methods. Approximately 40–50% of studies in developed countries deploy advanced or hybrid GIS environments, whereas the vast majority of studies in Latin America, Asia, and Africa continues to rely on foundational GIS platforms. A similar pattern appears in GIS–indicator integration, with around 60% of studies in Europe and North America showing high integration levels, compared with less than 20% in Asian and African contexts. Regarding spatial methods, the USA, Australia, and Canada apply predictive models, simulations, and econometric techniques such as Geographically Weighted Regression (GWR) and Multiscale Geographically Weighted Regression (MGWR) (30–40% of studies), whereas Bangladesh, Iran, and Egypt mainly use descriptive spatial analysis or basic multicriteria methods. Correspondingly, Fig. 10c integrates the temporal

dimension of the studies, illustrating significant variations in the analytical depth of the deployed geo-indicators. About 40% of studies in North America and Europe use time series longer than 20 years or include projections, whereas over 70% of studies in countries with lower institutional capacity rely on short time series (<5 years) or do not specify temporal coverage. This gap limits the ability to model long-term territorial dynamics, anticipate future scenarios, and develop geo-indicators for strategic planning. The escalating deployment of geo-indicators underscores the demand for spatially explicit instruments that integrate environmental, social, and economic data, sustained by robust spatial data infrastructures and advanced geospatial analysis (Ahamede and Atumane, 2021). However, the literature remains fragmented, with environmental indicators dominating and social and economic indicators less developed (Maynard *et al.,* 2020). This highlights the need for integrated geo-indicator frameworks to better represent the multidimensional nature of sustainability in territorial planning.

Integration of social and economic dimensions in land use sustainability indicators

A key challenge in land-use sustainability indicators is the dominance of environmental metrics over social and economic dimensions, limiting their ability to capture territorial complexity. Evidence shows that sustainability requires integrating environmental, social, and economic variables for holistic assessment (Malmir *et al.,* 2021). Socio-ecological studies integrate social acceptability and economic viability into spatial models, underscores the critical functions of infrastructural development and credit access in fostering territorial sustainability (Chrisendo *et al.,* 2026; Jiang *et al.,* 2022). Social sustainability research further emphasizes the importance of cultural and socioeconomic factors such as participation and equity (Hellberg, 2023). However, these dimensions remain underrepresented in operational systems, revealing a gap between theory and practice. This uneven development reflects differences in national capacities and indicator production histories. Consequently, the prevailing literature advocates for integrated frameworks that harmonize environmental, social, and economic dimensions to underpin robust geo-indicators tailored for policy formulation and territorial planning. Strengthening consolidated data infrastructures is also essential for improving comparability and validation of indicators.

Limitations of geospatial data and quality for sustainability geo-indicators

The quality and temporal resolution of geospatial data pose a critical challenge for developing reliable geo-indicators to assess land-use sustainability, as measurements based on discontinuous or low-resolution data can yield inaccurate or unrepresentative estimates of real processes (Jiménez-Espada *et al.,* 2023). For instance, urban-scale investigations utilizing GIS and spatial datasets frequently observe that constraints on the availability of open-access, contemporary data restrict both granular spatial analysis and for temporal longitudinal comparisons necessary for rigorous land-use change monitoring (Jiménez-Espada *et al.,* 2023). Furthermore, contemporary literature on geoinformation highlights that different types of satellite data have valuable applications but also present inherent limitations in spatial resolution, temporal frequency, and uniform coverage, which directly affect the accuracy of the indicators generated. These constraints compromise not only ecological and environmental estimates but also the incorporation of socioeconomic variables, which frequently rely on legacy administrative or

census data alongside geospatial imagery (Raffay *et al.,* 2025). Consequently, enhancing the quality, temporal consistency, and accessibility of geospatial data is a necessary methodological step for reinforcing the geo-indicators employed in land use sustainability studies and ensuring that they accurately represent genuine patterns instead of artefacts resulting from incomplete or low-resolution data (Jiménez-Espada *et al.,* 2023).

CONCLUSION

This study demonstrates that geo-indicators are a key approach for assessing land-use sustainability from a spatial perspective. The bibliometric analysis highlights the growing relevance of spatial data, GIS, and advanced modelling techniques in territorial sustainability research. The integration of geo-indicators with spatial analysis tools facilitates the detection of environmental pressures, socio-economic dynamics, and land-use configurations, thereby underpinning evidence-based territorial planning. The systematic review shows that most geo-indicator applications rely on GIS-based methodologies combined with multicriteria decision analysis, spatial modelling, and scenario simulation techniques. These methodologies facilitate the integration of heterogeneous datasets, thereby enabling multi-scalar sustainability assessments. However, the environmental dimension predominates due to the superior availability and standardization of remote sensing and GIS-based datasets. Conversely, socio-economic data exhibit greater heterogeneous and lower spatial consistency, thereby constraining their integration into modelling frameworks.This imbalance highlights the need for more integrated frameworks that unify environmental, social, and economic dimensions into a coherent geo-indicator system. Data temporality and fidelity constitute critical determinants influencing the precision and operational applicability of geo-indicators, particularly amidst rapid territorial transformations and climate variability. A primary limitation of this study stems from its exclusive reliance on the WoS databases, which inherently introduces indexing bias and may omit relevant regional studies. Furthermore, systematic variations in language constraints, indicator definitions, spatial resolutions, and methodological frameworks restrict direct comparability and preclude the execution of a quantitative meta-analysis. Future research should focus on developing standardised geo-indicator frameworks supported by emerging technologies such as cloud-based geospatial platforms, remote sensing big data, and machine learning approaches. Strengthening interoperability, harmonising methodological standards, and promoting institutional collaboration are essential to enable large-scale implementation of geo-indicators for sustainable land-use planning.

AUTHOR CONTRIBUTIONS

D. Freire-Granda contributed to the conceptualisation, research, formal analysis, methodology, software, drafting of the original document, project management, and supervision. A. Velastegui-Montoya contributed to the study, methodology, and drafting of the original document. A.M. Meiguins de Lima contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. M. Adami contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. A.D. Ramirez contributed to the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision. P. Escandón-Panchana contributed to

the conceptualisation, research, methodology, drafting of the original document, revision and editing, project management, and supervision.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
AHP	Analytical hierarchy process
DOI	Digital object identifier
DPSIR	Driving forces–pressures–state–impact–response
ESPOL	Escuela superior politécnica del litoral
FR	Frequency Ratio
GEE	Google earth engine
GIS	Geographic information system
GIS-MCDM	Geographic information system–multi-criteria decision making
GIS-MCE	Geographic information system–multi-criteria evaluation
GRG	Generalized reduced gradient
GWR	Geographically weighted regression
JBMUR	Jakarta–bandung mega urban region
KPIs	Key performance indicators
LSI	Local sustainability index
LULC	Land use and land cover
MA	Millennium ecosystem assessment
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MCE	Multi-criteria evaluation
MGD	Geographical detector model
MGWR	Multiscale geographically weighted regression
OLS	Ordinary least squares
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
QGIS	Quantum geographic information system
RS	Remote sensing
RStudio	an integrated development environment for R programming

RWSI	Rural water sustainability index
SDGs	Sustainable development goals
SEEA	System of environmental-economic accounting
SVM	Support vector machine
UN	United Nations
WoS	Web of Science

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REVIEW ARTICLE

Minimizing the environmental impact of hospitals by focusing on carbon footprint reduction

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ABSTRACT

The environmental sustainability of hospitals is an increasingly critical issue globally, as healthcare systems are expanding rapidly, together with the growing concerns about climate change and depletion of resources. With healthcare systems expanding, the environmental impact of hospitals, particularly their carbon footprint, has become a critical concern. The study aimed to examine a range of approaches aimed at minimizing the environmental impact of hospitals, with an emphasis on reducing carbon footprints to pinpoint effective strategies and underscore areas where research is lacking. Following the Preferred Reporting Items for systematic reviews and meta-analysis guidelines, a comprehensive search was conducted across PubMed, SCOPUS, and Embase databases from January 1, 2018, to December 31, 2024. The study included 17 studies highlighting effective strategies for reducing hospitals' carbon footprints. Key interventions included integrating renewable energy sources, energy-efficient technologies, and sustainable procurement practices. Hospitals implementing these strategies have noted considerable declines in carbon emissions, with certain facilities realizing reductions of as much as 40 percent by incorporating renewable energy sources. Waste reduction strategies, such as improved segregation, recycling programs, and reducing single-use plastics, contributed to lower indirect emissions. Despite these successes, challenges such as high initial investment costs, limited technical expertise, and resistance to change were noted, particularly in low- and middle-income countries. Key strategies such as renewable energy adoption, energy-efficient technologies, and sustainable procurement have effectively reduced carbon emissions and enhanced operational efficiency. However, high upfront costs, technical gaps, and resistance to change, especially in low-resource settings, hinder widespread implementation.

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INTRODUCTION

The environmental sustainability of hospitals is an increasingly critical issue globally, as healthcare systems are expanding rapidly, together with the growing concerns about climate change and depletion of resources (Soares *et al.,* 2023; Cristiano *et al.,* 2024). Hospitals consume a substantial portion of energy, water and natural resource (Maden and Kerse, 2026; Eckelman and Sherman, 2016; Vallée, 2024; WHO, 2020), and produce large amounts of waste generation, contributing to greenhouse gas (GHG) emissions and resource depletion (Melnyk *et al.,* 2023; Alhamza *et al.,* 2026; Akman *et al.,* 2026). Pichler *et al.* (2019) reported that the healthcare sector generates the environmental emission similar in size to the entire aviation industry. As healthcare institutions strive to enhance patient care, the necessity for sustainable practices that reduce their environmental impact has become essential (Li *et al.,* 2025; MacNeill *et al.,* 2017). Research estimates suggesting that the UK's National Health Service (NHS) is responsible for 4-5 percent of total emissions (Pencheon and Wight, 2020), and the U.S. healthcare system accounts for about 9-10 percent (Eckelman *et al.,* 2018). Global organizations now treat healthcare decarbonization as a top public health priority (Ma *et al.,* 2022). The World Health Organization (WHO) identifies climate action in healthcare as the most significant health opportunity of the 21st century, urging hospitals to reduce emissions and withstand climate impacts (WHO, 2025). Although much of these figures primarily focus on high-income contexts, the environmental impact of hospitals is a global concern, affecting nations at all levels of economic development (Cimprich and Young, 2023). The environmental effects of hospitals encompass various domains, including energy consumption, water use, waste management, and sustainable procurement practices (Seifert and Guenther, 2019). Integrating sustainable practices within daily operations can lead to considerable environmental benefits, improve public health outcomes, and enhance economic efficiency (Han *et al.,* 2024). Sustainable hospital designs lower operational expenses and elevate patient care by enhancing indoor environments through a focus on hospital design, energy management, waste management, and promoting behavioral change (Borges de Oliveira *et al.,* 2021; Borges de Oliveira *et al.,* 2022; Mostepaniuk *et al.,* 2023). To make healthcare green, systems must require the multi-step approaches that reduces the energy (Karliner *et al.,* 2023; Braithwaite *et al.,* 2024), and water consumption (Potgieter *et al.,* 2020). The design of hospital architecture significantly influences their environmental footprint (Stevanovic *et al.,* 2019). Research has shown that sustainable building practices can significantly reduce energy consumption and improve efficiency. The direct consumption of energy significantly impacts the operating expenses of hospitals. By integrating renewable energy solutions such as solar panels and co-generation systems, hospitals can bolster their energy security and simultaneously decrease greenhouse gas emissions (Borges de Oliveira *et al.,* 2022). Waste management is also a crucial component, as hospitals generate vast amounts of waste, much of which is hazardous. Various studies (Hennessy *et al.,* 2021; Kooner *et al.,* 2020; Thiel *et al.,* 2019) showed that disposable plastics and their waste made up a huge part of a hospital's carbon footprint such as recycling and composting. Furthermore, implementing circular economy strategies can assist hospitals in minimizing waste production by enhancing resource management (Nematollahi *et al.,* 2025; Saha *et al.,* 2025; Alighardashi *et al.,* 2024). The engagement of healthcare professionals suggests that staff behavior significantly influences resource use, and training programs promoting sustainable practices among healthcare workers can lead to more responsible consumption patterns (Kalogirou *et al.,* 2021). Hospitals encounter various challenges and opportunities as they move towards becoming green hospital

(Koh *et al.,* 2025; Ibrahim *et al.,* 2025; Aboueid *et al.,* 2023). This transition involves the implementation of innovative designs, efficient energy usage, effective waste management, and fostering a culture among staff that can eliminate (Abubakar *et al.,* 2022; Firoozi *et al.,* 2024). Hence, there is a need to design sustainability strategies tailored to healthcare systems' needs and capacities globally. Data-driven identification of major emission sources, combined with proven, targeted solutions, enables significant carbon footprint reductions across healthcare systems. This approach allows organizations to move from identifying pollution hotspots to implementing effective, high-impact sustainability improvements and stakeholder engagement (Rodríguez-Jiménez *et al.,* 2023; Alicante *et al.,* 2026). This systematic review explores a range of techniques and methodologies for decreasing the environmental footprint of hospitals on a global scale by consolidating existing studies to pinpoint effective approaches and underscore gaps in the literature. This review strengthens efforts to improve hospital sustainability worldwide by synthesizing current knowledge and identifying key areas for further research. This study has been conducted in the ASEAN Institute for Health Development, Mahidol University, Thailand in 2026.

METHODOLOGY

Guidelines

The review protocol was not registered with International Prospective Register of Systematic Reviews (PROSPERO), as the registry only accepts systematic reviews with health-related outcomes (Moher *et al.,* 2015). Preferred reporting items for systematic review and meta-analysis (PRISMA) checklist was conducted and is presented in Table 1 (Page *et al.,* 2021). Although the non-health focus precluded PROSPERO registration, methodological concern was maintained through a structured research question, a comprehensive multi-database search strategy, and standardized study selection procedures. The mixed methods appraisal tool (MMAT) was applied to evaluate the quality of the selected studies (Hong *et al.,* 2018).

Search strategy

Relevant peer-reviewed journal publications were identified via a comprehensive database search of PubMed, SCOPUS, and Embase spanning January 1, 2018, to December 31, 2025 because this review included publication sources under 10 years to gather relevant, up-to-date data without exceeding practical research limits (van der Braak *et al.,* 2020). These databases were extensively employed in academic research, offering thorough, multidisciplinary coverage across both the social and natural sciences (Álvarez Jaramillo *et al.,* 2019; Parmentola *et al.,* 2022). To ensure data credibility, the literature search was confined to peer-reviewed journals, using the specific search terms detailed in Table 1. This methodology ensured data quality by focusing exclusively on rigorous, academic literature. The designated tracking window was deliberately chosen to analyze contemporary advancements in mitigating the environmental impact of healthcare institutions. Descriptors for the search terms "Approaches," "Environmental Impact Reduction," and "Hospital" were created to facilitate a comprehensive review of relevant literature. To ensure a comprehensive retrieval of relevant literature and minimize the risk of omitting vital data, tailored search strategies were deployed across PubMed, SCOPUS, and Embase.

Eligibility criteria of the studies

The review's inclusion criteria were established using the population, intervention, comparison, and outcome (PICO) framework (Eriksen and Frandsen, 2018) and are itemized in Table 2. Studies eligible for inclusion in this systematic review were required to meet the established review criteria: a) Population: The environmental impact of hospitals caused by waste, energy use, and resource consumption; (b) Intervention:

Table 1: Search strategy adopted for systematic review

Search terms	Descriptors
1. Approaches	Approaches OR "strategies" OR "practices" OR "measures" OR "methods" OR "techniques" OR "solutions" OR "initiatives" OR "actions" OR "programs" OR "plans" OR "policies" OR "procedures" OR "frameworks" OR "models" OR "guidelines" OR "systems" OR "mechanisms" OR "processes"
2. Environmental Impact Reduction	"Sustainability" OR "green practice" OR "energy efficiency" OR "waste reduction" OR "carbon footprint reduction" OR "CO2 emissions reduction" OR "resource conservation" OR "eco-friendly practices" OR "low-impact technologies" OR "renewable energy adoption" OR "water conservation" OR "carbon neutrality" OR "waste management" OR "green initiatives" OR "eco-sustainability" OR "climate action" OR "environmental footprint reduction" OR "circular economy" OR "eco-efficiency" OR "green technologies" OR "sustainable procurement" OR "pollution reduction" OR "environmental protection"
3. Hospital	"Healthcare facility" OR "medical institution" OR "clinical setting" OR "health institution" OR "healthcare organization" OR "hospital setting" OR "patient care facility" OR "acute care hospital" OR "hospital environment" OR "healthcare system" OR "public hospital" OR "private hospital" OR "medical center" OR "hospital infrastructure" OR "healthcare building" OR "clinical environment" OR "hospital staff" OR "hospital administrators" OR "hospital managers"
Combination	#1 AND #2 AND #3

Table 2: The inclusion and exclusion criteria of review process for studies selected.

Items	Inclusion criteria
Population	The environmental impact of hospitals caused by waste, energy use, and resource consumption.
Intervention	Strategies or interventions to reduce environmental impact
Comparison	Hospitals without interventions or using traditional practices have a higher environmental impact.
Outcome	Reduction in environmental impact, energy consumption, carbon footprint, waste reduction, improved resource efficiency, sustainability certifications, cost savings, improved health outcomes from green practices
Study design	Cohort studies, longitudinal studies, randomized controlled trials, Quasi-experimental studies, and Cross-sectional studies.

Strategies or interventions to reduce environmental impact; (c) Comparison: Hospitals without interventions or using traditional practices that have a higher environment impact; (d) Outcome: Reduction in environmental impact, energy consumption, carbon footprint, waste reduction, improved resource efficiency, sustainability certifications, cost savings, improved health outcomes from green practices; (e) Study design: Randomized controlled trials (RCTs), Quasi-experimental studies, Cross-sectional studies, longitudinal studies, and Cohort studies; and (f) Language: English. To address complex problems requiring innovative interventions, this socio-environmental systematic review synthesizes literature across diverse fields, including technology, innovation, and the social sciences. Within this framework, literature reviews facilitate theoretical development through the systematic organization and temporal visualization of data, highlighting existing research gaps and charting future trends while emphasizing sustainability awareness initiatives (Eyzaguirre and Fernandes, 2024; Madhyamapurush, 2026).

Study selection and data extraction

Durach *et al.* (2017) minimized potential biases in their study by employing a standardized form to extract data from 17 selected articles. Coded information was categorized using a structured form that separated specific metadata, including author, title, and publication date from broader study characteristics, such as methodology, objectives, context, and journal. The study selection process was managed in Microsoft Excel after exporting the search results from the database. The analyzed data included publication years, geographic locations, sample characteristics, study designs, and targeted environmental reduction measures. The systematic review did not perform a meta-analysis

due to the variability in the outcome analyzed (Deeks *et al.,* 2019) because combining diverse data points through statistical pooling can yield misleading results, a narrative synthesis was deemed more appropriate (Biondi-Zoccai *et al.,* 2011).

Study quality assessment

The quality of the included studies was assessed using MMAT (Hong *et al.,* 2018). The scientific rigor of various research designs—spanning randomized controlled trials to descriptive surveys—was evaluated using the MMAT. This appraisal utilizes a two-step protocol, wherein all studies are initially subjected to screening questions to verify a study's relevance and methodological appropriateness. Subsequently, they are evaluated according to five distinct quality criteria that are customized for their particular study design. A comprehensive database search yielded 3,827 records, which were narrowed down to 17 eligible studies for final synthesis after screening and duplicate removal (Table 3 and Fig. 1).

RESULTS AND DISCUSSION

Search overview

Extensive empirical research demonstrates a systemic commitment to analyzing and minimizing the environmental impact of hospital facilities. Publication frequency peaked in 2024 with eight studies, followed by four in 2022, and three in 2019. In contrast, 2021 and 2023 accounted for a single study each. The systematic review findings are organized based on the key themes and patterns of hospital environmental sustainability initiatives being highlighted across the studies (Cristiano *et al.,* 2024).

Population

Spanning diverse international contexts, this systematic review synthesizes literature on healthcare practices across a wide array of countries and clinical environments. In Switzerland, one study analyzed 33 acute care hospitals, focusing on healthcare services provided by one full-time equivalent annually (Keller *et al.,* 2021), while another assessed 62 anaesthesia providers implementing sustainable guidelines (Gasciauskaite *et al.,* 2023), Similarly, in the United States, the research included surgeons at a tertiary academic center (Palmisano *et al.,* 2021). In contrast, an alternative study surveyed 14 Veterans Affairs (VA) hospital food service directors to examine the intersection of surgical support practices and foodservice management (Williams *et al.,* 2024). In Canada, a study focused on staff and patients at a primary care clinic (Ilona *et al.,* 2024), while in Italy, approximately 6,000 residents participated in health screenings in Tuscany (Benedetto *et al.,* 2024). France contributed studies on anesthesiologists, anaesthesia nurses [Society of Anesthesia, Critical Care, and Perioperative Medicine (SFAR) members] (Tordjman *et al.,* 2022), and hospital energy systems (Toughzaoui *et al.,* 2024). In Sweden, the focus was on 24 postgraduate intensive-care nursing students (Sundberg *et al.,* 2024). Libya examined healthcare delivery across 11 public hospitals in 8 cities (Badi *et al.,* 2019), while a study in Egypt examined hospitals in Alexandria (William *et al.,* 2019). Furthermore, a comprehensive study conducted worldwide, involving 2.5 million patients with respiratory ailments from 40 countries, has brought to light major health challenges (Wilkinson *et al.,* 2022). Additional studies included 48 healthcare workers from 45 facilities in Malawi (Tu *et al.,* 2022), 1,065 public buildings undergoing green remodelling in South Korea (Woo *et al.,* 2024), and evaluations of green lean six sigma (GLSS) in Greece (Vasileiou *et al.,* 2024). The study encompassed imaging techniques utilized in Australian hospitals (McAlister *et al.,* 2022) as well as environmental reports from German hospitals (Seifert and Guenther, 2019), emphasizing worldwide initiatives aimed at sustainable healthcare delivery, environmental responsibility, and operational efficiency through innovative resource management and evidence-based sustainability practices.

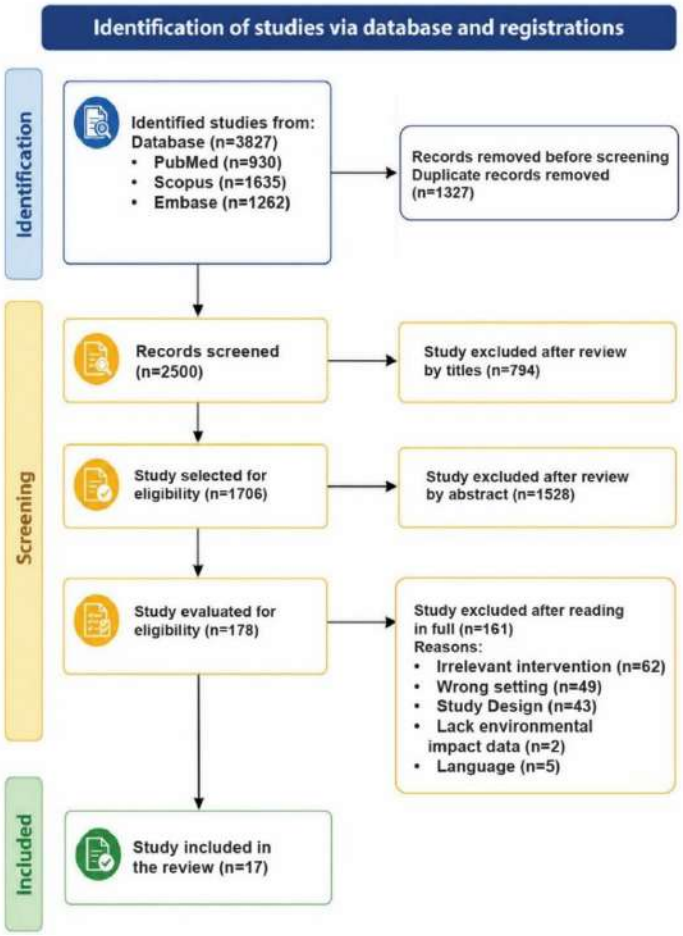

Fig. 1: PRISMA flowchart of the literature review search and selection process

Intervention

A systematic review highlights various initiatives aimed at improving environmental sustainability in healthcare settings across different countries. A study conducted in Switzerland used life cycle assessment (LCA) to evaluate 16 environmental impact categories in hospitals, identifying key areas such as catering, building infrastructure, heating, and electricity as significant contributors to greenhouse gas emissions (Keller *et al.,* 2021). In the United States, researchers investigated surgeon attitudes and practices regarding preference card optimization, highlighting institutional barriers that hinder sustainable healthcare practices (Williams *et al.,* 2024). A study in Canada focused on reducing waste by removing exam table paper in clinics (Ilona and Amanda, 2024), while Italy introduced a mobile screening unit for cancer detection (Benedetto *et al.,* 2024). A survey was conducted to evaluate environmentally sustainable anesthesiology practices, focusing on waste sorting and the reduction of polluting anaesthetic gases in France (Tordjman *et al.,* 2022). Researchers developed a grey-based assessment model in Libya to evaluate healthcare waste treatment technologies (Badi *et al.,* 2019). Another study in the U.S. also used an assessment of environmental sustainability standards in food service operations, emphasizing plant-forward dishes and local sourcing

(Woo *et al.,* 2024). In Switzerland, another study explored perceptions of environmental sustainability in anaesthesia through an online survey (Gasciauskaite *et al.,* 2023). While Greece adopted GLSS methodologies to improve, operational efficiency and quality of care (Vasileiou *et al.,* 2024). A global analysis quantified the carbon footprint of respiratory care across 40+ countries (Wilkinson *et al.,* 2022) and a thematic analysis was conducted in Malawi on barriers to infection prevention and control practices (Tu *et al.,* 2022). Geographic and technological approaches varied across the literature; for instance, Woo *et al*. (2024) assessed post-remodeling energy efficiency improvements in South Korean healthcare facilities. Conversely, research conducted in France shifted focus toward infrastructure development, modeling a solar- and hydrogen-powered fuel cell combined heat and power (FC–CHP) system (Toughzaoui *et al.,* 2024). In Sweden, experiences related to environmental sustainability in intensive care units were explored (Sundberg *et al.,* 2024), and Germany assessed environmental management in hospitals under the eco-management and audit scheme (EMAS) (Seifert and Guenther, 2019). Energy efficiency evaluations in hospitals were performed using retrofit techniques (Toughzaoui *et al.,* 2024). At the same time, the study executed in Australia analyzed CO_2e emissions from various imaging modalities (McAlister *et al.,* 2022).

Comparison

In the comparison section, this review evaluates institutional disparities in sustainability implementation and baseline environmental metrics within healthcare environments. Palmisano *et al.* (2024) compared early-career surgeons with mid-to-late-career surgeons regarding preference card maintenance and environmental stewardship in the United States. In Canada, Han *et al.* (2024) conducted a pre-and post-intervention analysis to measure changes following the removal of exam table paper in clinics. Benedetto *et al.* (2024) evaluated current cancer screening programs for their effectiveness and sustainability in Italy. Tordjman *et al.* (2022) explored differences in sustainable practices and training between early-career and mid-to-late-career providers in France. An assessment of healthcare waste management in Libya by Badi *et al*. (2019) compared traditional practices—specifically open-air burning and municipal dumping—with advanced waste segregation methodologies. In the U.S., Williams *et al.* (2024) analyzed self-rated implementation of sustainability standards in food services, identifying barriers and facilitators. Additionally, William *et al.* (2019) conducted a baseline energy consumption study in Egypt to inform energy efficiency improvements in hospitals, while McAlister *et al.* (2022) assessed baseline energy use and emissions from diagnostic imaging modalities in Australia.

Outcome

The interventions yielded diverse outcomes across environmental, operational, financial, and social dimensions. The reviewed studies demonstrate considerable environmental impacts associated with healthcare practices. Keller *et al.* (2021) found that the average carbon footprint per functional unit in Swiss hospitals is 3.2 tons carbon dioxide equivalent (t CO_2eq), with heating being the primary contributor at 0.82 t CO_2eq. Furthermore, research by Woo *et al*. (2021) documented a 30 percent (%) average increase in building energy efficiency, though the magnitude of these improvements varied regionally. Wilkinson *et al.* (2022) assessed the carbon footprint of various medications using life cycle assessment software to quantify emissions. Furthermore, McAlister *et al.* (2022) provided specific emissions data for imaging modalities, revealing that magnetic resonance imaging (MRI) contribute 17.5 kilograms (kg) CO_2e per scan, underscoring the need for targeted interventions to reduce these impacts. See (2023) reported the

implementing LCA to monitor environmental footprints, specifically focusing on water consumption, chemical toxicity, and resource consumption. By assessing the environmental impact resulting from waste generated in intensive care units (ICUs), supply chain requirements, and chemical contamination, these studies yielded practical information for sustainable hospital management.

Operational efficiency

Several studies emphasized the potential for operational efficiency improvements through sustainable practices. Han *et al.* (2024) indicated that the annual savings amounted to 718 United States dollars (USD), in addition to considerable ecological benefits derived from the removal of exam table paper, equating to the preservation of 10 trees and a reduction of 148 kg CO_2e on an annual basis. Williams *et al.* (2024) identified motivators for sustainability in food service, including reducing waste and serving healthier foods, while noting barriers such as patient preferences and contractual difficulties. The adoption of lean six sigma (LSS) methodologies in Greece was highlighted by Vasileiou *et al.* (2024), who acknowledged potential efficiency gains and waste reduction as key benefits. According to Rajagopalan *et al*. (2023), single hospitals can utilize their operational agility to circumvent bureaucratic delays and rapidly implement localized Scope 3 interventions. However, addressing systemic value-chain emissions requires enduring cooperation and active partnerships with external suppliers.

Financial benefits

Financial savings were evident in multiple studies. Benedetto *et al.* (2024) reported an annual reduction of over 110,238 USD in travel costs and productivity losses, alongside 35 tons of CO_2e travel emissions. Similarly, Tordjman *et al.* (2022) found that 69% of workplaces organized waste sorting, which could lead to long-term cost savings despite initial investment needs. Concurrently, research conducted in Egypt by William *et al*. (2019) demonstrated that mitigating heating, ventilation, and air conditioning (HVAC) energy demands by 55% directly correlates with enhanced long-term financial sustainability for hospitals.

Social and organizational impact

The social implications of sustainability initiatives were underscored by Gasciauskaite *et al.* (2021), where 89% of respondents deemed environmental sustainability essential in their work, and 95% reported implementing measures to "green" their practice. Furthermore, the study by Tordjman *et al*. (2022) revealed that a substantial majority of respondents (73%) advocated for expanded sustainability training, thereby emphasizing the necessity for robust educational frameworks within healthcare institutions.

Challenges and barriers

Despite positive outcomes associated with sustainability initiatives, several challenges persist. Furthermore, research by Tordjman *et al.* (2022) revealed that infrastructure development is hindered by two critical constraints: a lack of staff training (70%) and insufficient funding (66%). Badi *et al.* (2019) highlighted the limitations of current waste management practices in Libya, where open-air burning and inadequate segregation remain prevalent. Vasileiou *et al.* (2024) also noted concerns regarding resource limitations and the need for training as barriers to implementing sustainable practices effectively. Ultimately, these findings emphasize the significance of resolving educational deficits and reconfiguring resource allocation are foundational prerequisites for fostering long-term healthcare sustainability. Green hospital initiatives, such as using reusable materials and optimizing energy, improve clinical care and reduce infection risks while minimizing waste.

Table 3: Characteristics and study design of the selected studies

Study ID	Author(s), year	Study design	Study characteristics				Country	Key findings/ Recommendations
			Population	Intervention	Comparison	Outcome		
1	Keller *et al.*, 2021	Life Cycle Assessment	33 acute care hospitals	Life cycle assessment of 16 environmental impact categories in hospitals	N/A	Average carbon footprint: 3.2 tonnes CO_2eq per FU; main impact from heating (0.82 t CO_2eq per FU)	Switzerland	Hospital emissions are driven primarily by infrastructure and catering, heating and electricity. While waste, chemicals, and paper have a moderate footprint, direct water use, laundry, and heavy machinery show negligible effects.
2	Palmisano *et al.*, 2024	Mixed Methods	Surgeons at a single tertiary academic medical center	Assessment of surgeon perceptions and practices regarding preference card maintenance,	Comparison between early-career and mid-to-late-career surgeons	Frequency of card updates; accuracy of preference cards; perceived environmental impact; barriers to card maintenance	USA	46.1% of respondents rarely or never updated their preference cards; 98.9% observed unused items on their cards; most updates were made via verbal requests; unfamiliar processes (83.7%) and required effort (64.0%)
3	Hale *et al.*, 2024	Quality Improvement	Primary care clinic (staff and patients)	Removal of exam table paper from exam tables in the clinic	Pre-intervention baseline vs. post-intervention	Annual cost savings of USD 515; environmental savings of 8.2 km of exam table paper, preservation of 10 trees, and reduction of 148 kg CO_2e per year (equivalent to driving 1233 km)	Canada	The QI project demonstrated that eliminating exam table paper improves staff efficiency and motivation. (approximately 95,940 km of paper, 121,680 trees, USD 6,029,500, and a reduction of 3054 T carbon dioxide (CO_2) emissions annually)
4	Benedetto *et al.*, 2024	Cost and Environmental Analysis	Residents in an inner area of Tuscany; ~59,000 inhabitants	Introduction of comprehensive full-service mobile screening unit for cancer screening	Current screening programs	Annual reduction of over 110,238 USD in travel costs and productivity losses, and 35 tons of CO_2-equivalent travel emissions saved per year	Italy	The mobile screening unit model enhances sustainability and reduces non-medical costs. This study recommends combining environmental, social, and economic sustainability in rural health.
5	Tordjman *et al.*, 2022	Cross-sectional	Anesthesiologists and anesthesia nurses (SFAR members)	Evaluation of environmentally sustainable anesthesiology practices via a 28-question survey	Comparison between early-career and mid-to late-career providers	- Response rate: 10% (1092/10,877 recipients) - 69% of workplaces organized waste sorting	France	French anesthesia providers are generally aware and actively engaged in sustainable practices. However, barriers such as inadequate training, limited budgets, and insufficient administrative support hinder broader adoption.
6	Badi *et al.*, 2019	Case Study	11 public hospitals across eight cities	Developed a grey-based assessment model using grey systems theory	Compared to burning waste in the open air or disposing of	Microwave technology was identified as the best option for waste treatment, followed by steam sterilization, with	Libya	Poor waste segregation practices were noted to increase environmental and public health risks. It is recommended that decision-

				to evaluate four healthcare waste treatment	it in municipal dumps	landfilling being the least preferred.		makers adopt microwave technology and improve waste segregation to mitigate these risks.
7	Williams *et al.*, 2024	Mixed Methods	VA hospital food service directors (14 survey respondents; 11 interviewees)	Assessment of environmental sustainability implementation in food service	Comparison of self-rated implementation and experiences	Motivators included food waste reduction, healthier foods, and cost efficiency, while barriers involved patient preferences, contracts, and waste reduction costs.	USA	Despite barriers, food service directors identified solutions to improve sustainability initiatives and environmental performance in VA hospital food services.
8	Gasciauskait*et al.*, 2023	Qualitative Study	62 anesthesia providers at a center implementing internal environmentally sustainable anesthesia guidelines	Exploration of perceptions and practices regarding environmental sustainability in anesthesia	N/A	- 89% of respondents stated environmental sustainability is essential in their work - 95% reported implementing measures to “green” their practice - Conscious choice of anesthetics was the most common measure	Switzerland	The study suggests sustainable anesthesia initiatives have significant potential to reduce healthcare’s climate impact. Increased education and training are recommended to overcome barriers and enhance adoption of environmentally friendly practices.
9	Vasileiou *et al.*, 2024	Qualitative Study	Healthcare professionals and academics evaluating Green Lean Six Sigma (GLSS) in healthcare	Adoption of GLSS to improve operational efficiency, environmental sustainability, and quality of care	N/A	- Participants acknowledged the potential for efficiency gains and waste reduction - Concerns included resource limitations and the need for training	Greece	The study highlights a cautious but optimistic outlook on GLSS in healthcare. Comprehensive training and resource allocation are necessary for effective implementation.
10	Wilkinson *et al.*, 2022	Multinational observational study	Approximately 2.5 million patients with respiratory diseases from seven ongoing studies	Quantification of the carbon footprint of respiratory care, including medications and healthcare resource utilization (HCRU)	N/A	The carbon footprint of inhaled, oral, and injectable medications will be assessed using life cycle assessment software (SimaPro, Ecoinvent® data)	40+ countries	The study aims to quantify GHG emissions in asthma and COPD care, highlighting the role of well-controlled treatment in reducing environmental impact.
11	Tu *et al.*, 2022	Qualitative	48 healthcare workers (HCWs) from 45 healthcare facilities (HCFs)	Thematic analysis of facilitators and barriers to infection prevention and control (IPC) practices	N/A	- Facilitators: Disinfection practices, patient education, and waste management procedures - Barriers: Lack of IPC training, and personal protective equipment (PPE) shortages	Malawi	Improved IPC policies and infrastructure support are needed to protect HCWs and patients from HAIs. Decision-makers should address systemic barriers to enhance IPC adherence.
12	Woo *et al.*, 2024	Survey and simulation-based	1065 public buildings, public health centers,	Evaluation of energy efficiency and living condition	N/A	- Average energy efficiency improvement of 30% across buildings	South Korea	Strategic adjustments needed to ensure uniform benefits. The study highlights the role of green remodeling in reducing

		evaluation study	and medical institutions	improvements after green remodeling		- Highest gains observed in public health centers - Regional variations in effectiveness		emissions and improving public health.
13	Toughzaoui *et al.,* 2024	Optimization and Simulation Study	Hospital energy systems	Development and optimization of an FC–CHP system powered by solar energy and hydrogen storage	N/A	- Efficient allocation of energy between electricity, hydrogen production, and storage - Reduction in grid electricity costs	France	Genetic algorithms are used for system optimization. The FC–CHP system enhances energy efficiency and sustainability in hospital settings.
14	Sundberg *et al.,* 2024	Qualitative study	24 postgraduate intensive care nursing students	Exploring experiences of environmental sustainability in intensive care units	N/A	-Identified barriers and facilitators to sustainability in ICUs -Nurses expressed a need for better education awareness	Sweden	- Sustainability in ICUs is challenging but possible - Education and hospital management support are crucial for success.
15	Seifert and Guenther, 2019	Qualitative content analysis (using MaxQDA)	31 environmental statements from EMAS-registered hospitals	Environmental management in hospitals under the Eco-Management and Audit Scheme (EMAS)	N/A	- Hospitals focus on structural changes, training, waste separation, and energy efficiency. - Challenges include prioritizing financially beneficial measures, and material consumption	Germany	- Employee awareness campaigns improve engagement. - Digitalization and eco-friendly procurement reduce environmental impact. - Hospitals focus more on waste & energy than water & emissions.
16	William *et al.,* 2019	Case study with energy simulation (Design Builder)	Hospitals in Egypt (Alexandria)	Energy efficiency assessment in hospitals using retrofit and energy-efficient techniques.	Baseline energy consumption	- 55% reduction in HVAC energy consumption. - 59% reduction in total hospital energy consumption.	Egypt	- Implementing energy-efficient techniques can significantly reduce hospital energy use. - The study recommends future hospital designs in Alexandria, Egypt, to improve energy efficiency.
17	McAlister *et al.,* 2022	Life Cycle Assessment	Imaging modalities in Australian hospitals	Assessment of CO2e emissions from five imaging modalities (MRI, CT, CXR, MCXR, US).	Baseline energy use and emissions from diagnostic imaging	- CO2e emissions per scan: MRI (17.5 kg), CT (9.2 kg), CXR (0.8 kg), MCXR (0.5 kg), US (0.5 kg). - Reduced emissions when excluding standby power: MRI (1.1 kg), CT (1.1 kg), CXR (0.6 kg), MCXR (0.1 kg), US (0.1 kg).	Australia	- Reduce unnecessary imaging orders and prioritize low-impact modalities (X-ray, ultrasound) over MRI and CT when possible. - Turn off scanners when not in use to reduce emissions from standby power.
18	Present study	carbon footprint reduction	hosptials	Approach for carbon footprint reduction	Carbon foorprint	-40 percent decrease through renewable energy -lower indirect emissions	Thailand	-High upfront costs, technical gaps, and resistance to change, especially in low-resource settings, hinder widespread implementation.

Ultimately, these interventions prove that environmental sustainability and patient safety are mutually reinforcing priorities rather than competing objectives (Faizan *et al.,* 2025). By adopting a data-informed approach, healthcare facilities can simultaneously reduce environmental impact and strengthen defenses against climate hazards (Münzel *et al.,* 2026). For global perspective challenges, sustainable healthcare interventions frequently trigger unintended trade-offs across operations and finance, while systemic differences make these models highly difficult to replicate globally. A stark disparity exists in global healthcare sustainability: high-income nations fund systemic decarbonization and supply chain emission reductions, whereas climate-threatened areas must prioritize resource-constrained budgets for critical infrastructure resilience and primary care survival (Chen *et al.,* 2026).

Study design

The study design subsection of the systematic review highlights a range of methodologies employed across the included studies. LCA was used in two studies (Keller *et al.,* 2021; McAlister *et al.,* 2022). Mixed methods approaches were adopted in two studies (Palmisano *et al.,* 2024; Woo *et al.,* 2024). Methodological focuses varied across the literature; a quality improvement assessment was utilized by Ilona and Amanda, (2024), whereas cost and environmental analyses were each executed in only a single study. Keil *et al.,* (2024) indicated that while hospitals preferred the greenhouse gas protocol for top-down organizational footprint, International Organization for Standardization (ISO) 14064 provided superior auditability. Conversely, micro-level clinical pathways required bottom-up LCAs, though current methodological inconsistency limits cross-study comparison. Bridging the gap between corporate carbon reporting and clinical workflows, investigators introduce a unified hybrid framework combining organizational and product-level sustainability standards. A cross-sectional design (Tordjman *et al.,* 2022) was employed in one study, and case studies were used in two studies (Badi *et al.,* 2019; William *et al.,* 2019). Qualitative studies were conducted in four studies (Gasciauskaite *et al.,* 2023; Sundberg *et al.,* 2024; Tu *et al.,* 2022; Vasileiou *et al.,* 2024), while qualitative content analysis was performed in one study (Seifert and Guenther, 2019). An observational study framework was utilized in a particular study (Wilkinson *et al.,* 2022). Additionally, a survey and simulation-based evaluation study was conducted in one of the included studies (Woo *et al.,* 2024), and an optimization and simulation study was carried out in another study (Toughzaoui *et al.,* 2024).

Evaluation of the quality of the studies

Table 4 outlines the comprehensive classification framework applied during the quality assessment of the selected literature. The seventeen studies evaluated with the MMAT demonstrated strong overall quality; sixteen met high-quality standards, while one was rated moderate. All studies that were part of the systematic review satisfied the essential quality benchmarks, with none being classified as inadequate. This systematic review explores key areas to improve sustainability in healthcare, including lowering the carbon footprint, energy management, waste management through circular economy approaches, and considering policy and economic considerations for sustainable hospitals. The outcomes underscore the ways in which healthcare facilities can markedly advance their sustainability efforts.

Carbon footprint reduction

The studies revealed significant opportunities to reduce carbon footprints in healthcare. Building infrastructure and catering were identified as primary contributors to environmental impacts, followed by heating and electricity, while waste, pharmaceuticals, and medical products had

Table 4: Assessment of the quality of the study

ID	Sources	General screening (Pass/Fail)	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Total "Yes" ratings	Quality
1	Keller *et al.,* 2021	Pass	✓	✓	✓	✓	✓	5	High
2	Palmisano *et al.,* 2024	Pass	✓	✓	✓	✓	x	4	High
3	Hale *et al.,* 2024	Pass	✓	✓	✓	✓	x	4	High
4	Benedetto *et al.,* 2024	Pass	✓	✓	✓	✓	x	4	High
5	Tordjman *et al.,* 2022	Pass	✓	✓	✓	x	x	3	Moderate
6	Badi *et al.,* 2019	Pass	✓	✓	✓	✓	x	4	High
7	Williams *et al.,* 2024	Pass	✓	✓	✓	✓	✓	5	High
8	Gasciauskaite *et al.,* 2023	Pass	✓	✓	✓	✓	x	4	High
9	Vasileiou *et al.,* 2024	Pass	✓	✓	✓	✓	x	4	High
10	Wilkinson *et al.,* 2022	Pass	✓	✓	✓	✓	x	4	High
11	Tu *et al.,* 2022	Pass	✓	✓	✓	✓	x	4	High
12	Woo *et al.,* 2024	Pass	✓	✓	✓	✓	✓	5	High
13	Toughzaoui *et al.,* 2024	Pass	✓	✓	✓	✓	✓	5	High
14	Sundberg *et al.,* 2024	Pass	✓	✓	✓	✓	✓	5	High
15	Seifert and Guenther, 2019	Pass	✓	✓	✓	✓	✓	5	High
16	William *et al.,* 2019	Pass	✓	✓	✓	✓	✓	5	High
17	McAlister *et al.,* 2022	Pass	✓	✓	✓	✓	✓	5	High

notable effects (Keller *et al.,* 2021; Cole *et al.,* 2025). To address these systemic challenges, targeted interventions must be implemented to curtail superfluous imaging orders. Specifically, clinical protocols should favour low-impact modalities such as X-rays and ultrasound as first-line diagnostics over resource-intensive alternatives like CT and MRI scans (McAlister *et al.,* 2022). Additionally, eliminating exam table paper demonstrated the potential for substantial cumulative savings in emissions, resources, and costs if implemented nationwide (Ilona and Amanda, 2024; Raihan *et al.,* 2025). The implementation of standardized operational practices—specifically the optimization of surgical preference cards—offers a highly effective mechanism for reducing material and resource waste during operative procedures (Palmisano *et al.,* 2024). By removing unnecessary or rarely used items from surgical checklists, hospitals can significantly reduce the volume of discarded, opened-but-unused supplies, ultimately lowering costs and surgical preparation time (Perez *et al.,* 2026). The data suggest that adopting a comprehensive, cross-operational approach to mitigation can drive meaningful reductions in institutional carbon footprints (Feigin *et al.,* 2023).

Energy management and hospital sustainability

Energy efficiency emerged as a critical area for improving hospital sustainability (Chen *et al.,* 2024). Studies highlighted the effectiveness of implementing energy-efficient techniques, such as HVAC retrofits, which led to a 55 percent reduction in HVAC energy consumption in Egyptian hospitals (William *et al.,* 2019). Furthermore, leveraging FC–CHP technology powered by renewable substrates has been shown to optimize system-wide energy efficiency, reduce reliance on external power grids, lower greenhouse gas emissions, decrease operational costs, enhance energy resilience, and support the long-term environmental sustainability of healthcare facilities through efficient resource utilization and cleaner energy production (Toughzaoui *et al.,* 2024). Green remodeling efforts improved energy efficiency by an average of 30%, with the highest gains observed in public health centers in South Korea (Woo *et al.,* 2024). Institutional sustainability can be further enhanced through operational policies that mandate the deactivation of idle imaging equipment, thereby curbing superfluous standby power emissions (McAlister *et al.,* 2022; Shokoohi *et al.,* 2025). To achieve long-term sustainability,

healthcare facilities should prioritize investments in renewable energy systems and conduct regular energy audits to identify further opportunities for optimization (Vovk *et al.,* 2025; Sarker *et al.,* 2025). Green certifications like Leadership in energy and environmental design (LEED), Building research establishment environmental assessment method (BREEAM), excellence in design for greater efficiencies (EDGE), and the WELL building standard give hospitals clear, data-backed standards to cut their heavy energy use and carbon emissions, turning them into sustainable, eco-friendly spaces (Ak, 2025).

Waste management and circular economy in hospitals

Effective waste management is essential for advancing a circular economy within healthcare (Zikhathile *et al.,* 2026; de Souza Lima Cano *et al.,* 2025). While sub-optimal waste segregation practices remain a primary driver of environmental liabilities within healthcare facilities, empirical evidence positions microwave technology as the most effective waste-remediation alternative to conventional methods such as incineration and landfilling (Badi *et al.,* 2019). Food service operations also offer opportunities for improvement; best practices such as modifying familiar dishes to be plant-forward (Fechner *et al.,* 2026; Yi *et al.,* 2026) and conducting plate waste studies can help reduce food waste while maintaining patient satisfaction (Williams *et al.,* 2024; Hoteit *et al.,* 2024). Prior studies underscore food waste reduction within healthcare facilities as a primary mechanism for mitigating institutional environmental degradation and curbing lifecycle greenhouse gas emissions (Chatzipavlou *et al.,* 2024; Thiel *et al.,* 2021; Yip *et al.,* 2025). Sustainable anaesthesia practices, including minimising the use of highly polluting anaesthetic gases, were also highlighted as impactful measures (Gasciauskaite *et al.,* 2023; Tordjman *et al.,* 2022). Emissions from healthcare-related anesthetic gases and respiratory inhalers have been heavily documented and targeted for systemic mitigation across key global medical studies and climate action frameworks (Provenzani *et al.,* 2025) such as identifying that major portion of nitrous oxide are lost to atmospheric leaks in centralized piping networks (Devlin-Hegedus *et al.,* 2022). To address the challenges of regulated medical waste, implementing non-monetary operational interventions—including targeted staff education, cross-departmental collaboration, and optimized receptacle placement—demonstrated a substantial reduction in the ecological footprint and disposal costs of interventional infectious waste. Hospitals should integrate comprehensive waste segregation policies, promote recycling initiatives, and explore innovative reuse strategies to close material loops (Shah *et al.,* 2026; Moshawih *et al.,* 2025). Evidence confirmed that circular economy methods—such as reprocessing devices, reusing surgical kits, and recovering materials—effectively lower hospital waste. As detailed in recent lifecycle assessments, the isolated implementation of reusable textiles curbed municipal solid waste volumes by over 90% and drove a concurrent decrease in carbon emissions (Iskandar Shah *et al.,* 2026).

Policy and economic considerations for sustainable hospitals

Policy frameworks and economic incentives play a pivotal role in driving sustainability initiatives (Zarghami, 2025; Schetinger and Lucena, 2025). Numerous investigations have highlighted a significant correlation between deficient clinician awareness and sub-optimal environmental outcomes, thereby demonstrating the urgency for targeted professional training in healthcare sustainability (Gasciauskaite *et al.,* 2023; Tordjman *et al.,* 2022; Sundberg *et al.,* 2024). For the leadership commitment, organizational culture, staff attitudes, awareness, and institutional readiness are key determinants for hospital sustainability strategies. The study highlights that active management, positive workforce attitudes, environmental education,

and structural capacity are crucial for effective implementation. Specifically, the deployment of staff-focused educational campaigns serves as an effective mechanism for fostering organizational alignment with broader ecological initiatives (Seifert and Guenther, 2019). Standardized indicators of carbon footprint reduction such as total absolute GHG emissions, carbon intensity, renewable energy share and emissions reduction factor (Yu *et al.,* 2024), are crucial for hospital performance frameworks to enable fair benchmarking, monitor development over time, and foster continuous quality enhancement (Dolcini *et al.,* 2025). To ensure long-term efficacy, future policy interventions should be engineered to dismantle systemic barriers, specifically inadequate infection prevention infrastructure and restricted access to personal protective equipment (Tu *et al.,* 2022; Houghton *et al.,* 2020). Financially, integrating sustainability into hospital operations can yield substantial cost savings (Dolcini *et al.,* 2025; Olawade *et al.,* 2025). For instance, mobile cancer screening units reduced travel costs by over 110,238 USD annually while cutting CO_2 emissions by 35 tons yearly (Benedetto *et al.,* 2024). Addressing institutional carbon footprints requires strategic policy interventions, namely the targeted funding of sustainable architectural modifications and the deployment of economic incentives to promote eco-friendly hospital procurement practices (Schwab *et al.,* 2025; Tomaselli *et al.,* 2026). Digitalizing hospital operations including telemedicine, AI-assisted triage, remote monitoring, and electronic medical records can also streamline resource use with the carbon footprint reduction while promoting sustainable supply chain practices (Seifert and Guenther, 2019; Bobini *et al.,* 2025). Regarding the issue of national healthcare policy, environmental regulations, and green procurement standards collectively drive hospital sustainability and carbon reduction, transforming voluntary ecological goals into mandatory, measurable operational requirements (Schwab *et al.,* 2025).

Quality of the studies

The quality assessment of the included studies, as summarized in Table 4, reveals a predominantly high methodological standard, with 16 out of 17 studies classified as high-quality, achieving at least four out of five "Yes" ratings. Notably, life cycle assessments (Liu *et al.,* 2024), mixed-method studies (Johnson *et al.,* 2020), and qualitative research designs (Ahmed, 2024) demonstrated the highest methodological rigor, with eight studies receiving a perfect score. These studies exhibited clear research frameworks, strong data validity, and well-structured analytical techniques, ensuring the reliability of their findings. In particular, mixed-method investigations offered an integrated paradigm for analyzing healthcare sustainability interventions, balancing statistical effectiveness data with qualitative evidence regarding stakeholder buy-in and organizational barriers (Rana and Chimoriya, 2025; Kagoma *et al.,* 2025). Additionally, the life cycle assessments included in the review employed comprehensive environmental impact analyses, strengthening the evidence base for sustainability strategies (Munir *et al.,* 2024). A comprehensive assessment of study quality indicates a low risk of methodological bias across the literature. Consequently, the synthesized data exhibit high credibility, substantiating the overarching conclusions of this systematic review.

Study strengths

Methodological rigor was safeguarded through adherence to PRISMA standards and systematic MMAT appraisal. Of the 17 studies selected for synthesis, 16 were evaluated as high quality (94.1%), and none were categorized as low quality. Its comprehensive scope, encompassing diverse sustainability interventions such as carbon footprint reduction, energy management, waste minimization, sustainable procurement, and green hospital infrastructure, provides a holistic understanding of environmentally sustainable hospital practices (Orsini *et al.,* 2024; Almukhtar *et al.,* 2024) and directly saves lives by minimizing

healthcare pollution, which currently drives up to 5% of global emissions (Schwab *et al.,* 2024). Evidence suggests that green healthcare initiatives foster health equity via clinical waste optimization, expanded digital health access, and renewable energy adoption. Nevertheless, operationalizing these measures creates significant ethical friction, forcing a reconciliation between institutional sustainability goals, fair resource distribution, and patient-centered care. By incorporating evidence from high-income and low- and middle-income countries (LMICs), the review identifies contextual disparities in policy adoption, financial constraints, and infrastructure readiness, offering globally relevant insights. Notably, the integration of mixed-methods evidence enhances this analysis, ensuring that statistical evaluations of environmental and economic efficacy are contextualized by qualitative assessments of prevailing policy challenges, stakeholder alignment, and systemic institutional barriers (Gao *et al.,* 2025; Iliopoulos *et al.,* 2026). This study evaluates the effectiveness of sustainability interventions and critically examines barriers to implementation, providing policy-relevant recommendations to enhance feasibility in diverse healthcare settings (Haregu *et al.,* 2025; Vasileiou *et al.,* 2024). Furthermore, by emphasizing the long-term economic viability of sustainability initiatives, the review contributes to the ongoing discourse on cost-effectiveness and strategic investment in green healthcare systems. These findings align with broader sustainability research demonstrating that environmentally responsible practices are increasingly influenced by stakeholder awareness, behavioral drivers, and digital transformation, reinforcing the need for integrated and adaptive sustainability strategies across sectors (Soulami *et al.,* 2026). By pairing pragmatic, policy driven recommendations with rigorous methodology, This study significantly enriches the theoretical framework of healthcare sustainability management and provides a blueprint for future institutional interventions and policy development.

Limitations

The limitations of the review primarily occur from the variability in study quality and design, as highlighted by MMAT. Substantial methodological heterogeneity across the included studies—specifically regarding sustainability metrics, research designs, and reporting frameworks—precludes the synthesis of uniform conclusions. Furthermore, the absence of longitudinal studies is a significant limitation, as it prevents a comprehensive understanding of the long-term sustainability impacts (Wang *et al.,* 2025), which are essential for evaluating the lasting effects of the interventions over time because the results were fragmented, the synthesis lacked a structured framework and failed to capture real-time dynamics, ultimately providing inadequate guidance for tackling hospital sustainability challenges (Mostepaniuk *et al.,* 2023). Furthermore, the interpretation of these environmental metrics is cross-cut by macro-level determinants—namely, disparities in facility capacity, patient volume, climate zones, national energy grid portfolios, and health economics frameworks—which complicate direct cross-study comparisons. These gaps in study design and reporting hinder the ability to assess the true sustainability of the interventions reviewed.

Future research

Accelerating hospital decarbonization requires regulatory policies that embed carbon accounting into institutional management, enforceable through mandatory emissions tracking, public reporting protocols, and standardized reduction benchmarks. Financial incentives, such as subsidies, carbon credits, carbon pricing, green taxation, financial incentives, sustainability funding mechanisms and public-private partnerships, should be introduced to help hospitals transition to low-carbon models, particularly in resource-constrained settings. To facilitate sector-wide compliance, future policy interventions must deploy structured governance systems capable of mitigating regulatory friction

while enforcing rigorous operational accountability. Future research should explore context-specific sustainability strategies tailored to hospitals in various socioeconomic settings, investigate innovative green technologies like AI-driven energy management and biodegradable medical supplies, and assess the effectiveness of policy interventions and financial models that facilitate sustainability adoption. Moreover, tracking carbon-neutral hospital trajectories via longitudinal methodologies is imperative for identifying optimal, scalable interventions, whereas institutionalizing capacity-building programs ensures a sustainable transition by embedding green operational skills throughout the healthcare workforce. These policy and research recommendations can transform healthcare institutions into environmentally responsible and sustainable entities.

CONCLUSION

The Hospital consumption requires the substantial portion of energy, water and natural resource and produce large volumes of waste generation, contributing to greenhouse gas emissions and environmental impact. Ultimately, global healthcare frameworks position medical sector decarbonization as a critical public health objective of the twenty-first century, thereby driving hospitals to systematically reduce greenhouse gas emissions and clip localized climate impacts. The sustainable practices would be achieved the significant environmental benefits, improve public health outcomes, and enhance economic efficiency. The sustainable building practices can significantly reduce energy consumption and improve efficiency with implementing renewable energy sources and co-generation systems. In transitioning toward environmental sustainability, modern hospitals simultaneously face acute resource and regulatory constraints alongside emerging pathways for financial and clinical co-benefits. This review underscores the need for integrated, policy-driven approaches to hospital sustainability. The studies reviewed indicate significant environmental impacts associated with healthcare practices with the potential for operational efficiency improvements. Nevertheless, these institutional barriers elucidate the critical imperative of mitigating educational deficits and optimizing resource allocation to cultivate a resilient, sustainable healthcare delivery model. For the carbon footprint reduction, the building infrastructure and catering of hospitals were presented as primary contributors of environmental impacts, followed by heating and electricity, while waste, pharmaceuticals, and medical products also had notable effects. Furthermore, hospitals can achieve substantial energy load reductions by powering down diagnostic imaging modalities during non-operational intervals, thereby mitigating the baseline carbon emissions associated with standby power consumption. While carbon footprint reduction, energy management, waste reduction, and sustainable procurement show promising results, their widespread adoption remains hindered by financial, regulatory, and organizational barriers. It is essential for governments, hospital administrators, and global health organizations to collaborate in order to establish scalable, context-specific sustainability models. Future studies should explore long-term impacts, financial viability, and new green technologies that can facilitate the worldwide shift towards environmentally sustainable healthcare systems.

AUTHOR CONTRIBUTIONS

T. Buadit designed the conceptualization and methodology with the role of project administration and funding acquisition. J. Bhatta conducted the data curation and analysis, and prepared the first draft of manuscript. P.J. provided the role of supervision for the direction and trend of manuscript. W. Ounsaneha assisted the formal analysis of data and the revised the manuscript draft. C. Rattanapan the corresponding author supervised the first and co-authors, conceived the manuscript concept, and finalized the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, 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
BREEAM	Building research establishment environmental assessment method
CT	Computed tomography
EDGE	Excellence in design for greater efficiencies
FC–CHP	Fuel cell combined heat and power
GHG	Greenhouse gas
GLSS	Green lean six sigma
HVAC	Heating, ventilation, and air conditioning
ICU	Intensive care unit
ISO	International Organization for Standardization
Kg CO_2e	Kilogram carbon dioxide equivalent
LCA	Life Cycle Assessment
LEED	Leadership in energy and environmental design
LMICs	Low- and middle-income countries
MMAT	Mixed methods appraisal
MRI	Magnetic resonance imaging
NHS	National Health Service
Pico	Population, intervention, comparison, and outcome
PPE	Personal protective equipment
PRISMA	Preferred reporting items for systematic review and meta-analysis
PROSPERO	International Prospective Register of Systematic Reviews
RCTs	Randomized controlled trials
SFAR	Society of Anesthesia, Critical Care, and Perioperative Medicine
TCO_2e	Tan carbon dioxide equivalent
USD	United States dollar
WHO	World Health Organization
VA	Veterans affairs

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