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Rasbora argyrotaenia (Bleeker, 1850), photo by Wibowo Djatmiko

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The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Wildlife encroachment and local coping strategies in Kampung Laut mangrove villages, Indonesia

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Abstract. *Azzam AK, Agustina AT, Maulana FA, De Wela SM, Lailasari M, Sugiyarto, Buot Jr. IE, Setyawan AD. 2025. Wildlife encroachment and local coping strategies in Kampung Laut mangrove villages, Indonesia. Intl J Bonorowo Wetlands 15: 61-70.* Human-wildlife conflict (HWC) is an escalating concern in tropical coastal regions, where expanding settlements and agricultural activities increasingly overlap with wildlife habitats. This study examines the types, frequency, impacts, and community responses to wildlife disturbances in three mangrove-edge villages—Ujunggagak, Klaces, and Ujungalang—within Kampung Laut Sub-district, Cilacap, Indonesia. Using semi-structured interviews with 93 respondents, the research employed descriptive statistics and spatial comparisons to analyze patterns of conflict. Wild boars (*Sus scrofa*), rats (*Rattus* spp.), and monitor lizards (*Varanus salvator*) were identified as the most problematic species, frequently damaging crops and livestock and occasionally threatening human safety. Conflict intensity was highest in Klaces Village and peaked during the dry season. Local responses varied from passive tolerance and non-lethal deterrents to more aggressive measures, including poisoning and hunting. Response choices were influenced by gender, occupation, and prior experience. Although external support was limited, communities demonstrated adaptive strategies grounded in traditional knowledge. Nonetheless, the use of harmful methods such as indiscriminate poisoning remains a critical concern. These findings highlight the urgent need for community-based mitigation approaches that are ecologically sustainable and culturally appropriate. Strengthening local awareness, early warning systems, and participatory wildlife monitoring is essential to promote coexistence and biodiversity conservation in mangrove-dependent communities.

Keywords: Community response, human-wildlife conflict, mangrove village, *Sus scrofa*

INTRODUCTION

Human-wildlife conflict (HWC) is an increasing concern in regions where expanding human settlements intersect with wildlife habitats. Such interactions often lead to competition for space and resources, resulting in adverse impacts on both human livelihoods and wildlife populations (Dickman 2010; König et al. 2020). In coastal and mangrove ecosystems, these conflicts are further complicated by the ecological fragility of the environment and the socio-economic dependence of local communities on natural resources (Baral et al. 2021). Effective mitigation requires understanding not only species behavior and ecological stressors, but also the cultural and adaptive responses of affected communities (Hill 2021; Ferdin et al. 2024).

Mangrove ecosystems are globally recognized for their biodiversity and ecosystem services, including shoreline stabilization, carbon sequestration, and habitat provision for aquatic and terrestrial fauna (Hilmi et al. 2021; Osland et al. 2022). Indonesia holds one of the world's largest mangrove expanses—approximately 2.95 million hectares, or over 60% of Southeast Asia's total—making it a critical area for coastal biodiversity (Blanton et al. 2024). Among these, the Segara Anakan Lagoon in Cilacap District, Central Java, is ecologically significant for its dense stands of *Rhizophora apiculata*, *Avicennia marina*, *Sonneratia caseolaris*, and *Nypa fruticans*, which support a variety of wildlife including birds, reptiles, primates, and small mammals (Akbar et al. 2020; Kissinger et al. 2020).

However, mangrove degradation and increasing human encroachment have escalated HWC in recent years. In Kampung Laut Sub-district—comprising Ujungalang, Ujunggagak, and Klaces Villages—communities are experiencing growing disturbances from wildlife such as wild boars (*Sus scrofa*), monitor lizards (*Varanus salvator*), long-tailed macaques (*Macaca fascicularis*), and estuarine crocodiles (*Crocodylus porosus*) (Anrozi et al. 2019; Elisa et al. 2024). Rapid population growth, conversion of wetlands into farmland or housing, and sedimentation from upstream rivers have significantly altered wildlife corridors (Ardli and Wolff 2009).

Recent local media reports have documented several alarming cases, including the capture of large crocodiles near settlements and fishermen's nets, raising safety concerns among residents (Fahmi and Arief 2020). In addition to direct threats, villagers report frequent damage to crops, poultry, and property. These encounters are often seasonal, intensifying during dry periods when natural food sources in the mangrove forest become scarce (Braczkowski et al. 2023; Ullah et al. 2024). While some species have important ecological roles, their encroachment into human zones has provoked retaliatory actions—trapping, poisoning, and even habitat clearance—further exacerbating biodiversity loss (Chakuya et al. 2024).

Community responses to HWC in Kampung Laut vary in intensity and sustainability. Many households adopt traditional methods such as fencing, guard animals, or noise-based deterrents (Musa et al. 2020; Efriansyah et al. 2024), but in cases of economic loss, residents may turn to more harmful practices like poisoning or hunting (Makmur et al. 2024). These reactions raise ethical and ecological concerns, particularly when target species are of conservation interest or protected status (Zimmermann et al. 2020; Kidane et al. 2024). Addressing HWC thus requires not only practical tools, but also culturally informed and ecologically sensitive strategies.

Despite the ecological significance of the region, institutional support for conflict mitigation remains minimal. Kampung Laut lacks coordinated wildlife management plans, habitat restoration efforts, or early-warning systems (Breck et al. 2023). Most conflicts are handled informally by individuals or village leaders, without alignment with broader conservation agendas. This gap between local action and national policy limits long-term effectiveness and perpetuates a reactive cycle of degradation and conflict.

To respond effectively, detailed documentation of HWC patterns is essential—including species involved, types of damage, seasonality, and community coping mechanisms. Such information is critical to inform integrated conflict mitigation strategies, support policy design, and guide future education or ecotourism efforts (Kupika et al. 2024). Moreover, recognizing and integrating local ecological knowledge can strengthen participatory conservation and enhance social legitimacy.

This study aims to identify the primary wildlife species involved in human-wildlife conflicts, assess the types and frequency of disturbances, and examine local mitigation strategies employed by mangrove-edge communities in Kampung Laut Sub-district. The findings are expected to support inclusive, place-based solutions that promote coexistence, strengthen livelihoods, and safeguard biodiversity in tropical coastal ecosystems.

MATERIALS AND METHODS

Study area

This study was conducted in the Kampung Laut sub-district, a geographically isolated coastal area situated within the Segara Anakan Lagoon system in Cilacap District, Central Jawa Province, Indonesia (Figure 1). This region is distinguished by its expansive and ecologically vital mangrove ecosystem, which plays a crucial role in maintaining biodiversity, mitigating coastal erosion, and supporting the livelihoods of the surrounding communities (Hilmi et al. 2021; Osland et al. 2022). The study area extends approximately from 7°32′38.4″S to 7°47′24.0″S latitude and 108°48′36.0″E to 108°56′24.0″E longitude, encompassing low-lying coastal terrain with tidal influence. Administratively, Kampung Laut consists of several villages, three of which—Ujunggagak, Klaces, and Ujungalang (locally known as Motehan)—were selected as focal sites for this research due to their direct adjacency to dense mangrove stands and their recurrent experiences with human-wildlife conflict. Data collection was conducted in September and October 2024.

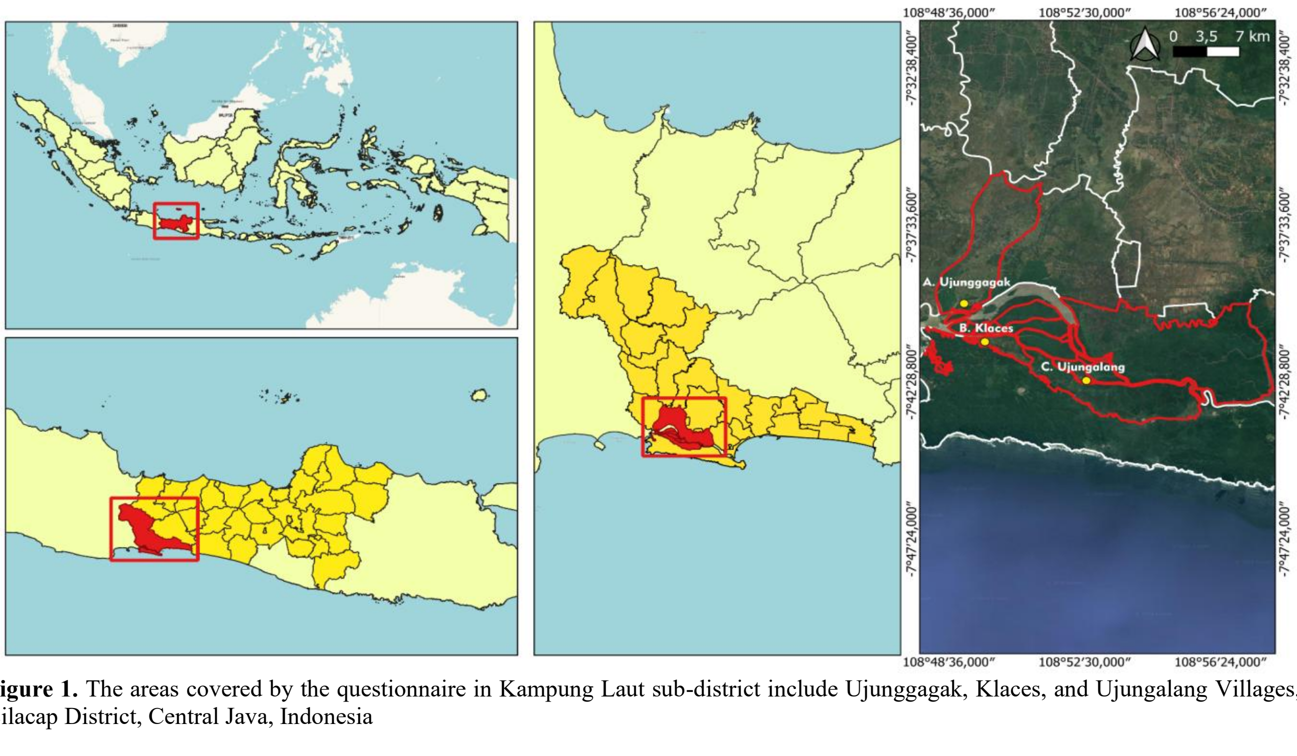

Figure 1. The areas covered by the questionnaire in Kampung Laut sub-district include Ujunggagak, Klaces, and Ujungalang Villages, Cilacap District, Central Java, Indonesia

Kampung Laut is located on the southern coastline of Java, facing the Indian Ocean and bordered by Nusa Kambangan Island. The sub-district is situated at a low elevation, approximately 1 meter above sea level, and experiences a tropical climate with average temperatures ranging from 27 to 31°C throughout the year. The area spans approximately 134.07 km² (BPS 2024) and is accessible only by water transportation, with travel times from Cilacap City averaging 1.5 to 2 hours (Ulya and Sanjatmiko 2018). This isolation has contributed to both the preservation of native vegetation and the infrastructural limitations affecting daily life.

The surveyed villages vary in demographic and spatial characteristics. Ujunggagak covers 26.59 km² and hosts approximately 4,544 residents; Klaces, the smallest, spans 2.21 km² with a population of 1,286; and Ujungalang is the largest, with 64.79 km² and around 4,265 inhabitants (Rahmayana and Handayani 2019; BPS 2024). The economy is primarily based on fishing, smallholder agriculture, and mangrove product harvesting (Setiawan and Sari 2018). Dominant mangrove species include *R. apiculata*, *A. marina*, *S. caseolaris*, and *N. fruticans*, providing essential habitat for wildlife (Kissinger et al. 2020; Hilmi et al. 2021). Yet, pressures from sedimentation, habitat conversion, and ecological degradation have increased, intensifying human-wildlife interactions in recent decades (Ardli and Wolff 2009). These dynamics render Kampung Laut an important case study for understanding wildlife conflict in mangrove landscapes.

Sampling and data collection

This research employed a purposive sampling approach followed by snowball referrals to identify local informants who had direct experience with wildlife in their immediate environment. The study targeted residents of Kampung Laut sub-district who were over 18 years of age and engaged in daily activities that involved frequent outdoor exposure, such as fishing, farming, and livestock raising. These criteria ensured the inclusion of participants with a high likelihood of encountering wildlife and being affected by human-wildlife conflict (Hill 2021; Ferdin et al. 2024).

Fieldwork was conducted throughout September to October 2024. Prior to field deployment, research permits were obtained from local authorities. Interviews were conducted face-to-face using a structured questionnaire, which allowed for consistent data collection while also accommodating brief elaborations from participants as needed. The interviews took place in three villages—Ujunggagak, Klaces, and Ujungalang—and were facilitated by local guides to ensure effective communication and cultural sensitivity.

A total of 93 residents were interviewed during the data collection process. Participants were selected based on their familiarity with local wildlife, willingness to share their experiences, and referrals provided by other villagers. This sampling strategy enabled the research team to capture a broad cross-section of occupations, age groups, and household roles. The final sample encompassed a diverse range of individuals, including fishermen, farmers, housewives, laborers, and small-scale entrepreneurs. The sample size was deemed sufficient based on the principle of thematic saturation, as no substantial new information emerged in the later stages of data collection. Moreover, this number represents a meaningful proportion of the adult population across the three villages, ensuring an adequate representation of local perspectives on human-wildlife conflict.

All interviews were conducted using printed forms in the Indonesian language, with assistance from trained enumerators familiar with the regional dialects and terminology. The interview protocol was designed to take approximately 15-25 minutes per respondent. Data were recorded manually and cross-checked at the end of each day to ensure completeness and accuracy. The questionnaire focused on respondents' experiences with specific wildlife species, the type and frequency of disturbances, and any mitigation measures they had implemented in response.

To enhance the validity of the interview data, especially regarding sensitive topics such as the use of poisons and wildlife hunting, the research team employed basic triangulation methods during fieldwork. Enumerators were instructed to cross-check respondents' answers with observable indicators in the field, such as the presence of traps, deterrent devices, or livestock enclosures. Where possible, informal discussions were conducted with non-participant villagers and community leaders to verify the consistency of reported conflict incidents and mitigation practices. Observations of environmental conditions—such as signs of wildlife intrusion, damage to crops, or remnants of deterrent measures—were recorded to support respondent statements. These triangulation steps, while limited in scope, provided supplementary evidence that increased the credibility of self-reported data in the context of human-wildlife conflict.

Questionnaire content

The questionnaire was designed to gather detailed information on the experiences of local residents with wildlife conflicts and their adaptive responses to these conflicts. It was structured into four main sections to ensure comprehensive data collection while maintaining clarity and ease of response for participants. The questions were formulated based on the literature on human-wildlife conflict in rural and mangrove landscapes (Dickman 2010; König et al. 2020; Elisa et al. 2024). Prior to field deployment, the questionnaire was pilot-tested with five respondents from non-sample households to assess clarity, relevance, and cultural appropriateness. Based on the feedback, minor revisions were made to improve wording, sequence, and the inclusion of locally understood terms.

The first section focused on identifying problematic wildlife species. Respondents were asked to list the animals they perceived as most disruptive or dangerous, whether from direct observation or local knowledge. Common taxonomic groups, such as mammals, reptiles, and birds, were included to guide responses, but the questionnaire also allowed for open-ended input to capture less expected species.

The second section explored the types of disturbance caused by wildlife. These disturbances were categorized into: (i) attacks on humans, (ii) damage to crops and plantations, (iii) predation of livestock, (iv) destruction of property or infrastructure, and (v) other forms of interference. Respondents were asked to indicate all types they had experienced and to describe the specific context of these events (e.g., time of day, season, location).

The third section examined the temporal aspects of wildlife conflict, asking respondents when they last experienced a disturbance. Response options were standardized into categories, including: within the last month, within 1-6 months, 6-12 months ago, more than a year ago, or never. This structure enabled the researchers to identify temporal trends and detect any seasonal patterns in conflict occurrence (Baral et al. 2021; Braczkowski et al. 2023).

The fourth section addressed the strategies used by residents to mitigate or prevent wildlife conflict. Participants were asked whether they had implemented specific measures, such as fencing, keeping guard animals (e.g., dogs), using repellents (e.g., scented cloths, noise makers), setting traps, or applying chemical deterrents (e.g., poisons). They were also asked whether they took no action at all, and if so, why. This section allowed for the analysis of both active and passive response patterns within the community.

In addition to conflict-specific questions, a fifth section collected basic socio-demographic data, including age, gender, occupation, and village of residence. This information was later used to examine potential correlations between livelihood type and exposure to wildlife conflict. The questionnaire design emphasized brevity and clarity, and was pilot-tested with five respondents prior to full deployment to ensure local comprehensibility and cultural appropriateness.

Data analysis

The data obtained from structured interviews were analyzed using a combination of descriptive and inferential statistical methods. All responses were manually tabulated and organized into thematic categories that followed the questionnaire's structure. These included the types of wildlife species involved in conflict, forms of disturbance experienced, timing of incidents, and mitigation strategies adopted. Frequencies and proportions were calculated for each variable, enabling comparisons across villages and respondent profiles such as occupation, age, and gender (Ferdin et al. 2024).

Descriptive statistics formed the core of the analysis, with results presented through bar charts, pie charts, and frequency tables to visualize spatial variations and the relative prominence of each conflict-related factor. Particular attention was given to identifying the most commonly reported nuisance species, sectors most affected (e.g., agriculture, livestock), and the seasonality of wildlife disturbances. This approach emphasized community-reported experiences and was deemed suitable for the study's goal of documenting real-world interactions in a rural mangrove context (Damastuti et al. 2022).

To address potential sources of bias, such as underreporting or exaggeration due to perceived expectations, the data were cross-checked through triangulation techniques. Field enumerators were instructed to verify responses where possible through direct observation, informal side interviews, and environmental cues such as the presence of traps, fences, or signs of crop damage. These verification steps aimed to increase the reliability and credibility of self-reported data.

In addition to descriptive summaries, an inferential statistical test was applied to assess whether the distribution of conflict mitigation strategies varied significantly across the three study villages. A Chi-square (χ^2) test of independence was conducted using the observed frequency distribution of six major mitigation categories: (i) doing nothing, (ii) use of guard animals or repellents, (iii) poisoning or extermination, (iv) direct hunting, (v) use of traps, and (vi) fencing. The analysis was performed using SPSS version 26, with a significance threshold set at $\alpha = 0.05$. The inclusion of this test allowed for a more robust interpretation of response patterns among villages and provided statistical support for the discussion of community-level behavioral consistency.

RESULTS AND DISCUSSION

Socio-demographic characteristics of respondents

A total of 93 respondents participated in the survey conducted across the three villages of Kampung Laut sub-district: Ujunggagak, Klaces, and Ujungalang. The demographic composition varied across age, gender, education, and occupation, reflecting the region's patterns of livelihood and household structures.

In terms of gender distribution, 53.76% of respondents were male (n=50), while 46.24% were female (n=43). Age groups were categorized into four intervals: 18-32 years (14 respondents), 33-47 years (28), 48-62 years (37), and 63 years and above (14) (Table 1). The most represented age group was 48-62 years, comprising 39.8% of the sample, indicating that middle-aged adults are more actively engaged in resource-based activities in Kampung Laut.

Educational attainment varied considerably among respondents. The majority had completed only elementary school (n=45), followed by junior high school (n=24), and senior high school (n=19). A small number had attained higher education (n=5), while a few respondents reported having no formal education at all (n=3). Ujunggagak and Ujungalang showed relatively higher rates of primary-level education, while Klaces had a notable portion of respondents with junior high schooling. This educational profile is typical of remote mangrove-based communities with limited access to formal education services (Setiawan and Sari 2018; Sukardi and Widiastuti 2020).

Regarding occupation, the respondents included 30 fishermen, 32 housewives, 10 farmers, 7 freelancers, 5 civil servants, and 9 individuals categorized under "others" (teachers, drivers, laborers, and the unemployed). Ujunggagak and Ujungalang Villages showed a higher number of fishermen (14 and 12, respectively), while Klaces had the highest proportion of farmers (n=7). The majority of female respondents identified as housewives, particularly in Klaces (n=12) and Ujungalang (n=10). This distribution reflects the strong dependence of Kampung Laut residents on aquatic and mangrove-based livelihoods, with farming playing a more limited role due to environmental constraints such as tidal exposure and wildlife disturbance.

Types and prevalence of wildlife damage

Residents of Kampung Laut sub-district reported frequent disturbances caused by various wildlife species, particularly those residing in or near the mangrove forest areas surrounding the villages. Of the 93 respondents interviewed, 68 reported having experienced wildlife disturbance, and 57 of them were able to identify the species responsible (Figure 2). Based on interview responses, wildlife-induced damage occurred across multiple sectors, including agriculture, livestock, and residential properties. Although most respondents were engaged in fishing, over 70% of them also kept livestock such as chickens, goats, or pigeons, or maintained small crop plots near their homes, making them vulnerable to wildlife interference.

Figure 2 shows the proportion of wildlife species reported as causing damage by residents of Kampung Laut Sub-district. Wild boars (*S. scrofa*) were identified as the most problematic species, accounting for 19.8% of all reported disturbances. They were followed by rats (*Rattus* spp.) at 16.7%, and monitor lizards (*V. salvator*) at 12.3%. Other notable species included monkeys (*M. fascicularis*, 10.5%) and snakes—such as *Naja sputatrix*, *Python reticulatus*, and *Boiga dendrophila*—which accounted for 8.7%. The remaining 32% were categorized as "Others," comprising less frequently cited or unidentified animals, including civets (*Paradoxurus hermaphroditus*), birds, and small carnivores. These animals were reported to destroy crops, prey on livestock, or cause structural damage to food storage areas and housing.

The frequency of wildlife disturbances also varied among the three study villages. As shown in Figure 3, Klaces Village experienced the highest average disturbance score (3.0), followed by Ujunggagak (2.23) and Ujungalang (1.73). A score of 3 indicated moderate impact (recurring or seasonal damage), 2 represented low-level but noticeable damage, and 1 indicated minimal or no perceived disturbance. The higher frequency in Klaces may be related to a greater prevalence of smallholder agriculture, which tends to attract wild boars and rodents, especially during the dry season when food sources are scarce.

These findings confirm that wildlife conflict is a widespread issue across Kampung Laut, with its severity varying by both species and location. Residents in more agricultural zones appeared to experience greater frequency and intensity of conflict, particularly from herbivorous and omnivorous mammals. These patterns are consistent with previous research that links habitat degradation and resource scarcity to increased human-wildlife interactions (Braczkowski et al. 2023; Ullah et al. 2024).

Temporal trends in wildlife conflict

The timing of recent wildlife disturbances reported by respondents offers valuable insight into both seasonal patterns and the persistence of human-wildlife conflict in Kampung Laut Sub-district. Interview data revealed that such conflicts occurred across varying timeframes, indicating both recurring and declining trends depending on location and exposure.

As shown in Figure 4, 27% of respondents (n=25) stated that they had never experienced any wildlife-related disturbance. In contrast, 8% (n=7) reported incidents within the past month, suggesting continued vulnerability in certain areas. Additionally, 19% (n=18) experienced disturbances within the past one to six months, while 11% (n=10) reported incidents within the past year. The largest proportion—35% (n=33)—indicated that their most recent wildlife encounter occurred more than one year ago.

Table 1. Demographic characteristics of respondents from Kampung Laut mangrove villages, Cilacap, Indonesia (n=93)

Category	Villages		
	Ujunggagak	Klaces	Ujungalang
Age			
18-32	7	5	2
33-47	12	9	7
48-62	7	16	14
>63	4	3	7
Gender			
Male	16	14	20
Female	14	19	10
Education			
No formal education	1	1	1
Elementary school	15	13	14
Junior high school	6	10	8
Senior high school	6	5	8
College and above	1	3	1
Occupation			
Fisherman	14	4	12
Housewife	10	12	10
Farmer	2	7	1
Freelance	1	2	4
Civil servant	1	3	1
Others	2	5	2

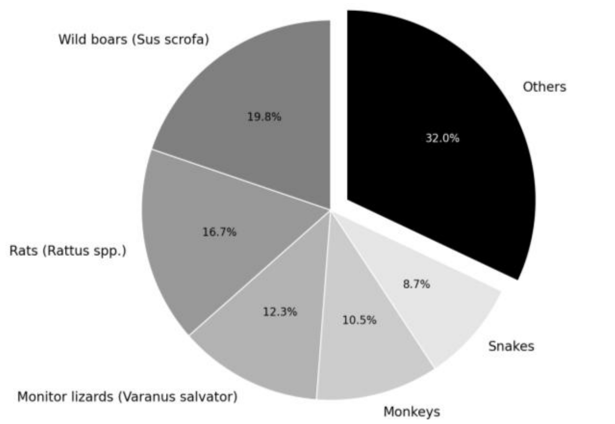

Figure 2. Proportion of wildlife species causing damage as reported by residents of Kampung Laut sub-district, Cilacap, Indonesia (n = 57)

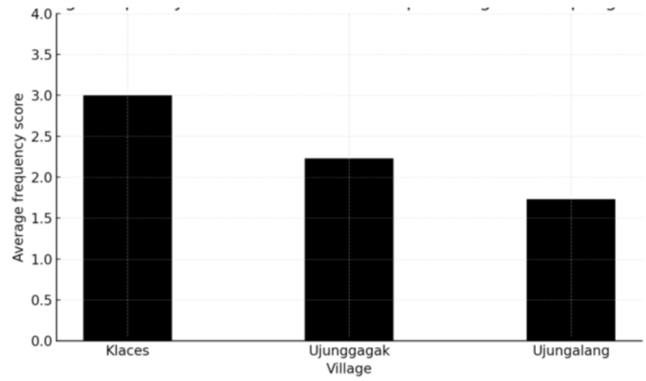

Figure 3. Average frequency of wildlife disturbances per village in Kampung Laut sub-district, Cilacap, Indonesia

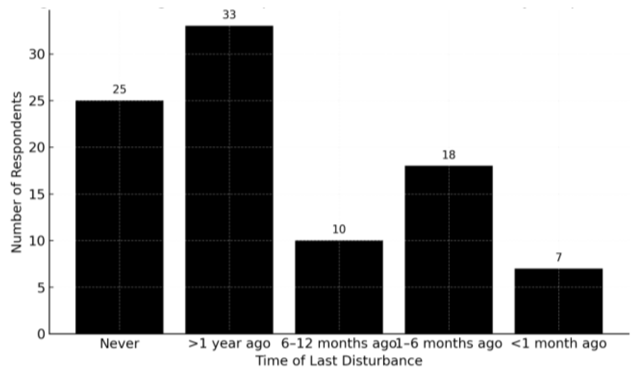

Figure 4. Timing of last reported wildlife disturbance by respondents in Kampung Laut sub-district, Cilacap, Indonesia

These findings suggest that while a portion of the community continues to face active or recent conflicts, a significant number perceive wildlife disturbances as declining. This may reflect seasonal shifts in wildlife foraging behavior, natural food availability in the mangrove ecosystem, or changes in human activity and land use. In some cases, the adoption of deterrent strategies or fencing may have contributed to reduced encounters.

However, the recurrence of conflict—particularly in agricultural zones during the dry season—indicates that human-wildlife interaction remains an ongoing concern (Ferdin et al. 2024). Several informants observed increased wild boar and rodent activity during periods of food scarcity, a pattern consistent with broader ecological studies on wildlife range expansion in degraded or fragmented habitats (Elisa et al. 2024). The fact that nearly 40% of respondents reported disturbances within the last year underscores the importance of seasonal and anticipatory mitigation strategies to protect livelihoods and reduce damage.

Wildlife-induced damage types

Wildlife-related disturbances reported by respondents in Kampung Laut sub-district were categorized into two major types: direct interference, which includes physical attacks on humans, and indirect interference, which involves damage to agriculture and livestock. The extent and distribution of these disturbances varied across the three villages studied.

As shown in Table 2, direct attacks on humans were relatively rare but carried serious implications, with a total of six incidents reported—one in Ujunggagak, four in Klaces, and one in Ujungalang. These incidents involved encounters with animals such as crocodiles, bees, snakes, wild boars, and rats. In most cases, the attacks occurred during routine outdoor activities, such as farming or fishing, and resulted in minor to moderate injuries. Although no fatalities were recorded, the incidents heightened fear among residents and prompted increased vigilance in the affected areas.

Indirect interference, on the other hand, was far more frequent and economically impactful. In the agricultural sector, a total of 56 incidents were reported across the three villages: 16 in Ujunggagak, 17 in Klaces, and 23 in Ujungalang. These incidents included rice fields being damaged by wild boars, as well as crops such as eggplants, chilies, and bananas being consumed by monkeys. Additionally, pest infestations were caused by bamboo insects and rats. Residents emphasized that such losses often coincided with dry periods or the early rainy season, when crops were most vulnerable.

The livestock sector also experienced notable disturbance, with a total of 22 reported incidents: 5 in Ujunggagak, 12 in Klaces, and 5 in Ujungalang. Chickens and ducks were reportedly preyed upon by civets (*P. hermaphroditus*) and weasels, especially at night or during planting seasons when human activity in the fields was lower. These attacks resulted in a reduction of household protein sources and, for some families, economic loss.

These findings underscore the diverse and location-specific nature of wildlife conflicts in Kampung Laut. Klaces Village, for instance, experienced the highest total number of livestock disturbances, likely due to its relatively more concentrated backyard farming. Ujungalang, despite being more remote, reported the highest level of agricultural interference, possibly due to the extensive presence of community gardens along forest edges.

Table 2. Wildlife-related disturbances affecting agriculture, livestock, and human safety across three villages

Variable	Category	Villages		
		Ujunggagak	Klaces	Ujungalang
Direct Interference	Attacks on humans	1	4	1
Indirect Interference	Agricultural sector	16	17	23
	Livestock sector	5	12	5

The persistent nature of indirect interference highlights the need for sustained, community-based responses to wildlife disturbance. Without appropriate mitigation, such interactions not only affect household economies but also influence negative attitudes toward wildlife, increasing the likelihood of retaliatory actions (Chakuya et al. 2024; Makmur et al. 2024).

Community responses and coping strategies

Residents of Kampung Laut sub-district employed various strategies to cope with and mitigate the effects of wildlife conflicts. These responses varied in terms of intensity, cost, and ecological impact, reflecting differences in resource availability, perceived risk, and cultural norms. Broadly, the community's strategies can be categorized into three main approaches: passive tolerance, deterrence, and active elimination.

As summarized in Table 3, one-third of respondents (33%) reported doing nothing when facing wildlife disturbances. This passive approach was typically linked to limited financial capacity, low perceived threat, or cultural beliefs that framed such events as seasonal, tolerable, or even "natural." In several cases, crop losses caused by rats or monkeys were accepted rather than actively countered, with respondents opting instead to replant or relocate their plots.

An equal proportion (33%) adopted deterrent-based strategies, including the use of guard animals (especially dogs), scented cloths to repel wild boars, physical renovation of livestock enclosures, or the creation of loud noises to frighten animals away. These techniques, while low-cost and locally derived, were reported to lose effectiveness over time, particularly against more persistent wildlife such as wild boars or civets.

Smaller subsets of respondents employed direct elimination measures. Approximately 13% reported using poison or chemical exterminators, primarily for controlling rodents and insects. Although such methods were effective in the short term, they pose ecological risks, including harm to non-target species and contamination of the surrounding environment (Efriansyah et al. 2024). Meanwhile, 6% of respondents engaged in direct hunting—often targeting wild boars or civets during peak disturbance seasons—while 5% reported using traps around gardens or animal enclosures.

Finally, 10% of respondents built fences around their agricultural plots or livestock areas to restrict access by wildlife. This method was considered effective against larger mammals but required a significant investment in materials and labor, making it difficult for lower-income households to implement independently. These findings indicate a strong reliance on traditional, household-level strategies with minimal use of external or institutional support. While deterrents and fencing can reduce conflict frequency, strategies such as poisoning and hunting risk undermining the long-term ecological balance; this underscores the importance of promoting ecologically sound alternatives.

To assess whether the use of mitigation strategies differed significantly across the three study villages, a Chi-square test of independence was conducted based on the observed frequency distribution in Table 3. The test revealed no statistically significant differences among villages ($\chi^2 < 0.1$, $df = 10$, $p > 0.95$), suggesting a relatively uniform pattern of response. This implies that residents across Kampung Laut, regardless of their village, tend to adopt similar coping behaviors when dealing with wildlife conflict.

Discussion

Ecological patterns of wildlife conflict

Human-wildlife conflict in Kampung Laut is primarily driven by a small set of adaptable species, including wild boars (*S. scrofa*), rats (*Rattus* spp.), and monitor lizards (*V. salvator*), as well as monkeys, snakes, and civets. These generalist animals thrive in fragmented or disturbed habitats and frequently enter human settlements in search of food, especially during the dry season when resources in the mangrove ecosystem are limited (König et al. 2020; Braczkowski et al. 2023).

Wild boars were the most frequently reported nuisance species (Figure 2), reflecting their strong foraging ability, destructive rooting behavior, and tendency to raid crops and gardens. Rats were associated with grain loss and damage to domestic storage, while monitor lizards, although ecologically beneficial, were often blamed for predation on poultry. These patterns align with other studies in tropical coastal regions, where human-wildlife conflict is closely linked to ecological edge effects and resource overlap (Massei et al. 2015).

Seasonal variation was evident in conflict timing (Figure 4), with over one-third of respondents reporting incidents in the previous year. Wildlife disturbances peaked during the dry season or early planting periods, consistent with seasonal food scarcity and habitat stress (Elisa et al. 2024; Ullah et al. 2024). Some households (35%) reported a gap of over a year since the last incident, possibly due to deterrent effectiveness, changes in land use, or conflict desensitization. These findings underscore the importance of understanding wildlife behavior and seasonal movements to inform anticipatory mitigation strategies.

Table 3. Distribution of mitigation strategies for wildlife conflict across three villages in Kampung Laut Sub-district, Cilacap, Indonesia (N=93)

Mitigation strategy	Villages			Total
	Ujunggagak	Klaces	Ujungalang	
Do nothing	10	11	10	31
Guard animals/ repellents	10	11	10	31
Poison/ extermination	4	4	4	12
Hunting	2	2	2	6
Traps	2	2	1	5
Fencing	2	3	3	8
Total	30	33	30	93

In addition to generalist species, several taxa with ecological and conservation significance were also reported, including snakes (e.g., *N. sputatrix*, *P. reticulatus*) and civets (*P. hermaphroditus*). While these animals are sometimes feared or perceived as pests, they play important ecological roles as predators of rodents and insects. Their presence indicates functioning food webs within the mangrove-village interface. However, due to fear or economic losses, these species are often subject to indiscriminate killing, which may reduce local biodiversity and disrupt ecological balance. Efforts to promote coexistence should therefore include public education on the ecological value of less understood or culturally stigmatized species, especially those with conservation relevance.

Demographic and spatial vulnerability

The intensity of wildlife conflict varied across villages, influenced by differences in land use patterns, mangrove cover, and proximity to wildlife corridors. Klaces Village reported the highest frequency of disturbances (Figure 3), likely due to its dense concentration of home gardens and smallholder farms located near forest margins. Ujungalang, while recording fewer total incidents, reported significant agricultural losses, suggesting the presence of spatial clusters with elevated exposure. In contrast, Ujunggagak exhibited a more balanced disturbance profile, situated between active fishing areas and degraded woodland edges, with lower concentrations of crop fields.

Vulnerability to conflict was also shaped by socio-demographic factors such as occupation, gender, and age. Fishermen and housewives were among the most affected, as their daily routines often coincided with dawn and dusk—periods of increased wildlife activity. Women, in particular, faced heightened exposure due to their roles in managing food storage, backyard livestock, and domestic waste, all of which may attract animals such as rodents and civets. The majority of reports came from middle-aged respondents (48-62 years), who typically serve as decision-makers in land use and household management (Baral et al. 2021). Across all groups, vulnerabilities were exacerbated by structural limitations, including inadequate fencing, unsecured livestock enclosures, and the absence of basic surveillance infrastructure.

These findings reinforce the notion that wildlife conflict is not random but spatially and socially structured—emerging from the intersection of ecological interfaces and human settlement behavior. Risk tends to concentrate in specific zones within the village landscape, often reflecting both environmental exposure and socio-economic capacity. Therefore, mitigation efforts must be place-based and context-sensitive, addressing not only ecological risk factors but also the roles and responsibilities embedded in household and gender dynamics. Interventions such as participatory conflict mapping, improvements in animal husbandry practices, and gender-inclusive training programs can enhance local resilience and reduce future conflict (Dickman 2010).

Damage to livelihoods and perceived risks

Wildlife conflict in Kampung Laut directly affects household livelihoods, particularly in the sectors of agriculture and small-scale animal husbandry. As shown in Table 2, crop damage was the most frequently reported form of disturbance, with wild boars, rats, and monkeys destroying rice, vegetables, and fruit crops. These events commonly occurred during the dry season or early planting periods, when crop defenses were minimal and agricultural inputs had already been invested. The losses were often sudden and severe, resulting in reduced food availability, economic setbacks, and growing disinterest in continued cultivation.

Although less frequent, livestock predation posed a significant threat to households relying on poultry or small ruminants for protein and supplemental income. Chickens and ducks were frequently preyed upon by civets (*P. hermaphroditus*), monitor lizards (*V. salvator*), and weasels, particularly at night or in periods of reduced human activity. In many cases, respondents reported that the absence of secure animal enclosures made their livestock highly vulnerable to attack.

Direct attacks on humans were rare but not negligible. Six incidents were documented across the three villages, involving injuries caused by wild boars, snakes, bees, and rodents. These encounters, although infrequent, contributed to heightened fear and behavioral disruption—especially among elderly residents, children, and individuals working alone in isolated areas. Interestingly, certain species such as crocodiles (*Crocodylus porosus*) continued to elicit strong fear responses, despite the absence of recent attacks, highlighting a gap between perceived and actual risk (Hill 2004; Barua et al. 2013).

The cumulative impact of wildlife conflict extended beyond economic losses. Respondents frequently described feelings of stress, frustration, and helplessness following repeated crop failures or livestock predation. In some instances, this emotional toll gave rise to retaliatory behaviors, including the use of poison or the destruction of nearby vegetation believed to shelter wildlife (Treves and Karanth 2003; Makmur et al. 2024). Such responses, while understandable, carry long-term ecological consequences and reflect the erosion of social resilience in the face of repeated disturbances.

These findings underscore that human-wildlife conflict is not solely a matter of material loss but also a source of psychological and social strain. Effective mitigation strategies must therefore consider both dimensions of risk—economic and emotional—by promoting early warning systems, protective infrastructure, and culturally sensitive outreach that helps rebuild trust in coexistence efforts and prevents cycles of ecological retribution.

Community-based mitigation practices

In the absence of institutional support, residents of Kampung Laut rely on self-initiated strategies to manage wildlife disturbances, ranging from passive tolerance to active elimination. As shown in Table 3, a third of respondents reported doing nothing in response to conflict, often due to limited financial capacity, fatalistic beliefs, or the perception that disturbances were tolerable and seasonal in nature. This passive stance reflects both cultural norms and structural constraints (Setyawan et al. 2022).

An equal proportion adopted non-lethal deterrents such as guard dogs, loud noises, or scented materials to repel animals like wild boars and monkeys. These methods are low-cost and locally embedded but often lose effectiveness over time. More aggressive tactics, including poisoning (13%), hunting (6%), and trapping (5%), were used selectively, particularly when economic losses were high. However, such methods pose ecological risks, including harm to non-target species and contamination of the mangrove environment (Chakuya et al. 2024; Efriansyah et al. 2024).

Physical fencing—employed by 10% of respondents—was generally viewed as effective but unaffordable for most households. The labor and material costs limited its use, especially among lower-income families. Communal or subsidized fencing initiatives were absent, although such schemes could provide more sustainable protection if implemented collaboratively. Statistical analysis revealed no significant differences in mitigation strategy use across villages (χ^2=0.044, $p\approx 1.00$), indicating behavioral convergence likely shaped by shared environmental pressures and cultural practices. This uniformity suggests that sub-district level interventions—rather than village-specific programs—may be more efficient, provided they are tailored to local realities.

Overall, the reliance on household-level responses, combined with limited access to technical assistance, underscores the need for integrated, community-based solutions. Participatory training, the promotion of ecologically safe deterrents, and co-management frameworks are essential for shifting from reactive to proactive conflict mitigation in mangrove-dependent communities.

Implications for human-wildlife coexistence in mangrove systems

The case of Kampung Laut illustrates the complex trade-offs between biodiversity conservation and livelihood security in tropical mangrove landscapes. Wildlife conflict in this region is not merely an ecological issue, but a socio-environmental challenge shaped by land-use patterns, poverty, and governance gaps. Species such as *S. scrofa*, *P. hermaphroditus*, and *V. salvator* exploit the edges between mangrove forests and human settlements, where food sources and habitat structures overlap (Braczkowski et al. 2023).

Current responses—from tolerance to direct elimination—reflect both adaptive resilience and systemic vulnerability. Without coordinated support, households rely on informal strategies that are often ecologically harmful or unsustainable. Limited infrastructure, low educational levels (Table 1), and the absence of formal conflict mitigation programs leave communities trapped in a reactive cycle of loss and retaliation (Ferdin et al. 2024).

Yet, the situation also presents opportunities. The presence of local ecological knowledge, social cohesion, and shared coping strategies across villages provides a strong foundation for participatory wildlife management. Tools such as community-based monitoring, conflict mapping, and seasonal early warning systems can be integrated into village governance to support coexistence initiatives. These approaches align with global calls for decentralized, culturally grounded conservation frameworks (König et al. 2020). Lessons from Kampung Laut are also relevant beyond Indonesia, as similar challenges persist in mangrove-dependent communities across Asia and Africa. Thus, this study contributes to broader efforts to develop equitable and ecologically sound models for human-wildlife coexistence in socio-ecological systems undergoing rapid transformation.

In conclusion, human-wildlife conflict in Kampung Laut Sub-district, Central Java, is shaped by the interactions between generalist species—particularly *S. scrofa*, *Rattus* spp., and *V. salvator*—and mangrove-edge communities experiencing livelihood vulnerabilities. Conflict intensity varies across both space and season, with Klaces Village experiencing the highest frequency of disturbances, especially during the dry season when natural food resources are limited. The most affected sectors include smallholder agriculture and backyard livestock, with indirect consequences for household food security and psychological well-being. Community responses remain largely traditional, encompassing a spectrum from passive tolerance to non-lethal deterrents, and in some cases, harmful practices such as poisoning and hunting. Notably, the similarity in coping strategies across villages reflects shared ecological stressors and cultural perceptions of wildlife. While institutional support for conflict mitigation remains minimal, strong local knowledge and community cohesion provide a valuable foundation for participatory, ecosystem-based management. Strengthening coexistence in mangrove-dependent landscapes will require strategic investments in affordable protective infrastructure, culturally grounded training programs, and decentralized wildlife monitoring systems. Such approaches can empower communities to manage conflict proactively while maintaining ecological integrity and enhancing social resilience.

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Multidimensional sustainability assessment of mangrove forests in the Segara Anakan Lagoon, Central Java, Indonesia

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[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ♥email: volatileoils@gmail.com
[2]Department of Biology, Faculty of Science, Universiti Putra Malaysia. 43400 UPM Serdang, Selangor, Malaysia
[3]Biodiversity Research Group, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia

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Abstract. *Ramadhani G, Wahyuningtyas J, Arifiandita DM, Ayuningtyas HR, Ashila J, Yap CK, Setyawan AD. 2025. Multidimensional sustainability assessment of mangrove forests in the Segara Anakan Lagoon, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 71-85.* Mangrove ecosystems play a crucial role in supporting biodiversity, coastal protection, and community livelihoods in tropical regions, yet they remain vulnerable to multidimensional pressures. This study assesses the sustainability of mangrove forests in the Segara Anakan Lagoon, Central Java, Indonesia, using a modified Rapfish framework based on Multidimensional Scaling (MDS) across four dimensions: ecological, economic, socio-cultural, and institutional. Data were collected from 115 households in three coastal villages—Ujunggagak, Klaces, and Ujungalang—through structured surveys and field observations. Results show that while the ecological (55.99) and institutional (58.89) dimensions are moderately sustainable, the socio-cultural (42.79) and economic (27.74) aspects remain fairly unsustainable. Leverage analysis identified key sensitive attributes, including salinity regulation, livelihood diversification, community participation, and governance presence. Monte Carlo simulation confirmed model robustness, with an average deviation of only 0.67% across dimensions. The study highlights the imbalance among sustainability dimensions and emphasizes the importance of targeted interventions based on leverage points. These findings offer a practical roadmap for policymakers and coastal managers to enhance integrated mangrove management, potentially leading to significant improvements in the sustainability of mangrove ecosystems. The methodological approach also demonstrates the applicability of the Rapfish tool in complex socio-ecological systems, particularly in data-limited, community-based conservation settings.

Keywords: Coastal management, leverage analysis, mangrove sustainability, Rapfish, Segara Anakan, socio-ecological systems

INTRODUCTION

Mangrove forests represent one of the most productive and ecologically significant coastal ecosystems in the tropics. These intertidal habitats are dominated by halophytic tree species that have evolved complex physiological and morphological adaptations to survive under high salinity, low oxygen soils, and frequent tidal inundation (Friess et al. 2016). Their multifunctional roles extend from supporting biodiversity, providing nursery habitats for marine life, and buffering coastal erosion to sequestering carbon and sustaining traditional livelihoods (Carugati et al. 2018; Blanton et al. 2024). In Indonesia, which possesses the largest area of mangrove forests in the world, mangroves are central to both ecological stability and the socio-economic fabric of coastal communities (Arifanti et al. 2022a; Handayani et al. 2023).

Despite their ecological value, mangrove ecosystems are increasingly under threat due to a combination of natural and anthropogenic pressures. These include land-use changes, unregulated aquaculture, infrastructure development, and climate-related phenomena such as sea-level rise and increased sedimentation (Bakri et al. 2023; Hidayah et al. 2024). The conversion of mangrove forests into fish ponds or agricultural lands has led to significant habitat degradation, reduced biodiversity, and disrupted ecosystem services (Murdiyarso et al. 2015; Kesavan et al. 2021). The impact of these pressures is particularly pronounced in areas like the Segara Anakan Lagoon in Cilacap District, Central Java, where intensive human activities intersect with fragile estuarine dynamics (Dharmawan et al. 2017; Hariyadi et al. 2018).

Mangrove degradation in the Segara Anakan region not only affects ecological integrity but also the well-being of local communities whose livelihoods depend on fisheries, aquaculture, and mangrove-based resources. Communities in the Segara Anakan Lagoon, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia for example, rely on mangrove forests for firewood, fishing grounds, and eco-cultural practices (Ismail et al. 2019; Basyuni et al. 2022). Consequently, understanding the sustainability of mangrove ecosystems in this region requires an integrated approach that considers ecological conditions alongside economic, socio-cultural, and institutional factors (Sahputra et al. 2021; Gong et al. 2024). This multi-dimensional perspective is essential for informing effective conservation, restoration, and management strategies.

Several previous studies have highlighted the importance of combining ecological data with socio-economic indicators to evaluate mangrove sustainability

(Sofian et al. 2019; Hilmi et al. 2021). For instance, community-based mangrove management efforts in other parts of Indonesia have shown that local participation, policy enforcement, and awareness can significantly improve sustainability outcomes (Buncag 2021; Damastuti et al. 2022). However, such efforts remain uneven, and the absence of structured evaluation tools often hampers long-term planning and stakeholder coordination. In this context, multidimensional sustainability assessment becomes a powerful diagnostic tool to identify which dimensions or attributes are most vulnerable and where intervention is most needed (Chaliluddin et al. 2023; Zuhry et al. 2023).

To operationalize such assessments, methods like Rapid Appraisal for Fisheries (Rapfish) and Multidimensional Scaling (MDS) have been widely used for evaluating complex ecological-social systems (Melo et al. 2020; Fadilah et al. 2021). These methods allow the visualization of sustainability status across various dimensions and provide a quantifiable basis for comparing sites or management strategies. In addition to providing sustainability scores, leverage analysis can pinpoint which factors most influence each dimension, while Monte Carlo simulations validate the robustness of results (Hermawan 2025). In recent studies across Indonesia's coastal zones, this integrated approach has helped guide decision-making in mangrove restoration, tourism zoning, and stakeholder engagement (Sabrina et al. 2022; Hidayah et al. 2024).

The mangrove ecosystem in the Segara Anakan Lagoon provides an ideal case for multidimensional sustainability analysis. The area is characterized by its high biodiversity, traditional fishing communities, and governance complexity involving multiple stakeholders (Nordhaus et al. 2019; Ardiyanto et al. 2024). However, it is also one of the most threatened mangrove systems in Java due to sedimentation, pollution, and competing land use. Previous efforts have documented changes in mangrove health and biomass (Widyastuti et al. 2018), but comprehensive assessments that integrate ecological metrics with socio-institutional realities remain limited.

Given these challenges, the present study seeks to assess the sustainability status of mangrove forests in Segara Anakan Lagoon, Kampung Laut Sub-district, Cilacap District, using an integrated, multidimensional approach. Specifically, the study evaluates four key dimensions—ecological, economic, socio-cultural, and institutional—across three representative villages in the region. The analysis is intended to not only quantify the current sustainability index but also identify leverage attributes and propose targeted recommendations. Ultimately, the findings aim to support the development of inclusive, adaptive, and evidence-based strategies for sustainable mangrove management in Indonesia's coastal regions.

MATERIALS AND METHODS

Study area

This study was conducted in Segara Anakan Lagoon, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia—an area known for its extensive mangrove forests and complex estuarine ecosystems within the Segara Anakan Lagoon. The sub-district consists of several coastal villages whose residents rely heavily on mangrove-related ecosystem services. Three villages—Ujunggagak, Klaces, and Ujungalang—were selected for field research due to their representative ecological gradients and varying degrees of anthropogenic pressure (Figure 1).

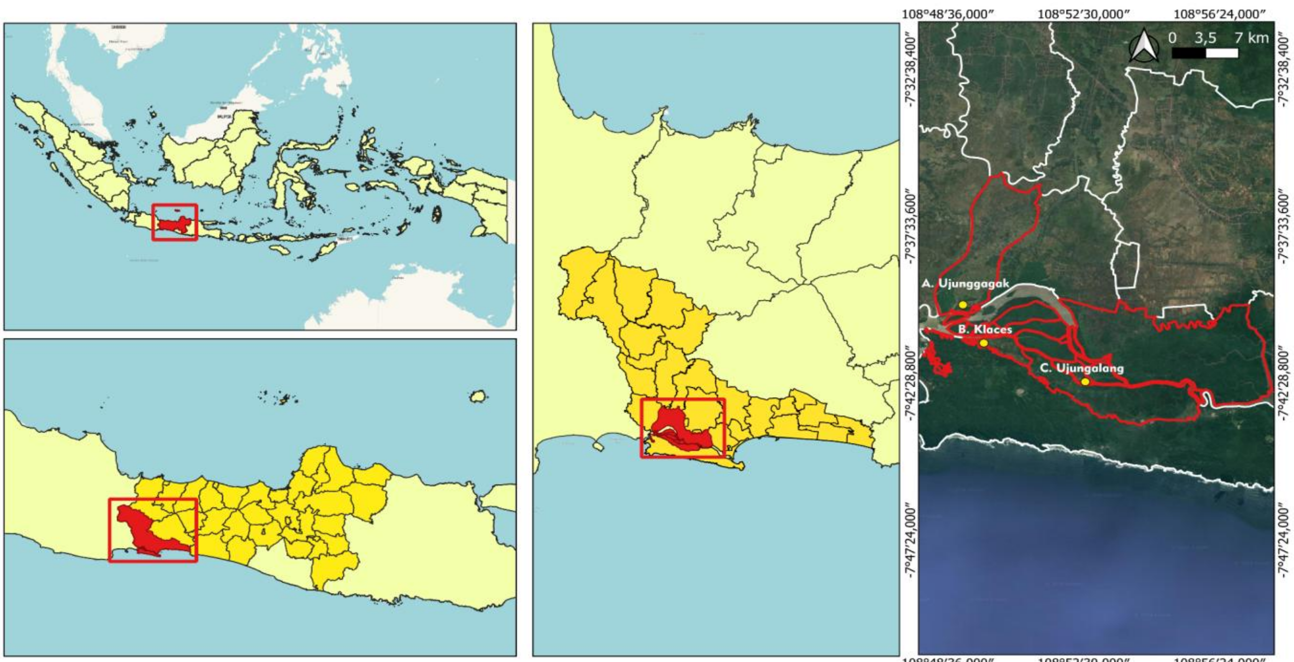

Figure 1. Map of study sites in Segara Anakan Lagoon, i.e. Ujunggagak, Klaces, and Ujungalang Villages, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia

The area's topography is characterized by low-lying coastal plains with an average elevation of about 1 masl. Annual rainfall ranges between 2,000 and 3,500 mm, influenced by monsoonal cycles (BPS 2024). Tidal channels, brackish ponds, and mudflats support a diversity of aquatic and mangrove species, including *Avicennia marina* and *Bruguiera gymnorhiza* (Ismail et al. 2019; Widyastuti et al. 2018). Ecologically, Segara Anakan functions as a sediment-trapping estuary shaped by both fluvial and marine processes (Widayani 2014). However, sedimentation, land conversion, and upstream hydrological changes have increasingly disrupted its dynamics and altered mangrove distribution.

Administratively, Kampung Laut falls under a multi-scalar governance structure involving local village authorities and higher-level institutions (Nordhaus et al. 2019; Ardiyanto et al. 2024). The local economy depends on small-scale fisheries, aquaculture, and informal trade. Transportation is dominated by wooden boats and *supit*, as limited infrastructure restricts land access. Community dependence on mangroves extends beyond subsistence to include social functions such as customary practices and collective conservation (Basyuni et al. 2022; Handayani et al. 2023). This socio-ecological complexity makes Segara Anakan Lagoon, Kampung Laut an ideal case for evaluating mangrove sustainability through integrated, multidimensional indicators that capture both environmental and human dimensions.

Data collection

Community survey and questionnaire

Primary data on ecological perceptions, economic uses, socio-cultural practices, and institutional conditions were gathered through community-based surveys in Ujunggagak, Klaces, and Ujungalang Villages. A semi-structured questionnaire, combining closed and open-ended questions, was developed to align with four sustainability dimensions: ecology, economy, socio-cultural, and institutional. The questions were adapted from previous mangrove sustainability studies to reflect the specific context of Segara Anakan Lagoon, Kampung Laut (Theresia et al. 2015; Sahputra et al. 2021).

A total of 115 respondents were selected via random sampling from residents aged over 17. This approach minimized bias and ensured representation across gender, age, education, and occupation. Respondents included fishers, farmers, traders, housewives, and village officials, ensuring diverse perspectives on mangrove resource use and management (Sahputra et al. 2021).

The questionnaire was organized thematically. Ecological items focused on perceptions of mangrove cover, species diversity, and environmental quality. Economic questions addressed household reliance on mangrove products, income contribution, and livelihood alternatives. Socio-cultural aspects explored traditional practices, conflicts, and knowledge transfer. Institutional indicators assessed awareness of regulations, the presence of field officers, and participation in conservation activities (Damastuti et al. 2022; Koesdaryanto et al. 2024).

The instrument was pre-tested for clarity and cultural relevance prior to deployment. Enumerators were trained in ethical and culturally sensitive data collection, and respondents provided informed consent. Anonymity and confidentiality were emphasized to ensure honest responses. Demographic data were recorded to support the analysis of sustainability awareness across social groups. The finalized data set was coded and inputted into a structured database for scoring and further analysis using the Rapfish-MDS framework (Fadilah et al. 2021; Chaliluddin et al. 2023).

Field observation and ecological measurements

Ecological data were collected through direct field observations and in situ measurements at selected mangrove sites across Ujunggagak, Klaces, and Ujungalang Villages. Sampling locations were chosen to reflect environmental variation in tidal exposure, human proximity, and land-use intensity. Observations targeted key attributes relevant to mangrove sustainability—species diversity, vegetation density, and canopy cover—using rapid appraisal methods adapted from previous Indonesian studies (Fadilah et al. 2021; Basyuni et al. 2022; Sabrina et al. 2022).

Species were identified using standard botanical keys and validated with local knowledge. Diversity was calculated within 10 × 10 m plots, vegetation density was measured by stem counts, and canopy cover was assessed via spherical densiometers or photos. These indicators provided insight into habitat structure and degradation levels (Widyastuti et al. 2018).

Salinity measurements were obtained using a portable refractometer (ATAGO Master-S/Millα), calibrated regularly, and used during high tide to ensure consistency. Each site was sampled three times and averaged. Salinity, expressed in permille (‰), served as a key ecological stress indicator due to its influence on species composition and seedling success (Ismail et al. 2019; Kesavan et al. 2021). Supplementary indicators such as TDS, watercolor, pollutant presence, and physical damage (e.g., cutting, trampling) were evaluated using qualitative scores adapted from national monitoring protocols (Kementerian LHK 2017). Observers also documented signs of degradation, such as waste buildup, erosion, and invasive species.

Each plot was georeferenced with a handheld GPS and cross-validated with satellite imagery to ensure spatial accuracy. Field data were later matched with community perceptions to identify gaps or alignment between ecological realities and local knowledge, enhancing the diagnostic value of the sustainability assessment (Sahputra et al. 2021; Chaliluddin et al. 2023).

Sustainability indicators and attributes

To evaluate the sustainability of mangrove ecosystems in Segara Anakan Lagoon, Kampung Laut, this study adopted a multidimensional framework comprising four key dimensions: ecological, economic, socio-cultural, and institutional. Each dimension was represented by five attributes, selected based on their contextual relevance, measurability, and alignment with local conditions. The selection process was guided by national monitoring protocols and prior applications of the Rapfish method in coastal ecosystem assessments (Fadilah et al. 2021; Damastuti et al. 2022).

The ecological dimension included salinity fluctuation, mangrove vegetation density, waste or garbage accumulation, seedling survival rate, and biodiversity observation. These indicators reflect habitat condition, environmental stress, and regeneration capacity (Ismail et al. 2019; Basyuni et al. 2022). The economic dimension focused on livelihood dynamics and resource dependency, including mangrove product use, livelihood diversification, energy cost reduction, income increase perception, and access to capital or market networks. These variables highlight how mangrove-related benefits support economic resilience in vulnerable coastal communities (Hilmi et al. 2021; Sahputra et al. 2021). The socio-cultural dimension captured collective behaviors and cultural values, including participation in mangrove programs, conflict over mangrove use, traditional knowledge application, environmental awareness, and intergenerational value transmission. These attributes shape long-term stewardship and social cohesion (Theresia et al. 2015; Ardiyanto et al. 2024). The institutional dimension assessed governance and regulatory mechanisms, comprising the presence of field officers, existence of village-level regulations, community compliance with rules, access to external government or NGO programs, and coordination among relevant institutions (Koesdaryanto et al. 2024).

Each attribute was scored on a standardized scale from 0 (worst) to 3 (best) using a combination of field observations, structured interviews, and expert judgment. All attributes were weighted equally. The resulting data matrix was used as input for the Rapfish-MDS analysis to generate sustainability indices and leverage diagnostics (Pitcher and Preikshot 2001; Melo et al. 2020). This structured set of 20 attributes (5 per dimension), as summarized in Table 1, provides a robust analytical foundation for identifying sensitive factors and informing targeted interventions in mangrove sustainability management in Segara Anakan Lagoon.

Table 1. Sustainability attributes and indicators per dimension

Dimension	Attribute	Brief definition	Scoring scale
Ecological	Salinity fluctuation	Degree of variation in salinity affecting mangrove health and regeneration	0 = >30‰, 3 = <15‰
	Mangrove vegetation density	Number of stems per hectare reflecting structural complexity	0 = <1000 stems/ha, 3 = >2500 stems/ha
	Waste/garbage accumulation	Presence and extent of plastic or household waste	0 = widespread, 3 = none
	Mangrove seedling survival rate	Percentage of naturally surviving seedlings in mangrove stands	0 = <30%, 3 = >80%
	Biodiversity observation (crab/fish)	Number of aquatic species observed (e.g., crabs, fish)	0 = <2 species, 3 = >5 species
Economic	Mangrove product use	Extent of livelihood reliance on mangrove-based products	0 = none, 3 = multiple products used
	Livelihood diversification	Availability of alternative, non-mangrove income sources	0 = none, 3 = >3 alternatives
	Energy cost reduction	Use of mangrove (e.g., wood) that substitutes household energy needs	0 = no use, 3 = significantly reduces costs
	Income increase perception	Community perception of income improvement from mangrove-related activities	0 = no improvement, 3 = high contribution
	Access to capital/market	Ability to market products and access financial support	0 = no access, 3 = regular and open access
Socio-cultural	Participation in mangrove programs	Involvement in planting, clean-ups, or conservation efforts	0 = none, 3 = frequent participation
	Conflict over mangrove use	Presence of disputes over mangrove access or use rights	0 = high conflict, 3 = no conflict
	Traditional knowledge use	Application of local ecological knowledge in mangrove management	0 = none, 3 = consistently used
	Environmental awareness	Understanding of mangrove functions and importance	0 = unaware, 3 = highly aware
	Generational transmission of values	Practice of passing knowledge to the next generation	0 = none, 3 = well established
Institutional	Presence of field officers	Active involvement of forestry officers or environmental facilitators	0 = absent, 3 = continuous and visible presence
	Existence of village regulations	Availability of formal or customary rules governing mangrove use	0 = absent, 3 = comprehensive and enforced
	Community compliance with rules	Degree of adherence to mangrove regulations by local communities	0 = low, 3 = consistently high
	Government program access	Frequency and quality of external program support	0 = none, 3 = regular and targeted
	Coordination among agencies	Synergy and cooperation between related institutions	0 = none, 3 = highly coordinated

Data analysis

This study applied the Rapfish (Rapid Appraisal for Fisheries) approach, which employs Multidimensional Scaling (MDS) to evaluate the sustainability status of mangrove ecosystems across multiple dimensions. Rapfish enables rapid, semi-quantitative assessments by transforming qualitative or categorical data into numerical scores and plotting them in a two-dimensional ordination space (Pitcher and Preikshot 2001; Melo et al. 2020).

A total of 20 sustainability attributes, evenly distributed across four dimensions—ecological, economic, socio-cultural, and institutional—were scored based on field observations and structured community surveys. Each attribute was assigned a value ranging from 0 (least sustainable) to 3 (most sustainable), using standardized criteria. The scoring process was conducted in Microsoft Excel and analyzed with the Rapfish plugin, which produced MDS ordinations and sustainability indices for each dimension.

The MDS technique calculates the relative dissimilarity among observed units (in this case, the three study villages) by minimizing the stress value, which quantifies distortion between input data and the resulting ordination. A stress value below 0.25 is considered acceptable for sustainability modeling, ensuring reliable representation of inter-village variation (Sofian et al. 2019).

Each sustainability dimension was assessed independently to produce index scores on a scale from 0 to 100, reflecting the relative sustainability status of each village in a given dimension. These scores were then interpreted using a classification system adapted from Fadilah et al. (2021), which categorizes sustainability performance into four levels. Scores ranging from 0.00 to 25.00 are considered unsustainable, indicating critical conditions requiring urgent intervention. Values between 25.01 and 50.00 fall under the fairly unsustainable category, suggesting notable deficiencies and the need for substantial improvement. Scores from 51.01 to 75.00 are classified as moderately sustainable, implying that core functions are maintained but with room for enhancement. Finally, scores between 75.01 and 100.00 denote a fully sustainable status, reflecting well-balanced ecological and socio-institutional conditions. This classification framework allows for clear interpretation of index results and facilitates cross-dimensional comparisons to inform strategic planning and priority setting in mangrove management.

Importantly, the MDS analysis in this study was conducted using a unified data matrix for each dimension, where attribute scores from the three villages—Ujunggagak, Klaces, and Ujungalang—were combined into a single configuration. The Rapfish-MDS analysis also produced visual outputs, including radar (kite) diagrams and dimension-specific ordination plots. These tools illustrated the relative sustainability positioning of each village, highlighting which dimensions were relatively strong or weak.

Finally, the MDS results served as a foundation for leverage analysis and Monte Carlo simulation, both of which were used to assess the sensitivity and robustness of the sustainability scores. The integration of these complementary tools supports a comprehensive and evidence-based framework for diagnosing socio-ecological conditions and informing adaptive mangrove management strategies (Fadilah et al. 2021).

Leverage analysis

To identify the most influential factors affecting the sustainability scores within each dimension, this study conducted a leverage analysis using the Root Mean Square (RMS) output provided by the Rapfish software. Leverage analysis quantifies the sensitivity of each attribute by estimating how changes in its score affect the overall Multidimensional Scaling (MDS) ordination. Higher RMS values indicate that the attribute exerts a stronger influence on the sustainability status of the corresponding dimension (Pitcher and Preikshot 2001; Sofian et al. 2019).

For each of the four dimensions—ecological, economic, socio-cultural, and institutional—the RMS values were calculated, and attributes were ranked based on their sensitivity. Attributes with RMS values significantly above the median were classified as "sensitive" and considered priority areas for management intervention. Conversely, attributes with low RMS values were deemed less sensitive, indicating that changes in these variables would have a minimal effect on the sustainability index.

The distribution of RMS values across sustainability dimensions highlights the attributes with the greatest influence on the MDS results. Identifying these leverage points is essential for policymakers and local stakeholders, as it helps prioritize the most strategic variables capable of driving meaningful improvements in the overall sustainability of mangrove management in Segara Anakan Lagoon, Kampung Laut.

By focusing on sensitive attributes, leverage analysis enables targeted interventions and more efficient resource allocation in sustainability planning. It complements the MDS index by adding explanatory depth to the observed patterns and supports adaptive management approaches that are responsive to both ecological feedback and community dynamics (Fadilah et al. 2021; Chaliluddin et al. 2023).

Monte Carlo simulation and model validation

To evaluate the robustness of the sustainability assessment model, this study employed Monte Carlo simulation following the Rapfish-MDS protocol (Pitcher and Preikshot 2001; Melo et al. 2020). The simulation introduced controlled random variations (±0.1) into the attribute scores over 100 iterations for each sustainability dimension—ecological, economic, socio-cultural, and institutional. This procedure tested the sensitivity of the Multidimensional Scaling (MDS) configuration to minor fluctuations in input data.

In addition to Monte Carlo deviation, two statistical measures were used to assess model validity: the stress value and the coefficient of determination (R^2). A stress value below 0.25 indicates a satisfactory goodness-of-fit between input data and the ordination space (Sofian et al. 2019), while an R^2 above 0.90 demonstrates that the MDS configuration captures the majority of variance in the dataset. These combined metrics ensured that the results generated were stable and suitable for further interpretation and policy application.

RESULTS AND DISCUSSION

Characteristics of respondents

The survey involved 115 respondents from Ujunggagak, Klaces, and Ujungalang Villages, forming the basis for analyzing community interactions with mangrove ecosystems in Segara Anakan Lagoon, Kampung Laut. Their demographic characteristics provide essential context for interpreting environmental perceptions and patterns of institutional engagement.

As presented in Table 2, male respondents accounted for 68.70% of the sample, reflecting the gendered structure of fisheries and other resource-based livelihoods. Nevertheless, women played important roles in domestic resource use and informal conservation. A majority of respondents (53.04%) were between 30 and 49 years of age, while 13.04% were under 30 and 33.91% were 50 or older. This age structure indicates active participation from working-age adults who are directly involved in mangrove utilization and decision-making.

Education levels were relatively low, with 53.04% of respondents having completed only elementary school, and just 9.57% having attained higher education. Such limitations in formal education may influence the extent of environmental literacy and participation in structured conservation programs. In terms of occupation, fisheries dominated (40.00%), followed by farming or aquaculture (26.96%), small-scale trading and services (20.00%), and fish/crab traders (13.04%). These figures illustrate a high dependence on mangrove resources for both livelihood and subsistence, reinforcing the importance of designing sustainability strategies that are locally grounded and contextually sensitive (Theresia et al. 2015; Damastuti et al. 2022).

Table 3 and Figure 2 summarize community perceptions of mangrove-related benefits and threats, which offer critical insights that complement the demographic data. The most widely recognized ecosystem services included coastal protection (90.37%), nursery habitat functions (81.53%), and prevention of seawater intrusion (64.17%). These high recognition rates point to a relatively strong awareness of the ecological value of mangroves among local communities. In parallel, the most frequently cited threats were plastic and household waste (71.90%), illegal logging (60.13%), and land-use conversion (50.60%). Respondents also noted governance-related issues, including weak institutional supervision (27.97%) and conflict over resource use (35.83%).

Table 2. Demographic characteristics of respondents in Segara Anakan Lagoon, Kampung Laut, Indonesia

Variable	Category	Ujunggagak (n=40)	Klaces (n=35)	Ujungalang (n=40)	Total (n=115)
Sex	Male	29	22	28	79 (68.70%)
	Female	11	13	12	36 (31.30%)
Age Group	< 30 years	6	5	4	15 (13.04%)
	30-49 years	21	18	22	61 (53.04%)
	≥ 50 years	13	12	14	39 (33.91%)
Education Level	No formal education	4	2	3	9 (7.83%)
	Primary school	22	18	21	61 (53.04%)
	Secondary school	11	12	11	34 (29.57%)
	Higher education	3	3	5	11 (9.57%)
Occupation	Fisherman	18	12	16	46 (40.00%)
	Fish/Crab trader	6	5	4	15 (13.04%)
	Farmer/Aquaculture	10	9	12	31 (26.96%)
	Other (e.g., services)	6	9	8	23 (20.00%)

Table 3. Community perceptions of mangrove benefits and threats

Aspect	Response category	Ujunggagak (%)	Klaces (%)	Ujungalang (%)	Overall (%)
Perceived Benefits	Coastal protection (abrasion/flood)	90.0	88.6	92.5	90.37
	Breeding habitat for fish/crabs	82.5	77.1	85.0	81.53
	Preventing seawater intrusion	65.0	60.0	67.5	64.17
	Source of firewood/timber	42.5	54.3	47.5	48.10
	Tourism/recreation potential	17.5	22.9	20.0	20.13
Perceived Threats	Plastic and household waste	72.5	65.7	77.5	71.90
	Illegal logging	60.0	62.9	57.5	60.13
	Conversion to ponds/farms	47.5	54.3	50.0	50.60
	Conflict over land/resource use	35.0	40.0	32.5	35.83
	Lack of government supervision	27.5	31.4	25.0	27.97

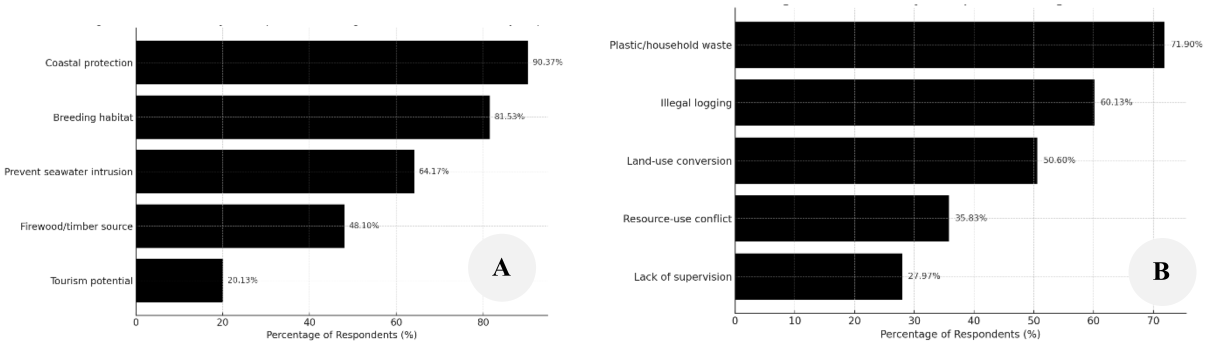

Figure 2. Community perceptions of mangrove ecosystem services and threats: A. Perceived benefits and B. Perceived threats

The alignment between perception-based insights and the quantitative RAP analysis (Table 5) further validates the relevance of these findings. Community recognition of key ecosystem functions corresponds to sensitive socio-cultural attributes identified through RAP, such as awareness of mangrove roles, cultural importance, and traditional knowledge. Similarly, the most perceived threats—such as waste accumulation and land-use conversion—corroborate sensitive ecological and institutional leverage points like pollution control, rule enforcement, and field supervision. These consistencies highlight the value of integrating local perceptions into formal sustainability assessments, ensuring that management responses are both empirically informed and grounded in lived experience.

Ecological and environmental conditions

Field observations revealed notable variation in ecological conditions across the three study villages—Ujunggagak, Klaces, and Ujungalang. These differences, particularly in salinity, vegetation structure, and signs of environmental degradation, underscore the importance of site-specific assessments to support the physical sustainability and resilience of local mangrove ecosystems.

Salinity levels, measured using handheld refractometers, ranged from 10.2 to 24.7‰ across all sites and significantly influenced ecological characteristics. Ujunggagak recorded the highest average salinity (22.8‰), consistent with its proximity to open marine inlets. In contrast, Klaces and Ujungalang exhibited lower and more variable salinity (17.4 and 14.6‰, respectively), with observable ecological impacts. This salinity gradient affected mangrove species composition, seedling establishment, and zonation patterns (Ahmed et al. 2023; Wang et al. 2024a).

Regarding vegetation structure, Ujungalang demonstrated the highest stem density and canopy closure, indicative of better ecological integrity and lower disturbance levels. Conversely, Ujunggagak exhibited partial deforestation and reduced species diversity, likely linked to its proximity to active fishing areas and settlements. Commonly observed species included *Avicennia marina*, *Rhizophora mucronata*, and *Bruguiera gymnorhiza*, with *Sonneratia alba* occasionally present in less disturbed zones (Widyastuti et al. 2018).

Substrate conditions also varied among sites. Klaces and Ujungalang featured relatively stable muddy-sand substrates, while Ujunggagak showed compacted soils with signs of erosion. Visible pollutants such as plastic debris, timber waste, and aquaculture residue were more frequently observed in Ujunggagak and Klaces, corresponding to higher human activity densities.

Indicators of environmental degradation included cutting, trampling, and illegal dumping, especially near settlements and aquaculture zones. These anthropogenic pressures reduce biodiversity and habitat quality. Observations indicated that Ujungalang was comparatively more regulated, with lower levels of direct human impact.

These findings indicate that while all three villages maintain ecologically functional mangrove systems, the degree of environmental stress and habitat integrity differs markedly. These differences likely stem from variations in local management, accessibility, and exposure to tidal and anthropogenic factors. Table 4 summarizes the ecological attributes recorded at each site.

Field-based ecological observations summarized in Table 4 provide the empirical foundation for the ecological dimension of the sustainability assessment in Table 5. Variations in salinity across the villages—ranging from high (22.8‰) in Ujunggagak to low (14.6‰) in Ujungalang—support the designation of *salinity fluctuation* as a sensitive attribute with high RMS values. Likewise, differences in stem density and canopy cover, with Ujungalang exhibiting the highest vegetation density (2,300 stems/ha), reinforce the classification of mangrove vegetation density as a key ecological driver. Observed waste accumulation, particularly in Ujunggagak and Klaces, aligns with the sensitivity of the waste/garbage accumulation attribute, reflecting direct human impact on mangrove habitats. Although some attributes such as seedling survival rate and biodiversity observation are not directly detailed in Table 4, the degradation indicators and dominant species presence provide contextual evidence for their inclusion and relative sensitivity. Overall, the site-specific ecological patterns in Table 4 substantiate the attribute rankings and RMS outputs in Table 5, ensuring that the sustainability analysis remains grounded in real-world environmental conditions.

Table 4. Summary of ecological attributes observed in the study villages

Ecological attribute	Ujunggagak	Klaces	Ujungalang
Average salinity (‰)	22.8	17.4	14.6
Salinity fluctuation	Moderate	Moderate-high	Low
Dominant mangrove species	*Avicennia marina*, *Rhizophora mucronata*	*Rhizophora mucronata*, *Bruguiera gymnorhiza*	*Rhizophora mucronata*, *Sonneratia alba*
Stem density (stems/ha)	1,200	1,850	2,300
Canopy cover (%)	~40	~60	~80
Substrate condition	Compacted, eroded	Muddy-sand, stable	Muddy-sand, stable
Visible pollutants	Plastic waste, timber debris, feed residues	Plastic debris	Minor organic litter only
Environmental degradation	Deforestation signs, garbage dumping, trampling	Moderate human disturbance	Low disturbance, better protection
Anthropogenic pressure	High (near settlements/fishing)	Medium	Low
Seedling survival rate (%)	45	60	78
Crab/fish species observed	2-3	3-4	5-6

Sustainability index per dimension

The scoring results of individual sustainability attributes across ecological, economic, socio-cultural, and institutional dimensions are presented in Table 5. These scores were used to compute sustainability indices, Root Mean Square (RMS) values, and leverage factors, as visualized in Figure 3.

The multidimensional scaling (MDS) analysis yielded distinct sustainability index scores for each of the four dimensions—ecological, economic, socio-cultural, and institutional—across the three study villages. These scores provide a comparative overview of the strengths and weaknesses in the sustainability profile of mangrove ecosystems in the Segara Anakan Lagoon (Figure 3).

The ecological dimension recorded the highest index value, with an overall score of 55.99, indicating a moderately sustainable status. This score reflects fair vegetation conditions and species presence, but also highlights issues such as localized pollution and pressure from land use conversion, particularly in Ujunggagak. The presence of tolerant species like *A. marina* may contribute to ecological persistence, but reduced structural diversity and increasing salinity stress remain concerns (Wilda et al. 2020; Haseeba et al. 2025). The institutional dimension followed closely, with a score of 58.89, also categorized as moderately sustainable. This reflects the partial effectiveness of village-level regulations, the presence of field officers, and moderate community involvement in management activities. While awareness of mangrove rules exists, enforcement and integration across administrative scales remain uneven (Damastuti et al. 2022). The socio-cultural dimension scored 42.79, which falls under the category of fairly unsustainable. Although there is local knowledge about the importance of mangroves and some engagement in conservation, social conflict, low youth involvement, and weak intergenerational transmission of environmental values limit overall sustainability (Akram et al. 2023; Wang et al. 2024b).

The economic dimension obtained the lowest score at 27.74, indicating a fairly unsustainable status. This reflects strong dependence on primary resources with limited diversification of income sources, lack of access to formal markets, and minimal support for alternative livelihoods. Economic vulnerability is exacerbated by seasonal income fluctuation and limited infrastructure (Hilmi et al. 2021; Sahputra et al. 2021). Low scores in attributes such as energy cost reduction and income increase perception further underscore the fragility of economic resilience across the villages.

Table 6 presents the complete sustainability index values for each dimension based on the MDS output. These results highlight the need for multidimensional interventions, especially in economic empowerment and social cohesion, to support long-term mangrove conservation in the region.

Overall sustainability status

A comprehensive evaluation of sustainability in Segara Anakan Lagoon, Kampung Laut's mangrove management was achieved by integrating the index scores across four key dimensions: ecological, economic, socio-cultural, and institutional. This composite analysis offers a holistic view of the system's current condition and highlights areas of relative strength and critical weakness.

As illustrated in Figure 4, the kite diagram presents a clear asymmetry in sustainability performance across dimensions. The ecological (55.99) and institutional (58.89) dimensions appear at the outer edges of the diagram, reflecting moderately sustainable conditions. These findings suggest that, at present, the physical condition of the mangrove ecosystem and the institutional framework supporting its governance are functioning with moderate effectiveness.

In contrast, the economic (27.74) and socio-cultural (42.79) dimensions lie closer to the center of the diagram, indicating fairly unsustainable conditions. The economic dimension in particular shows the lowest score, reflecting severe challenges in livelihood diversification, value chain access, and overall economic resilience. Meanwhile, the socio-cultural dimension points to gaps in intergenerational knowledge transfer, limited youth engagement, and insufficient community participation, despite strong local dependency on mangrove resources.

Table 5. Root Mean Square (RMS) values and sensitivity categories for sustainability attributes in mangrove management

Dimension	Attribute	RMS value	Sensitivity category
Ecological	Salinity fluctuation	8.45	Sensitive
	Mangrove vegetation density	7.66	Sensitive
	Waste/garbage accumulation	7.12	Sensitive
	Mangrove seedling survival rate	5.23	Less Sensitive
	Biodiversity observation (crab/fish)	4.67	Less Sensitive
Median RMS		—	6.87
Economic	Mangrove product use	9.21	Sensitive
	Livelihood diversification	8.78	Sensitive
	Energy cost reduction	6.04	Sensitive
	Income increase perception	5.27	Less Sensitive
	Access to capital/market	4.12	Less Sensitive
Median RMS		—	6.04
Socio-cultural	Participation in mangrove programs	8.02	Sensitive
	Conflict over mangrove use	7.88	Sensitive
	Traditional knowledge use	5.61	Less Sensitive
	Environmental awareness	5.07	Less Sensitive
	Generational transmission of values	4.83	Less Sensitive
Median RMS		—	5.61
Institutional	Presence of field officers	9.34	Sensitive
	Existence of village regulations	8.16	Sensitive
	Community compliance with rules	7.42	Sensitive
	Government program access	5.28	Less Sensitive
	Coordination among agencies	4.51	Less Sensitive
Median RMS		—	7.42

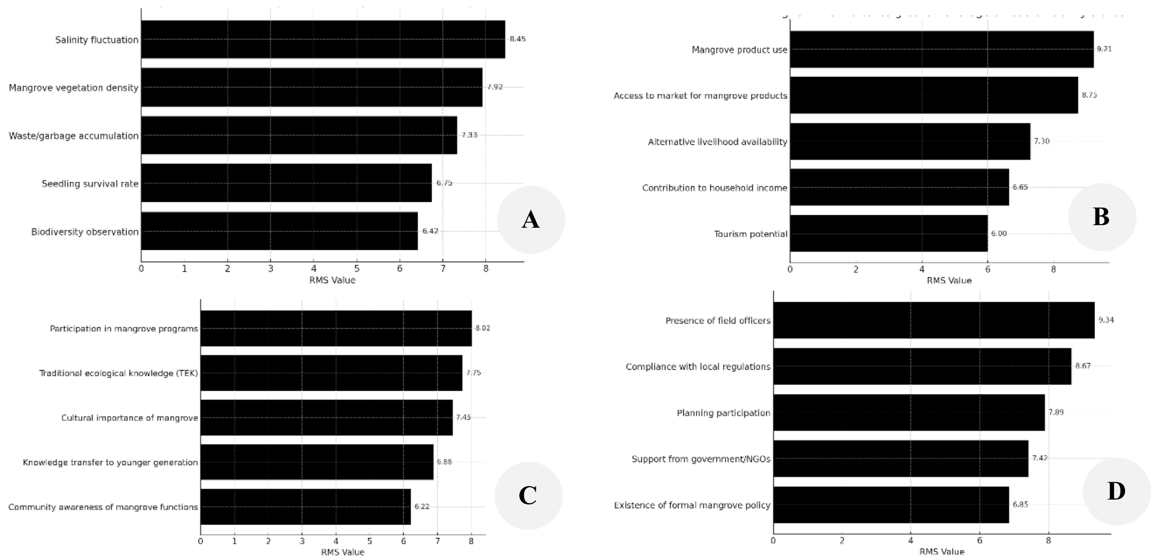

Figure 3. Root Mean Square (RMS) values of key sustainability attributes across four dimensions: A. Ecological, B. Economic, C. Socio-cultural, and D. Institutional

Table 6. Sustainability index per dimension of mangrove management in Segara Anakan Lagoon, Kampung Laut, Indonesia

Sustainability dimension	MDS score	Sustainability status
Ecological	55.99	Moderately sustainable
Economic	27.74	Fairly unsustainable
Socio-cultural	42.79	Fairly unsustainable
Institutional	58.89	Moderately sustainable

The visual asymmetry of the kite diagram (Figure 4) underscores an unbalanced sustainability profile, where progress in ecological and institutional areas is not matched by equivalent development in social and economic sectors. Without targeted interventions, this imbalance threatens the long-term viability of the mangrove management system (Fadilah et al. 2021; Chaliluddin et al. 2023).

In addition, Figure 2 depict community perceptions regarding mangrove benefits and threats, respectively.

These figures, derived from the data in Table 3, complement the sustainability index analysis by highlighting local awareness and concerns. For example, communities show high recognition of ecosystem services like coastal protection and fish nursery functions, but also express strong concern about threats such as plastic waste, illegal logging, and land conversion.

Together, these findings emphasize the urgency of a more integrated, cross-dimensional strategy for mangrove sustainability. Enhancing economic opportunities and strengthening socio-cultural engagement are essential to support the more resilient ecological and institutional pillars, thereby improving the system's overall sustainability and adaptability to future challenges.

Sensitive attributes in each dimension

Leverage analysis identified a set of high-impact attributes within each sustainability dimension based on their Root Mean Square (RMS) values. Attributes with RMS values equal to or greater than the median for their respective dimension were classified as sensitive, indicating a strong influence on the overall sustainability index. Improvements in these sensitive attributes are likely to result in significant changes in sustainability performance, making them strategic entry points for targeted interventions and policy enhancement.

In the ecological dimension, the most sensitive attributes included salinity fluctuation (RMS=8.45), mangrove vegetation density (7.66), and waste or garbage accumulation (7.12), all exceeding the median RMS of 6.87. These findings highlight the need for salinity regulation, restoration of vegetation structure, and waste management to sustain ecological integrity. Conversely, seedling survival rate (5.23) and biodiversity observation (4.67) were classified as less sensitive, indicating limited short-term leverage. These patterns align with earlier studies emphasizing the importance of abiotic conditions and canopy structure in maintaining mangrove ecosystem function (Akram et al. 2023).

In the economic dimension, the highest leverage was found in mangrove product use (RMS=9.21), livelihood diversification (8.78), and energy cost reduction (6.04)—the latter meeting the median threshold and thus classified as sensitive. These attributes reflect strong dependence on mangrove resources and highlight the vulnerability of the local economy to ecological change. In contrast, income increase perception (5.27) and access to capital or markets (4.12) were less sensitive, suggesting limited influence on the current sustainability profile. It is important to note that although tourism potential was recognized by a portion of the community (see Table 3), it was excluded from RMS analysis due to its low relative importance and underdeveloped status across the study sites. This indicates that tourism has yet to emerge as a key economic driver in the current sustainability landscape.

In the socio-cultural dimension, participation in mangrove programs (8.02), conflict over mangrove use (7.88), and traditional knowledge use (5.61) met or exceeded the median RMS of 5.61 and were categorized as sensitive. These findings underscore the importance of participatory mechanisms, social cohesion, and the integration of traditional knowledge in sustaining collective stewardship. Meanwhile, environmental awareness (5.07) and intergenerational knowledge transmission (4.83) were found to be less sensitive, suggesting they may require complementary interventions to enhance their impact on sustainability.

The institutional dimension showed the highest leverage in presence of field officers (RMS=9.34), existence of village regulations (8.16), and community compliance with rules (7.42), all equal to or above the median RMS of 7.42. These results emphasize the central role of governance presence, regulatory clarity, and enforcement in ensuring effective mangrove management. Attributes such as government program access (5.28) and inter-agency coordination (4.51), though important, were less sensitive and likely play enabling rather than immediate roles in influencing sustainability outcomes.

These RMS distributions are visualized in Figure 3, showing the relative influence of each attribute within its respective dimension. The full list of RMS values and sensitivity classifications is presented in Table 5, while Table 7 highlights the top leverage attributes along with recommended management strategies.

Table 7. Strategic leverage attributes per dimension

Dimension	Sensitive attribute	RMS value	Recommended strategic action
Ecological	Salinity fluctuation	8.45	Hydrological restoration and salinity control
Economic	Mangrove product use	9.21	Support for product processing and market access
Socio-cultural	Participation in mangrove programs	8.02	Community engagement and co-management schemes
Institutional	Presence of field officers	9.34	Continuous field facilitation and enforcement

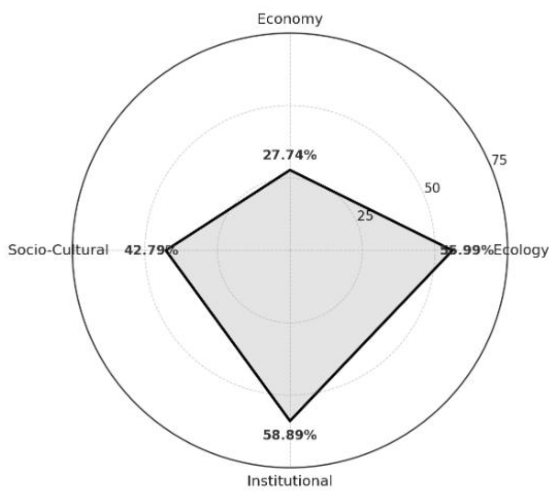

Figure 4. Kite diagram of multidimensional sustainability

Model robustness and validation

The Monte Carlo simulation results confirmed that the sustainability assessment model was statistically robust and reliable across all four dimensions. Deviations between original and simulated MDS scores were minimal: 0.83% for the ecological dimension, 0.65% for economic, 0.58% for socio-cultural, and 0.63% for institutional, yielding an average deviation of 0.67%—well below the 5% threshold widely accepted in sustainability modeling (Fadilah et al. 2021).

In terms of model fit, the MDS analysis produced stress values ranging from 0.09 to 0.14, indicating excellent correspondence between the input data structure and two-dimensional ordination. Additionally, all dimensions achieved coefficients of determination (R^2) above 0.94, confirming the high explanatory power of the ordination results.

These validation metrics are summarized in Table 8, and their consistency is visually represented in Figure 5, which shows the alignment between original MDS scores and those generated through simulation. This high degree of reliability reinforces the credibility of the leverage analysis and the identified sensitive attributes. It also supports the broader use of the Rapfish-MDS framework as a practical tool for assessing complex (Sahputra et al. 2021; Chaliluddin et al. 2023), community-based socio-ecological systems like those found in the Segara Anakan Lagoon.

Discussion

Ecological dimensions of sustainability

The ecological sustainability of mangrove ecosystems in Segara Anakan Lagoon, Kampung Laut demonstrates a balance between residual resilience and emerging ecological pressures. The MDS analysis yielded a moderate sustainability score of 55.99, suggesting that while core ecological functions persist, several environmental stressors pose long-term threats. Among the most sensitive attributes identified, salinity level had the strongest influence on ecological scores. Variability in salinity—especially high readings in Ujunggagak—was associated with reduced species diversity and the dominance of stress-tolerant taxa like *A. marina*. Similar patterns in Southeast Asian estuaries have shown that altered tidal regimes and reduced freshwater input limit mangrove regeneration and vertical growth (Blanton et al. 2024).

Vegetation density and canopy cover were also key leverage points. Sites with denser vegetation, notably Ujungalang, achieved higher ecological scores due to intact regeneration and minimal disturbance. These findings align with Basyuni et al. (2022), who linked structured canopy layers to higher biodiversity and hydrological function. In contrast, thinning canopies in Klaces and Ujunggagak indicate early-stage degradation, often linked to wood harvesting, aquaculture, or unmanaged waste near settlements.

Pollutant presence, especially plastic debris and aquaculture residues, further degraded ecological integrity. Plastics disrupt substrate quality, impede pneumatophore function, and inhibit seedling establishment. Similar impacts have been recorded in urban-influenced mangroves across Indonesia (Cordova et al. 2023; Jamili et al. 2023). Although substrate condition was a less sensitive attribute, its role in root anchorage and nutrient cycling remains important. Erosion and compaction—observed in some Ujunggagak plots—may reduce the establishment of less adaptive species, affecting long-term resilience (Alongi 2014).

Overall, Segara Anakan Lagoon, Kampung Laut's mangrove ecosystems remain ecologically functional but are increasingly vulnerable to both climatic and anthropogenic stressors. Effective management should focus on mitigating salinity fluctuations via hydrological restoration, reducing physical disturbance, and addressing pollution. Conservation strategies that include reforestation with native species and community-based stewardship could help maintain ecological functions and enhance resilience (Gunawan et al. 2025).

Institutional support and governance effectiveness

The institutional dimension of mangrove sustainability in Segara Anakan Lagoon, Kampung Laut received a moderately sustainable score of 58.89, indicating that governance structures—both formal and informal—play a meaningful, though still limited, role in supporting conservation. Leverage analysis identified three high-impact attributes: the presence of field officers, the existence of regulatory frameworks, and the level of community compliance.

Table 8. Monte Carlo validation results and model stress values

Dimension	Stress Value	R^2	Monte Carlo	Interpretation
Ecological	0.14	0.942	0.83	Robust
Economic	0.13	0.951	0.65	Robust
Socio-cultural	0.11	0.961	0.58	Robust
Institutional	0.09	0.972	0.63	Robust
Average	0.12	0.957	0.67	Statistically Valid

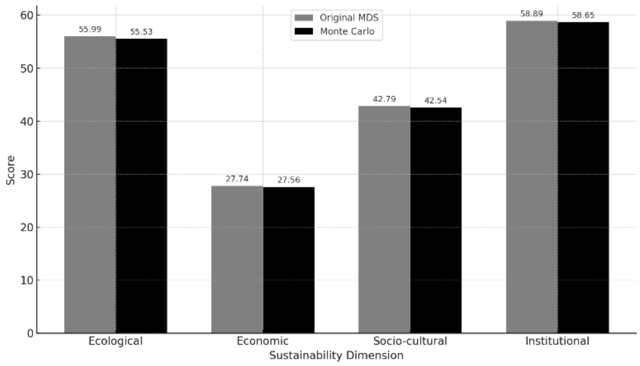

Figure 5. Monte Carlo vs. MDS score comparison

Field officers, including forestry staff, local coordinators, and NGO facilitators, significantly influenced institutional performance. In villages like Ujungalang, consistent field-level presence corresponded with higher institutional scores. These findings echo Castillo et al. (2024), who argue that visible enforcement fosters accountability and knowledge transfer and reduces illegal activities in coastal zones. The availability of local regulations—both customary (*awig-awig*) and formal decrees (*perdes*)—also contributed positively, although enforcement varied widely. In some cases, regulations existed but lacked effective dissemination, political support, or funding. This discrepancy between regulation and implementation is common in Indonesia's decentralized governance systems (Arifanti et al. 2022b; Damastuti et al. 2022).

Community compliance further underscored the importance of legitimacy and local trust. Villages with participatory governance processes exhibited stronger compliance, while those with top-down or poorly enforced rules showed weaker adherence. These patterns align with Chaliluddin et al. (2023), who highlight the role of co-management and community engagement in sustaining resource governance. Lower leverage attributes—such as inter-agency coordination or access to national programs—suggest that higher-level governance frameworks play a background role in day-to-day sustainability outcomes. While they do not have a direct impact, they have latent potential that could be unlocked through better institutional integration.

In short, institutional sustainability in Segara Anakan Lagoon, Kampung Laut is shaped by the strength of local enforcement, rule clarity, and participatory mechanisms. Although governance systems are present, their effectiveness remains uneven across villages. Enhancing this dimension requires refining regulatory instruments and fostering adaptive governance practices that embed community participation, monitoring, and responsive decision-making into everyday resource management (Sahputra et al. 2021; Ardiyanto et al. 2024).

Economic vulnerability and resource dependency

The economic dimension of mangrove sustainability in Segara Anakan Lagoon, Kampung Laut received the lowest index score (27.74), placing it in the fairly unsustainable category. This reflects typical challenges in resource-dependent coastal communities, where economic fragility is closely linked to environmental conditions and limited institutional support. Leverage analysis identified key vulnerabilities: high dependency on mangrove-based resources, lack of alternative livelihoods, and restricted access to capital or market networks. Low scores in attributes such as energy cost reduction and income increase perception further underscore the fragility of economic resilience across the villages. These results suggest that even subsistence-level economic benefits from mangroves are perceived as insufficient, and opportunities for financial improvement remain limited.

Across all villages, respondents reported heavy reliance on fishing, crab and shrimp trapping, and some firewood collection. These activities are highly sensitive to mangrove health and seasonal fluctuations. As resource availability declines due to ecological degradation, households become more exposed to external shocks such as extreme tides, declining catch, or regulatory limits (Theresia et al. 2015; Hilmi et al. 2021).

A particularly critical issue is the absence of diversified income sources. While firewood collection contributes marginally to household energy needs and is reflected in the energy cost reduction indicator, its contribution is small and potentially unsustainable. In the long term, dependence on mangrove wood risks exacerbating forest degradation, especially if not balanced with replanting or harvesting regulations (Fadilah et al. 2021). Meanwhile, perceptions regarding income increase remain low, indicating that mangrove-related activities—though widespread—have not substantially improved household financial security.

Although tourism potential was recognized by some community members (Table 3), it was not included in the RMS-based analysis due to its low prioritization and the lack of formal infrastructure or organized initiatives supporting ecotourism. This suggests that while the idea of mangrove-based tourism exists, it remains aspirational rather than operational in the current economic landscape.

Market access also remains limited due to the remoteness of the villages, poor transportation infrastructure, and lack of institutional support such as cooperatives or value chain facilitation. As a result, many residents rely on middlemen to sell fish or crabs, resulting in low and unstable prices. Credit access is also restricted, and financial literacy programs are largely absent from the villages studied.

The economic sustainability of mangrove communities in Segara Anakan Lagoon, Kampung Laut is undermined by low diversification, marginal income perception, and the absence of enabling conditions for economic transformation. Interventions must prioritize capacity-building, support for product processing and value addition, and improved access to both physical markets and financial institutions. Without these foundational changes, the economic contributions of mangrove ecosystems will remain limited and volatile.

Socio-cultural participation and environmental values

The socio-cultural dimension received a fairly unsustainable score of 42.79, reflecting challenges in translating community awareness into consistent engagement and pro-environmental behavior. While many respondents acknowledged the ecological importance of mangroves, this understanding has not resulted in widespread participation in conservation efforts.

Leverage analysis revealed that environmental conflict and participation in mangrove programs were the most sensitive attributes. In several villages, overlapping land claims between fishpond operators, customary rights holders, and government authorities created tensions that undermined cooperation. This issue is common in other parts of coastal Java and Southeast Asia, where externally imposed rules lacking local consultation often erode trust and social capital (Theresia et al. 2015; Koesdaryanto et al. 2024).

Community involvement was generally limited to symbolic activities such as tree planting or coastal clean-ups without sustained roles in planning, monitoring, or benefit-sharing. Villages with long-term NGO presence demonstrated better engagement, suggesting that consistent facilitation is crucial to fostering a sense of local ownership (Damastuti et al. 2022). Although not the most sensitive in leverage terms, cultural attachment to mangroves, traditional knowledge, and intergenerational value transmission remain vital for long-term stewardship. However, younger generations are reportedly less engaged in mangrove-related practices, often due to migration or changing aspirations. This generational disconnect threatens the continuity of ecological values, especially in areas where mangrove use was once embedded in customary rituals and tenure systems (Ardiyanto et al. 2024).

Furthermore, limited formal education—evident in the respondent demographics—may reduce the community's access to scientific knowledge and lessen the impact of top-down awareness programs. Without alignment to local languages, norms, and livelihoods, environmental messaging may fail to resonate. To address this, context-specific communication strategies involving oral traditions, community role models, and peer learning are needed.

Overall, strengthening the socio-cultural dimension requires more inclusive and sustained community engagement. Empowering local institutions, integrating cultural systems, and resolving underlying social tensions are essential to converting passive awareness into active participation, ensuring that ecological and institutional progress is embraced and upheld by the communities themselves (Fadilah et al. 2021; Chaliluddin et al. 2023).

Strategic leverage points for sustainable intervention

Identifying sensitive attributes across the four sustainability dimensions offers actionable entry points for targeted intervention in Segara Anakan Lagoon, Kampung Laut. By focusing on leverage points—variables with the highest influence on sustainability outcomes—decision-makers can direct resources toward solutions with systemic benefits.

Within the ecological dimension, salinity regulation, vegetation density, and waste control emerged as critical. These suggest prioritizing hydrological restoration (e.g., water flow rechanneling), reforestation using native mangrove species, and localized waste management systems. Such actions not only address ecological degradation but also align with community preferences for visible environmental improvements (Kesavan et al. 2021; Basyuni et al. 2022).

The economic dimension highlighted leverage in mangrove-based livelihoods, income diversification, and cost-saving behavior. Interventions should include training in product processing, support for cooperatives, and improved access to microcredit. Linking local products to broader markets—such as sustainable seafood or eco-labeling platforms—can increase economic resilience and reduce dependence on extractive activities (Hilmi et al. 2021; Sahputra et al. 2021).

In the socio-cultural dimension, the most influential attributes were community participation and conflict resolution. Addressing these requires more than technical inputs; it involves participatory planning, social facilitation, and mechanisms to mediate overlapping claims. Engagement of youth and women's groups is also key to maintaining long-term stewardship and preventing generational disengagement (Theresia et al. 2015).

For the institutional dimension, the presence of field officers and the clarity of local regulations were decisive. Enhancing these requires sustained field-based facilitation, regular policy reviews, and capacity building at the village level. Establishing multi-stakeholder platforms could improve coordination among governmental, customary, and civil actors, fostering legitimacy and shared governance (Damastuti et al. 2022; Chaliluddin et al. 2023).

Several cross-cutting leverage points—such as environmental education, access to information, and participatory governance—should be integrated across dimensions rather than addressed in isolation. The Rapfish-MDS framework enables visualization of these interconnected priorities and supports adaptive, multi-sectoral management. In complex socio-ecological systems like Segara Anakan Lagoon, Kampung Laut, where livelihoods, ecology, and institutions are tightly linked, translating leverage insights into policy and practice will depend not only on technical solutions but also on sustained political commitment and community trust.

Methodological robustness and applicability of Rapfish

The Rapfish (Rapid Appraisal for Fisheries) framework, adapted for assessing mangrove sustainability, demonstrated strong methodological robustness and analytical utility in this study. By applying Multidimensional Scaling (MDS) to a diverse set of qualitative and semi-quantitative indicators, the method provided a comprehensive overview of ecological, economic, socio-cultural, and institutional conditions in Segara Anakan Lagoon, Kampung Laut.

Validation through Monte Carlo simulations revealed a mean deviation of only 0.67% across all four dimensions, well below the commonly accepted threshold of 5%, confirming the model's statistical stability. Furthermore, stress values remained between 0.09 and 0.14, and coefficients of determination (R^2) exceeded 0.94, indicating a high degree of fit between the ordination configuration and the underlying dataset. These findings affirm that the results are not only methodologically sound but also reliable for guiding real-world decision-making (Pitcher and Preikshot 2001; Melo et al. 2020).

One of Rapfish's key strengths is its flexibility to integrate multiple data types—from perception-based surveys to ecological observations—without requiring a high level of data standardization. This makes it highly suitable for data-limited coastal settings, where complex interdependencies between resource systems and social institutions often preclude purely quantitative modeling (Fadilah et al. 2021). In this study, Rapfish allowed for rapid yet holistic diagnostics, enabling stakeholders to visualize trade-offs and prioritize interventions using the kite diagram and leverage plots.

However, several limitations should be acknowledged. First, the subjective scoring of indicators—although cross-validated—may introduce biases based on respondent knowledge or enumerator interpretation. Second, while Rapfish is effective in comparative diagnostics, it does not inherently model causal relationships or simulate future trajectories. For that purpose, integration with system dynamics models, scenario planning, or spatial mapping could strengthen decision support.

Another consideration is the scale of analysis. Rapfish performs well at the community or village level, but its application at larger governance scales (e.g., district or provincial) may require significant adaptation in indicator selection, weighting, and stakeholder involvement. Moreover, the method's communicative value—while high among trained researchers—may be less intuitive to policymakers or community members unfamiliar with MDS outputs, requiring deliberate translation into actionable insights (Damastuti et al. 2022).

Despite these caveats, the study reaffirms Rapfish's utility as a diagnostic and participatory assessment tool for mangrove systems. When combined with leverage analysis and robust stakeholder engagement, it offers a strategic framework for evidence-based, cross-sectoral sustainability planning. Its application in the Segara Anakan Lagoon serves as a model for other complex, resource-dependent coastal landscapes in Indonesia and beyond.

In conclusion, this study assessed the multidimensional sustainability of mangrove ecosystems in Segara Anakan Lagoon, Kampung Laut, Indonesia, revealing a clear imbalance across dimensions. While the ecological and institutional aspects were moderately sustainable, the economic and socio-cultural dimensions remained fairly unsustainable due to limited livelihood diversification, weak income contribution from mangrove resources, and low community engagement. Leverage analysis identified key attributes driving these outcomes, including salinity fluctuation, vegetation density, energy cost reduction, income increase perception, community participation, and governance presence. Although tourism potential was recognized by some community members, it was excluded from the scoring matrix due to low prioritization and minimal development across the villages. The Rapfish-MDS method, validated through Monte Carlo simulation with a mean deviation of 0.67%, effectively highlighted sensitive leverage points for targeted intervention. To improve sustainability, recommended strategies include ecological restoration, support for income-generating activities, participatory governance, and strengthened intergenerational knowledge transfer. The study demonstrates the value of combining community-based data with semi-quantitative tools for diagnosing socio-ecological systems and informing adaptive management. Its findings provide a practical entry point for policy alignment and capacity-building in coastal regions experiencing ecological stress and economic vulnerability.

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Diversity and potential utilization of macrofungi in the riparian area of the Samin River, Central Java, Indonesia

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Abstract. *Putri RRA, Fajri R, Rahmadhani SE, Salsabila S, Himawan W, Septiasari A, Yap CK, Setyawan AD. 2025. Diversity and potential utilization of macrofungi in the riparian area of the Samin River, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 86-102.* Macrofungi play essential roles in decomposition, nutrient cycling, and ecosystem functioning, yet their diversity in the riparian habitats of Java (Indonesia) remains poorly documented. This study provides a comprehensive assessment of macrofungal communities along the Samin River, Central Java, covering upstream, middle, and downstream segments. Surveys were conducted in March-April 2024 using belt-transect observations (10 m × 100 m per station) across six locations. All encountered fruiting bodies were recorded, photographed, and identified based on macromorphological and microscopical features, with substrate type categorized into weathered logs (W), leaf litter (L), soil (S), tree bark (T), and animal dung (A). Diversity indices (Shannon–Wiener H', Simpson D, Margalef R, and Evenness E) and substrate distributions were analyzed to evaluate spatial patterns in community structure. A total of 98 macrofungal species belonging to 38 families, 13 orders, and two phyla (Ascomycota and Basidiomycota) were confirmed, with Basidiomycota predominating. The most species-rich families were Mycenaceae, Polyporaceae, Marasmiaceae, and Agaricaceae. Species richness was comparable between the upstream and middle sections (41 species each), but the upstream section exhibited the highest ecological diversity as reflected by diversity indices (H' = 3.03, R = 6.40), whereas downstream areas showed lower diversity values (H' = 2.29, R = 3.88). These patterns reflect environmental gradients in humidity, canopy cover, light intensity, and substrate availability along the river continuum. Weathered logs were the most frequently colonized substrate, supporting more than half of all species, including ecologically important lignicolous taxa (e.g., *Xylaria*, *Crepidotus*, *Cerrena*, *Schizophyllum*). Several species displayed multi-substrate flexibility (e.g., *Marasmius elegans*), indicating functional adaptability to riparian microhabitats. Edible and medicinal taxa—such as *Auricularia auricula-judae*, *Termitomyces* sp., and *Schizophyllum commune* —highlight the biocultural and biotechnological value of riparian macrofungi. The Samin River corridor serves as a biodiversity reservoir that merits greater conservation attention and provides promising opportunities for sustainable fungal utilization.

Keywords: Lignicolous fungi, macrofungal diversity, riparian ecosystem, Samin River, substrate ecology

INTRODUCTION

Macrofungi play an essential role in maintaining ecological processes across terrestrial landscapes, particularly in humid tropical environments where organic matter decomposes rapidly. These organisms function as primary decomposers capable of breaking down lignin, cellulose, and other complex organic compounds, thereby facilitating nutrient cycling and maintaining soil fertility (Boa 2004; Miles and Chang 2004). Their presence often reflects the ecological condition of an ecosystem since macrofungi respond sensitively to microclimatic variation, substrate availability, and habitat disturbance. As a result, macrofungal communities provide valuable insights into environmental stability and habitat quality in both natural and human-modified ecosystems (Boddy and Heilmann-Clausen 2018).

Beyond their fundamental ecological roles, many macrofungal taxa possess substantial potential for utilization as food, medicine, and sources of bioactive compounds. Species belonging to genera such as *Auricularia*, *Termitomyces*, *Ganoderma*, and *Schizophyllum* are well known for their nutritional, antimicrobial, immunomodulatory, and antioxidant properties (Elkhateeb and Daba 2021; Bibi et al. 2023; Mayra et al. 2024). Several saprophytic taxa have also attracted scientific interest due to their biotechnological applications, such as enzyme production, bioconversion of agricultural waste, and environmental remediation (Cohen et al. 2002). Despite this potential, baseline information on macrofungal richness, distribution patterns, and substrate associations remains limited in many tropical regions, including Indonesia. Such knowledge gaps constrain the development of sustainable resource utilization and ecological monitoring frameworks.

Riparian ecosystems function as transitional ecotones where terrestrial and aquatic processes intersect, creating unique microhabitats that support diverse fungal communities. Continuous input of woody debris, leaf litter, and organic sediment provides a wide variety of substrates for colonization, while fluctuating humidity and canopy structure further enhance habitat heterogeneity. Studies in tropical forest systems have shown that macrofungal assemblages are strongly structured by substrate type and habitat heterogeneity, with woody debris and leaf litter supporting a large proportion of recorded taxa and driving patterns of fungal diversity and ecological function (Kumar et al. 2013). These conditions are favorable for saprophytic, lignicolous, and soil-dwelling macrofungi, many of which depend on stable moisture regimes and shaded microenvironments for sporocarp formation (Rahmi et al. 2021; Mahardhika et al. 2022). In tropical riparian systems, the interplay between hydrology, vegetation, and substrate dynamics produces fungal assemblages distinct from those found in upland forests or agricultural ecosystems. However, such habitats remain understudied compared with forest reserves, mangroves, or highland ecosystems.

In Indonesia, research on macrofungi has predominantly focused on forested regions, community-based foraging practices, or market surveys. Studies that document macrofungal diversity in riparian landscapes are rare, particularly those employing quantitative ecological indices such as Shannon-Wiener, Simpson, species richness, and evenness metrics. Moreover, existing works often emphasize taxonomic inventories without integrating analyses of substrate-specific distribution or ecological function (Putra 2020; Yusran et al. 2024). This imbalance limits understanding of how environmental gradients, land-use patterns, and substrate availability shape macrofungal assemblages across different habitat types.

The Samin River in Central Java represents a critical ecological corridor flowing through a heterogeneous landscape composed of mixed agriculture, community forests, and rural settlements. Such mosaics generate varied microhabitats that potentially influence macrofungal distribution, especially in terms of substrate availability, disturbance intensity, and moisture conditions. Despite its ecological significance, no comprehensive assessment has been conducted to document macrofungal diversity along the this river. In particular, information on substrate associations-whether species prefers weathered logs, leaf litter, soil, tree trunks, or animal dung-remains unavailable. This gap restricts efforts to compare riparian fungal communities with other habitats and inhibits the identification of species with potential nutritional or medicinal value.

Given the ecological importance of macrofungi and the lack of systematic studies in riparian environments of Central Java, therefore, this study aims to: (i) document macrofungal species occurring along upstream, middle, and downstream sections of the Samin River, (ii) evaluate community structure using Shannon-Wiener, Simpson, richness, and evenness indices (Madsen and Crook 2021), and (iii) analyze substrate-specific associations and their implications for ecological function and potential utilization. We hypothesize that macrofungal diversity and community composition decrease from upstream to downstream sections of the river, with upstream zones exhibiting higher richness, diversity, and substrate heterogeneity due to more stable microclimatic conditions and greater availability of coarse woody debris, whereas fewer, disturbance-tolerant species dominate downstream zones. This research provides the first integrated baseline on riparian macrofungi in the Samin River and contributes to broader efforts to understand, conserve, and sustainably utilize fungal diversity in tropical ecosystems.

MATERIALS AND METHODS

Study area

The research was conducted along the riparian zone of the Samin River, a tributary of the Bengawan Solo, located in Central Java, Indonesia. The main river originates in the highlands of Tawangmangu Sub-district, Karanganyar District, and flows westward through Matesih and Karanganyar Sub-districts before reaching the lowland agricultural-urban interface of Sukoharjo District in the border area between Mojolaban and Grogol Sub-districts. This geographical setting forms a natural ecological gradient from upland montane environments to increasingly modified downstream landscapes. Sampling encompassed six stations distributed across three river sections-upstream, middle, and downstream-to capture spatial variation in habitat structure and fungal substrates (Figure 1, Table 1).

Climatically, the region falls under the tropical monsoon system with pronounced wet and dry seasons. Annual rainfall typically ranges between 2,200-2,800 mm, while average temperatures vary from 22-30°C (BMKG 2025). Field sampling was conducted in March-April 2024, a transitional period from the rainy to the dry season, during which humidity remained high and sporadic rainfall still occurred, conditions known to promote macrofungal fruiting (Miles and Chang 2004; Stamets 2005). Riparian vegetation includes secondary forest patches, bamboo stands, agroforestry plots dominated by *Albizia chinensis*, *Tectona grandis*, and *Swietenia* spp., and mixed shrub assemblages. These vegetation types continuously supply organic substrates such as coarse woody debris, leaf litter, and weathered logs, forming microhabitats favorable for saprophytic and lignicolous fungi.

The upstream stations (Kalisoro and Nglurah, Tawangmangu) are situated in cooler, more forested environments characterized by steep terrain and dense canopy cover. Middle stations (Girilayu and Plosorejo, Matesih) represent mixed agroforestry and semi-residential areas where vegetation is patchy and substrate availability is shaped by human management. Downstream stations (Telukan, Grogol, and Tegalmade, Mojolaban) occur in more open and warmer conditions influenced by agriculture and peri-urban land use, resulting in reduced tree cover and altered substrate composition. These contrasts allow examination of how macrofungal richness and substrate specificity vary along the river's environmental gradient.

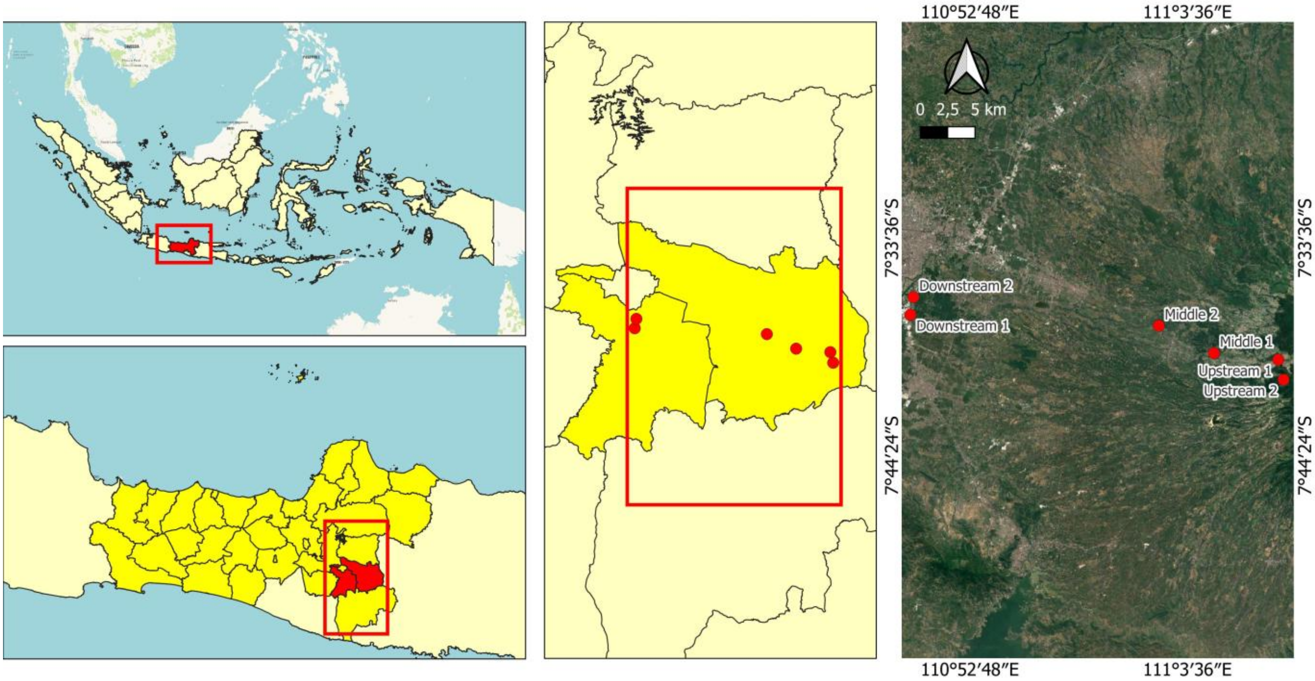

Figure 1. Map of the Samin River showing upstream, middle, and downstream sampling zones in Central Java, Indonesia

Table 1. Samin river location data in Central Java, Indonesia

River section	Location	Coordinate
Upstream	Kalisoro, Tawangmangu, Karanganyar	7°39'37.8"S 111°08'07.5"E
	Nglurah, Tawangmangu, Karanganyar	7°40'37.2"S 111°08'23.4"E
Middle	Girilayu, Matesih, Karanganyar	7°39'18.3"S 111°04'55.8"E
	Plosorejo, Matesih, Karanganyar	7°37'56.7"S 111°02'11.6"E
Downstream	Telukan, Grogol, Sukoharjo	7°37'23.9"S 110°49'51.1"E
	Tegalmade, Mojolaban, Sukoharjo	7°36'31.2"S 110°50'00.3"E

Sampling and identification

Macrofungal sampling was conducted systematically across six stations representing the upstream, middle, and downstream sections of the Samin River. Each station contained one belt transect measuring 10 × 100 m (1,000 m²), resulting in a total surveyed area of 6,000 m². Belt transects were selected because they enable efficient detection of sporocarps across heterogeneous microhabitats and are widely applied in macrofungal ecological studies (Mueller et al. 2004). Field surveys were carried out during March-April 2024, a transitional period known for high humidity and active substrate decomposition, which together promote optimal fruiting of many tropical macrofungi. Observations were conducted in the morning and late afternoon to reduce the likelihood of missing sporocarps that desiccate during midday hours.

Macrofungal observation methods

All visible sporocarps within each transect were recorded, photographed, and collected when necessary. Sampling followed a modified opportunistic-systematic approach in which observers walked slowly along the transect line and examined diverse microhabitats, including leaf litter layers, woody debris, soil patches, and the bases of living trees. This method is particularly suitable for riparian systems, where substrate distribution is highly variable, and microhabitats change rapidly with hydrological conditions (Lodge et al. 2004). Only macrofungi with mature, identifiable fruiting bodies were included to ensure accuracy in taxonomic determination.

Substrate-based sampling procedure

To evaluate substrate specificity, each encountered sporocarp was assigned to the substrate from which it emerged. Substrates were categorized as: (i) weathered logs (W), including decayed trunks, branches, and coarse woody debris, (ii) leaf litter (L), comprising decomposing leaves and small organic detritus, (iii) soil (S), including mineral soil and humus-rich layers, (iv) tree (T), consisting of living bark or standing trunks, and (v) animal dung (A), typically from herbivores common along riparian margins. Substrate type was recorded at the point of collection following the guidelines of Lodge et al. (2004). In cases where sporocarps occurred at the interface of multiple substrates-such as wood partially embedded in soil-the dominant supporting substrate was determined based on visual assessment. Species capable of emerging from more than one substrate type were noted for subsequent ecological interpretation.

Documentation and morphological identification

All macrofungi were photographed in situ using a digital camera equipped with scale markers to document diagnostic morphological features, including pileus form, stipe structure, hymenophore type, color changes, and substrate association. Specimens requiring detailed examination were collected and stored in paper envelopes to maintain dryness and prevent rapid decay. Identification was conducted using macroscopic and microscopic criteria based on established taxonomic keys such as Largent (1977), McKnight and McKnight 1987, and Kibby (2006). Diagnostic traits were further verified through comparison with authoritative nomenclatural databases, including MycoBank and Index Fungorum, ensuring accuracy and consistency in species recognition.

Substrate classification for analysis

For analytical purposes, each species was assigned to one or more substrate categories (W, L, S, T, A), allowing quantification of substrate-specific richness and assessment of ecological allocation along the riparian gradient. Substrate-based grouping is essential because many saprotrophic fungi show strong microhabitat preferences shaped by moisture levels, decomposition stages, and substrate chemistry (Lodge et al. 2004). Species recorded on multiple substrates were retained across categories, acknowledging their ecological plasticity and potential roles as generalist decomposers within the riparian ecosystem.

Data analysis

Data analysis focused on quantifying macrofungal diversity, evaluating substrate-use patterns, and assessing potential utilization of recorded species. All observations from the six transects were compiled into a master dataset that included species identity, family, substrate category, and collection location. Analytical procedures were conducted using Microsoft Excel and R version 4.2.2, following widely adopted ecological frameworks for macrofungal community studies (Magurran 2004).

Diversity index calculations (H', D, R, E)

Several diversity indices were computed to characterize macrofungal community structure across the upstream, middle, and downstream sections of the Samin River.

Shannon-Wiener Diversity Index (H')

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where pi is the proportion of individuals belonging to species i. This index integrates both richness and evenness and is widely used in fungal diversity studies due to its sensitivity to infrequent species (Shannon and Weaver 1963; Magurran 2004).

Simpson Diversity Index (D)

$$D = 1 - \sum p_i^2$$

This metric emphasizes dominance patterns, with higher values indicating more even communities and lower dominance by a few taxa (Simpson 1949).

Species Richness Index (R)

The Margalef index was applied:

$$R = \frac{S-1}{\ln N}$$

Where S represents the total number of species and N the total number of individuals recorded (Odum 1971).

Evenness Index (E)

$$E = \frac{H'}{\ln S}$$

This index measures how evenly species are distributed within each river section (Pielou 1966). These indices enabled comparative assessment of macrofungal community composition along the environmental gradient of the Samin River.

Substrate distribution analysis

Each species was assigned to one or more of the five substrate categories: weathered logs (W), leaf litter (L), soil (S), tree (T), and animal dung (A). The frequency of species associated with each substrate was tabulated, with multi-substrate species recorded across all relevant categories. Substrate preferences were interpreted to infer ecological roles, including lignicolous, litter-decomposing, humicolous, or coprophilous tendencies (Lodge et al. 2004). A substrate composition pie chart was produced to visualize the relative contribution of each substrate type to overall species richness.

Assessment of potential utilization

Species with documented ethnomycological, nutritional, medicinal, or biotechnological value-such as *Auricularia*, *Termitomyces*, *Lentinus*, and *Ganoderma*-were identified through literature reviews (Miles and Chang 2004; Hyde et al. 2018). Information on edibility, pharmacological activity, enzymatic properties, and ecosystem services was compiled to highlight the applied significance of macrofungi found along the Samin River corridor.

Data visualization

Two primary visualizations were generated to support ecological interpretation: (i) A histogram of species counts per family, illustrating the taxonomic distribution of macrofungi across the study area. (ii) A pie chart of substrate composition, showing relative species richness associated with W, L, S, T, and A substrates. Together, these graphical outputs reinforce the analysis of spatial patterns and ecological associations within the macrofungal community.

Ethical and permitting statement

All field activities were conducted with permission from local authorities and land managers in Karanganyar, Matesih, and Sukoharjo, Central Java, Indonesia. Access to the Samin River riparian zone was coordinated with village leaders, and sampling was restricted to publicly accessible and community-managed lands, avoiding strictly protected conservation areas. Macrofungal sampling followed non-destructive survey practices. Only a limited number of fruiting bodies were collected for taxonomic confirmation, while most specimens were documented in situ. Substrates such as coarse woody debris, leaf litter, and soil were minimally disturbed, and no vegetation was intentionally damaged (Miles and Chang 2004; Lodge et al. 2004). Based on available national and regional checklists, none of the recorded taxa were legally protected or critically endangered in Indonesia at the time of the study.

RESULTS AND DISCUSSION

Species richness and taxonomic composition

A total of 98 macrofungal species were recorded along the Samin River riparian ecosystem, representing 38 families, 13 orders, and two major phyla (Ascomycota and Basidiomycota) (Table 2), with species richness distributed unevenly across the riparian zones, comprising 41 species in the upstream section, 41 species in the midstream section, and 24 species in the downstream section. Basidiomycota predominated, comprising the vast majority of taxa, while Ascomycota contributed a smaller but ecologically significant proportion of decomposer lineages. This broad taxonomic representation reflects the environmental heterogeneity of riparian habitats, where variations in canopy cover, moisture, and substrate availability support diverse assemblages of both lignicolous and litter-dwelling fungi. The distribution of species across families (summarized in Figure 2) highlights Mycenaceae, Polyporaceae, and Marasmiaceae as the most species-rich families, underscoring the dominance of wood- and litter-decaying functional groups in this system.

Several families dominated the macrofungal community. Mycenaceae, Polyporaceae, and Marasmiaceae emerged as the three most species-rich families, collectively accounting for 40 species (approximately 40% of the total taxa). Members of the Mycenaceae, particularly species of *Mycena* and *Hemimycena*, were abundant on weathered wood and leaf litter, demonstrating their strong role as early colonizers of decaying plant material. The Polyporaceae, which include *Trametes*, *Cerrena*, *Ganoderma*, and *Pycnoporus*, were widespread on well-decomposed logs, functioning as major agents of lignin degradation. Meanwhile, the Marasmiaceae-represented by *Marasmius*, *Crinipellis*, and *Tetrapyrgos*-occurred primarily on fine woody debris and moist litter substrates, consistent with their ecological niche in forest-floor decomposition.

The dominance of Basidiomycota over Ascomycota aligns with patterns observed in other humid tropical riparian zones, where wood-decaying basidiomycetes thrive under high humidity and continuous litter input. Ascomycota, although less diverse in this study, were represented by ecologically significant groups such as the Xylariaceae (e.g., *Xylaria longiana*, *X. filiformis*), Nectriaceae (*Tubercularia lateritia*), and Pezizaceae (*Peziza* sp.). These genera are typically associated with early to mid-stage decomposition, contributing to cellulose degradation and substrate fragmentation that facilitate colonization by basidiomycetes. The presence of multiple *Xylaria* and *Scutellinia* species indicates that the Samin River riparian zone supports a well-structured decomposition continuum.

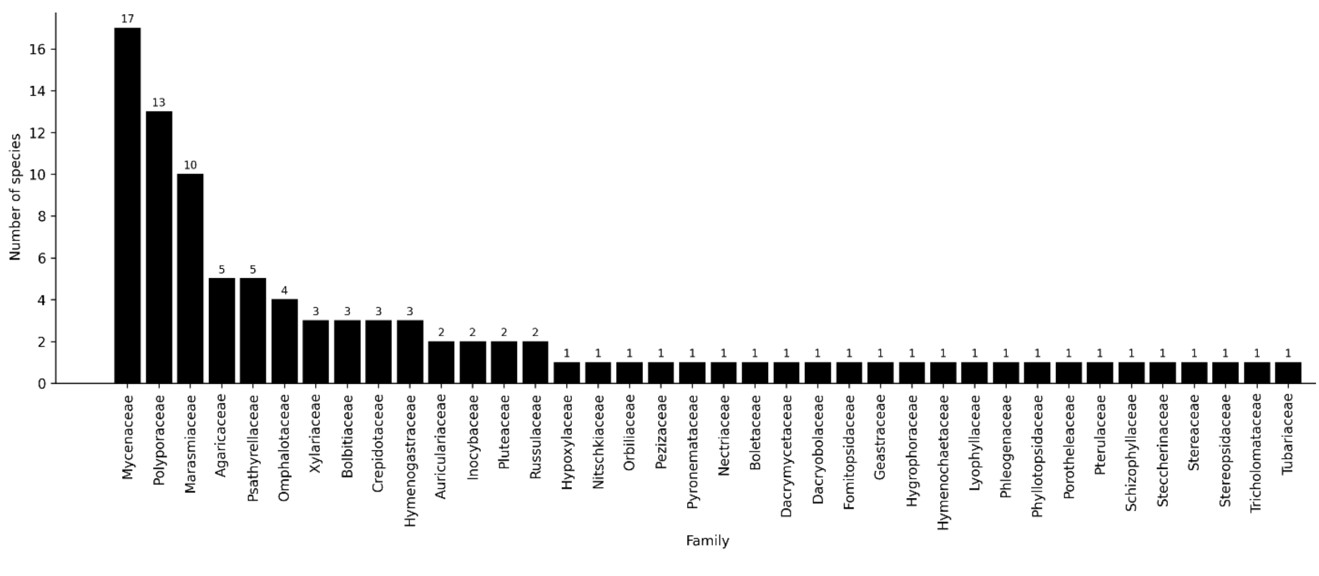

Figure 2. The number of macrofungi species for each family documented in the study sites of Samin River, Central Java, Indonesia

Table 2. Macrofungi found at the research location in Samin River, Central Java, Indonesia

Phylum Order	Family	Species	Substrates	Location			Potential utilization	
				Upstream	Middle	Down	Use	Reference
Ascomycota								
Xylariales	Hypoxylaceae	*Daldinia concentrica* (Bolton) Ces. & De Not.	W			✓	M	Feng et al. (2013)
Xylariales	Nitschkiaceae	*Nitschkia* sp.	W	✓			-	-
Orbiliales	Orbiliaceae	*Orbilia xanthostigma* (Fr.) Fr.	W		✓		-	-
Pezizales	Pezizaceae	*Peziza* sp.	L	✓			P	Madsen and Crook (2021)
Pezizales	Pyronemataceae	*Scutellinia scutellata* (L.) Lambotte	W		✓		P	Elkhateeb and Daba (2021)
Xylariales	Xylariaceae	*Xylaria filiformis* (Alb. & Schwein.) Fr.	L		✓		-	-
Xylariales	Xylariaceae	*Xylaria longiana* Rehm	L, W		✓		-	-
Xylariales	Xylariaceae	*Xylaria longipes* Nitschke	W			✓	M	Fikri et al. (2023)
Hypocreales	Nectriaceae	*Tubercularia lateritia* (Berk.) Seifert	W		✓	✓	-	-
Basidiomycota								
Agaricales	Agaricaceae	*Lepiota* sp.1	L			✓	-	-
Agaricales	Agaricaceae	*Lepiota* sp.2	W		✓		-	-
Agaricales	Agaricaceae	*Lepiota* sp.3	S		✓		-	-
Agaricales	Agaricaceae	*Leucocoprinus* sp.	S			✓	-	-
Agaricales	Agaricaceae	*Micropsalliota* sp.	S		✓		-	-
Auriculariales	Auriculariaceae	*Auricularia auricula-judae* (Bull.) Quél.	W	✓			F, M	Miles and Chang (2004), Mayra et al. (2024), Yusran et al. (2024),
Auriculariales	Auriculariaceae	*Auricularia nigricans* (Sw.) Birkebak, Looney & Sánchez-García	W	✓	✓	✓	F, M	Elkhateeb and Daba (2021)
Agaricales	Bolbitiaceae	*Bolbitius coprophilus* (Peck) Hongo	A	✓			-	-
Agaricales	Bolbitiaceae	*Conocybe* sp.1	L	✓			-	-
Agaricales	Bolbitiaceae	*Conocybe* sp.2	L	✓			-	-
Boletales	Boletaceae	*Hortiboletus* sp.	S	✓			-	-
Agaricales	Crepidotaceae	*Crepidotus cesatii* (Rabenh.) Sacc.	L		✓		-	-
Agaricales	Crepidotaceae	*Crepidotus mollis* (Schaeff.) Staude	W	✓			M	On et al. (2021)
Agaricales	Crepidotaceae	*Crepidotus* sp.	W	✓			-	-
Dacrymycetales	Dacrymycetaceae	*Dacryopinax spathularia* (Schwein.) G.W.Martin	W			✓	M, F	Kumar et al. (2019)
Dacryobolales	Dacryobolaceae	*Ptychogaster albus* Corda	W		✓		-	-
Fomitopsidales	Fomitopsidaceae	*Pilatoporus hemitephrus* (Berk.) Zmitr.	T		✓		-	-
Geastrales	Geastraceae	*Geastrum saccatum* Fr.	S		✓		M	Amaral-Machado et al. (2020)
Agaricales	Hygrophoraceae	*Hygrocybe miniata* (Fr.) P. Kumm.	S		✓		-	-
Hymenochaetales	Hymenochaetaceae	*Coltricia perennis* (L.) Murrill	S	✓			-	-
Agaricales	Hymenogastraceae	*Gymnopilus* sp.	W		✓		-	-
Agaricales	Hymenogastraceae	*Gymnopilus penetrans* (Fr.) Murrill	W	✓			M	Mahardhika et al. (2022)
Agaricales	Hymenogastraceae	*Psilocybe* sp.	A	✓			-	-

Agaricales	Inocybaceae	*Inocybe geophylla* P.Kumm.	L	✓			P	Benjamin (1995), Patocka et al. (2021)
Agaricales	Inocybaceae	*Inocybe lacera* (Fr.) P.Kumm.	L			✓	P	Michelot and Melendez-Howell (2003), Al-Momany (2025)
Agaricales	Lyophyllaceae	*Termitomyces* sp.	S	✓			M, F	Boa (2004), Sitotaw et al. (2020), Yusran et al. (2024)
Agaricales	Marasmiaceae	*Crinipellis setipes* (Peck) Singer	W	✓			-	-
Agaricales	Marasmiaceae	*Marasmius elegans* (Cleland) Grgur.	L, W	✓	✓		-	-
Agaricales	Marasmiaceae	*Marasmius siccus* (Schwein.) Fr.	W	✓			M	Ryoo and Lee (2024)
Agaricales	Marasmiaceae	*Marasmius sullivantii* Mont.	L, W	✓			-	-
Agaricales	Marasmiaceae	*Marasmius* sp.1	L			✓	M	Putra (2020)
Agaricales	Marasmiaceae	*Marasmius* sp.2	L		✓		M	Putra (2020)
Agaricales	Marasmiaceae	*Marasmius* sp.3	W		✓		M	Putra (2020)
Agaricales	Marasmiaceae	*Marasmius* sp.4	W	✓			-	-
Agaricales	Marasmiaceae	*Marasmius* sp.5	L	✓			-	-
Agaricales	Marasmiaceae	*Tetrapyrgos nigripes* (Corner) Pegler	W			✓	P	Mahardhika et al. (2022)
Agaricales	Mycenaceae	*Hemimycena lactea* (Pers.) Singer	L		✓		P	Kirk et al. (2008)
Agaricales	Mycenaceae	*Favolaschia* sp.	T		✓		-	-
Agaricales	Mycenaceae	*Hemimycena* sp.	W		✓		-	-
Agaricales	Mycenaceae	*Mycena tenerrima* (Berk.) Quél.	W	✓			-	-
Agaricales	Mycenaceae	*Mycena adscendens* Maas Geest.	L, W	✓			-	-
Agaricales	Mycenaceae	*Mycena chlorophos* (Berk. & M.A. Curtis) Sacc.	L, W	✓			-	-
Agaricales	Mycenaceae	*Mycena fumosa* (Pers.) Quél.	L, W	✓			-	-
Agaricales	Mycenaceae	*Mycena leptocephala* (Pers.) Gillet	W	✓			-	-
Agaricales	Mycenaceae	*Mycena galericulata* (Scop.) Gray	W	✓			-	-
Agaricales	Mycenaceae	*Mycena leptophylla* (Peck) Sacc.	W	✓			-	-
Agaricales	Mycenaceae	*Mycena* sp.1	W			✓	-	-
Agaricales	Mycenaceae	*Mycena* sp.2	W			✓	-	-
Agaricales	Mycenaceae	*Mycena* sp.3	L		✓		-	-
Agaricales	Mycenaceae	*Mycena* sp.4	W		✓		-	-
Agaricales	Mycenaceae	*Mycena* sp.5	W		✓		-	-
Agaricales	Mycenaceae	*Mycena* sp.6	W	✓			-	-
Agaricales	Mycenaceae	*Mycena* sp.7	L	✓			-	-
Agaricales	Omphalotaceae	*Marasmiellus candidus* (Fr.) Singer	L, W		✓		-	-
Agaricales	Omphalotaceae	*Marasmiellus* sp.	L		✓		F	Armadhan et al. (2023)
Agaricales	Omphalotaceae	*Gymnopus ceraceicola* J.A.Cooper & P.Leonard	W		✓		-	-
Agaricales	Omphalotaceae	*Gymnopus* sp.	W	✓			-	-
Pterulales	Phleogenaceae	*Phleogena* sp.	T		✓		-	-
Agaricales	Phyllotopsidaceae	*Phyllotopsis nidulans* (Pers.) Singer	W			✓	-	-

Agaricales	Pluteaceae	*Pluteus umbrosus* (Pers.) P.Kumm.	W		✓		F	Abdalla et al. (2016)
Agaricales	Pluteaceae	*Pluteus salicinus* (Pers.) P.Kumm.	W			✓	-	-
Polyporales	Polyporaceae	*Cerrena unicolor* (Bull.) Murrill	W		✓		M	Sondej et al. (2025)
Polyporales	Polyporaceae	*Datronia* sp.	W			✓	-	-
Polyporales	Polyporaceae	*Lentinus arcularius* (Batsch) Zmitr.	W			✓	M	Le et al. (2022)
Polyporales	Polyporaceae	*Hexagonia tenuis* (Fr.) Fr.	W		✓		-	-
Polyporales	Polyporaceae	*Perenniporia ohiensis* (Berk.) Ryvarden	W			✓	-	-
Polyporales	Polyporaceae	*Coriolopsis gallica* (Fr.) Ryvarden	W			✓	M	Staita et al. (2024)
Polyporales	Polyporaceae	*Fomes fasciatus* (Sw.) Cooke	W		✓		-	-
Polyporales	Polyporaceae	*Ganoderma* sp.	W		✓		M	Bibi et al. (2023)
Polyporales	Polyporaceae	*Neofavolus alveolaris* (DC.) Sotome & T. Hatt.	W			✓	F	Fawwaz et al. (2024)
Polyporales	Polyporaceae	*Pycnoporus sanguineus* (L.) Murrill	W		✓		M	Huang et al. (2023)
Polyporales	Polyporaceae	*Trametes* sp.	W			✓	M	Srivastava et al. (2024)
Polyporales	Polyporaceae	*Bresadolia uda* (Jungh.) Audet	W	✓			-	-
Polyporales	Polyporaceae	*Favolus grammocephalus* (Berk.) Imazeki	W	✓			-	-
Agaricales	Porotheleaceae	*Phloeomana speirea* (Fr.) Redhead	W		✓		-	-
Agaricales	Psathyrellaceae	*Coprinellus disseminatus* (Pers.) J.E.Lange	W	✓	✓		F	Boa (2004)
Agaricales	Psathyrellaceae	*Coprinopsis lagopus* (Fr.) Redhead, Vilgalys & Moncalvo	L, W			✓	P	Benjamin (1995)
Agaricales	Psathyrellaceae	*Coprinopsis* sp.	W		✓		-	-
Agaricales	Psathyrellaceae	*Cystoagaricus* sp.	S		✓		-	-
Agaricales	Psathyrellaceae	*Parasola plicatilis* (Curtis) Redhead, Vilgalys & Hopple	L, W	✓		✓	-	-
Pterulales	Pterulaceae	*Pterula multifida* (Fr.) Bon	L, W			✓	-	-
Russulales	Russulaceae	*Lactarius* sp.	S	✓			-	-
Russulales	Russulaceae	*Russula* sp.	S	✓			P	Beug et al. (2014)
Hymenochaetales	Schizophyllaceae	*Schizophyllum commune* Fr.	W	✓	✓	✓	M, F	Kumar et al. (2019)
Hymenochaetales	Steccherinaceae	*Nigroporus vinosus* (Berk.) Murrill	W	✓			-	-
Hymenochaetales	Stereaceae	*Stereum ostrea* (Blume & T. Nees) Fr.	W	✓			P	Rahmi et al. (2021)
Hymenochaetales	Stereopsidaceae	*Stereopsis hiscens* (Mont.) D.A.Reid	S		✓		-	-
Agaricales	Tricholomataceae	*Collybia* sp.	T	✓			-	-
Agaricales	Tubariaceae	*Tubaria* sp.	S		✓		-	-
Total: 13	38	98						

Note: Taxonomic nomenclature and family assignments follow MycoBank and Index Fungorum (accessed 2024-2025). Potential utilization: F: Food, M: Medicine, P: Poisonous, -: unknown. Substrates: W: Weathered logs, S: soil, T: Tree, L: Leaf litters, A: Animal dung

Spatial patterns of species composition revealed clear contrasts among upstream, middle, and downstream sites. Species richness was similarly high in the upstream and middle sections (41 species each), while the downstream zone supported substantially fewer species (24 species) (Table 2). The relatively high richness in the middle zone likely reflects its heterogeneous habitat structure, combining agroforestry vegetation with semi-open riparian conditions. In contrast, the upstream zone, characterized by cooler temperatures, higher humidity, and denser canopy cover, supported numerous moisture- and shade-associated taxa such as *Marasmius elegans*, *Inocybe geophylla*, and *Mycena adscendens*. The downstream zone, influenced by greater human activity and more open vegetation, exhibited lower overall richness but was dominated by widespread generalist species including *Auricularia nigricans*, *Dacryopinax spathularia*, and *Schizophyllum commune*.

At the species level, several taxa were identified as ecological indicators of riparian habitats. *Xylaria* spp., often detected on partially decomposed logs, signify stable moisture regimes and continuous woody substrate availability. *Crepidotus* and *Pluteus* species reflect the presence of fine decomposing debris on shaded banks. The widespread occurrence of *S. commune* across all three zones indicates disturbance-tolerant conditions, as this species readily colonizes both natural and anthropogenic woody substrates. Meanwhile, *Auricularia* spp., which appeared in multiple locations, highlight the presence of well-decayed logs and sustained humidity, conditions typical of tropical riparian forests.

An important ecological feature in the Samin River fungal community is the presence of multi-substrate species, which exhibit flexible colonization strategies. Based on Table 2, species such as *Coprinopsis lagopus, M. elegans, Marasmius sullivantii, Marasmiellus candidus, M. adscendens, Mycena chlorophos, Mycena fumosa, Parasola plicatilis, Pterula multifida,* dan *X. longiana* were found on more than one substrate type, including combinations of weathered wood (W), leaf litter (L), and soil (S). This versatility suggests that these taxa play key roles in maintaining decomposition continuity across microhabitats. Multi-substrate species also help stabilize ecosystem functions by sustaining decomposition even under conditions of fluctuating substrate availability.

Several taxa exhibited restricted distributions and may represent location-specific specialists. For example, *Hortiboletus* sp., *Peziza* sp. and *Lactarius* sp. were recorded only in the upstream zone, while *Scutellinia scutellata* occurred exclusively in the middle zone. These patterns may relate to differences in canopy cover, soil moisture, and organic matter accumulation across river sections.

The species richness and taxonomic composition of macrofungi along the Samin River reflect a complex interaction between environmental gradients, substrate diversity, and habitat structure. The dominance of decomposer families, the presence of indicator species, and the occurrence of multi-substrate taxa underscore the ecological importance of riparian zones as reservoirs of fungal diversity in tropical landscapes.

Spatial patterns of diversity and community structure

Macrofungal diversity varied distinctly across the three river sections, with measurable differences in species richness, dominance patterns, and community evenness. The diversity indices presented in Table 3 show that macrofungal assemblages in the upstream, middle, and downstream zones form a clear ecological gradient aligned with environmental heterogeneity and substrate availability along the Samin River.

The upstream zone exhibited the highest overall diversity, with a Shannon-Wiener Index (H') of 3.03, categorized as high diversity. This section also recorded the highest Simpson Index (D = 0.93), Species Richness Index (R = 6.40), and Evenness Index (E = 0.81). These values indicate not only a large number of species but also a relatively balanced distribution among species, with no single taxonomic group exerting strong dominance. The upstream assemblage was characterized by a mixture of lignicolous taxa-such as *Ganoderma*, *Xylaria,* and *Auricularia* -and numerous litter- and soil-associated species (*Marasmius*, *Mycena*, *Inocybe*), reflecting substrate and microhabitat diversity.

In contrast, the middle zone displayed moderate but substantial diversity (H' = 2.57, D = 0.86, R = 6.02, E = 0.68). Species richness in the middle zone was only slightly lower than in the upstream section, yet community evenness showed a greater skew toward a few abundant taxa. This section harbored several species not observed upstream, including *S. scutellata*, *Crepidotus cesatii*, and *Gymnopus ceraceicola*, which were associated with mixed agroforestry substrates and semi-open habitats. The presence of both shaded and open microsites contributed to a heterogeneous species pool but also allowed certain species, such as *A. nigricans* and *Coprinellus disseminatus*, to occur more frequently and reduce evenness.

Table 3. Summary of macrofungal diversity indices at the Samin River riparian area, Central Java, Indonesia

Location	Shannon-Wiener (H')	Category	Simpson (D)	Category	Richness (R)	Category	Evenness (E)	Category
Upstream	3.03	High	0.93	High	6.40	High	0.81	High
Middle	2.57	Moderate	0.86	High	6.02	High	0.68	High
Downstream	2.29	Moderate	0.85	High	3.88	Moderate	0.71	High

Table 4. Results of abiotic factor measurements at Samin River riparian area, Central Java, Indonesia

Abiotic factors	Locations		
	Upstream	Middle	Down
Soil Temperature (°C)	21-23	24-28	28-31
Soil pH	6.3-6.7	6.7-7.0	6.9-7.2
Soil Moisture (%)	7.5-10.5	6.5-8.5	5.5-7.5
Wind Speed (m/s)	0.2-1.0	1.2-3.0	1.0-2.5
Light intensity (lux)	4,000-9,000	10,000-22,000	25,000-32,000
Air Humidity (%)	85-91	61-81	40-51
Air Temperature (°C)	23.2-25.5	28.3-30.2	31.7-33.4
Height (masl)	1,116-1,123	360-614	89-91

The downstream zone supported the lowest macrofungal diversity, with H' = 2.29, D = 0.85, R = 3.88, and E = 0.71. Although evenness remained relatively high, species richness was markedly lower than in the upstream and middle zones. The downstream community was dominated by disturbance-tolerant species such as *S. commune*, *D. spathularia*, and *Trametes*, many of which colonize exposed or degraded woody substrates. Generalist saprotrophs comprised a greater proportion of the community in this section, reflecting simplified habitat structure.

The spatial variation in diversity aligns closely with differences in environmental conditions along the river gradient. Table 4 shows that upstream sites were characterized by lower temperatures (23-25.5°C), higher humidity (85-91%), and markedly lower light intensity (4,000-9,000 lux), conditions that favor the fruiting of lignicolous and litter-decaying fungi. In contrast, downstream sites experienced higher temperatures (31.7-33.4°C), lower humidity (40-51%), and much stronger illumination (25,000-32,000 lux), conditions that reduce moisture-dependent fungal fruiting and limit the availability of intact decomposing substrates.

Differences in substrate composition also contributed to the observed diversity patterns. The upstream section contained abundant weathered logs and dense leaf litter, supporting both Basidiomycota (Polyporaceae, Mycenaceae) and Ascomycota (Xylariaceae, Pyronemataceae). The middle zone had a mixture of woody debris, riparian vegetation, and agroforestry inputs, leading to a broader but uneven species distribution. In the downstream zone, reduced tree cover and increased anthropogenic activity limited substrate diversity, with many specimens found on small woody fragments or scattered leaf litter rather than on large decaying logs. Correspondingly, the number of multi-substrate species (see Table 2) declined downstream, while upstream zones recorded more substrate-flexible taxa such as *M. sullivantii*, *M. adscendens*, and *P. plicatilis*.

The diversity indices demonstrate a clear ecological trend: upstream > middle > downstream for most metrics, despite comparable species richness between the upstream and middle sections, indicating that structural habitat complexity and microclimatic stability strongly shape macrofungal community patterns along the Samin River. These results highlight the spatially structured nature of fungal assemblages in riparian ecosystems and provide a quantitative foundation for understanding the ecological drivers of macrofungal diversity in subsequent discussion sections.

Substrate-specific distribution and ecological allocation

Macrofungal occurrence along the Samin River showed strong variation in substrate preference, reflecting the structural heterogeneity of riparian habitats. Substrate distribution is summarized in Figure 3, which illustrates that the majority of species were associated with weathered logs (W), followed by leaf litter (L), soil (S), tree trunks (T), and animal dung (A). This pattern aligns with the availability and stability of organic materials found in the riparian zone.

Weathered logs (W) constituted the dominant substrate category, representing the highest proportion of recorded species. Numerous taxa in Table 2 were exclusively or predominantly lignicolous, including *Crepidotus mollis*, *Ganoderma* sp., *Trametes* sp., *Coriolopsis gallica*, *Hexagonia tenuis*, and *Cerrena unicolor*. Weathered logs provide long-lasting moisture retention, structural stability, and complex microhabitats that support extended fungal colonization. Their abundance in the upstream and middle zones, where canopy cover is dense, further explains the dominance of W-associated species. Several indicator species of decomposing woody substrates-such as *S. commune*, *Pycnoporus sanguineus*, and *Mycena galericulata*-were consistently found on logs and stumps, reinforcing the significance of lignicolous niches in the river corridor.

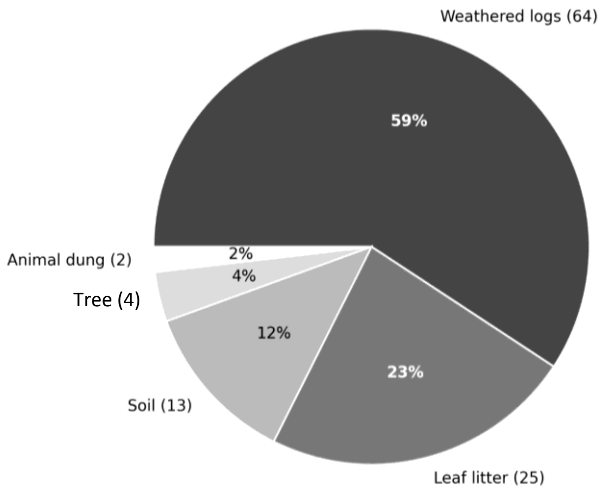

Figure 3. Diagram of types of fungal substrates in the Samin River riparian area, Central Java, Indonesia. Some species occupied multiple substrate types, each substrate was counted separately (see Table 2). Note: Species occurring on multiple substrates were counted separately (total substrate records, n = 108)

Leaf litter (L) formed the second most important substrate, supporting numerous saprotrophic species adapted to rapidly decomposing organic layers. Representative taxa include *Peziza* sp., *Conocybe* sp.1, *I. geophylla*, *Marasmius* sp.2, *Mycena* sp.3 and *Hemimycena lactea*. Leaf litter substrates were particularly abundant in the upstream zone, where mixed broadleaf vegetation and high moisture favored the development of litter-decaying communities. Several species occupied both litter and wood substrates-such as *M. elegans*, *M. adscendens*, and *P. plicatilis*-demonstrating substrate flexibility in taxa adapted to fluctuating riparian conditions.

Soil (S) substrates supported a smaller but ecologically distinct group of macrofungi. Species occurring exclusively on soil included *Geastrum saccatum*, *Hygrocybe miniata*, *Lactarius* sp., and *Russula* sp.. Soil-based occurrences were more frequent in the middle zone, where open areas and reduced canopy cover increased direct contact between fruiting bodies and exposed ground surfaces. The presence of genera such as *Geastrum* and *Russula* indicates the coexistence of both saprotrophic and ectomycorrhizal guilds in localized patches of the riparian system.

Tree trunks (T) represented a minor but specialized substrate category. Tree-associated species included *Pilatoporus hemitephrus*, *Favolaschia* sp., *Phleogena* sp., and *Collybia* sp. (Table 2). These taxa were primarily found in the middle zone, where riparian trees such as bamboo, Albizia, and Mahogany produced shaded, moisture-rich stem surfaces. Although less abundant, T-substrates contributed to overall substrate diversity and supported species not observed on other materials.

Animal dung (A) hosted the smallest number of species, exemplified by *Bolbitius coprophilus* and *Psilocybe* sp. (Table 2). Their restricted occurrence reflects the limited and patchy availability of dung substrates along the sampling transects, mainly in areas where livestock occasionally entered the riparian zone. These species serve as clear indicators of nutrient-rich ephemeral substrates and were found predominantly in the upstream sites.

A notable feature of the Samin River macrofungal assemblage is the presence of multi-substrate species, which occupied more than one substrate category and contributed to increased flexibility in habitat use. Examples include *X. longiana* (L, W), *M. chlorophos* (L, W), *M. fumosa* (L, W), *M. candidus* (L, W), *C. lagopus* (L, W), *P. plicatilis* (L, W), and *P. multifida* (L, W). These species generally occurred in humid microsites where mixed organic materials accumulated, a characteristic feature of riparian habitats influenced by periodic flooding, litter deposition, and vegetation turnover. Substrate-specific patterns underscore the importance of organic material heterogeneity in structuring macrofungal distribution along the Samin River. Weathered logs remain the most critical resource, while leaf litter and soil provide additional niche opportunities supporting a diverse assemblage across the riparian gradient.

Potential utilization of recorded macrofungi

Several macrofungal species documented along the Samin River possess notable potential for food, medicinal, and biotechnological applications, while a smaller subset is known to be toxic. Information extracted from Table 2 indicates that the riparian habitats support a functionally diverse fungal assemblage, reflecting both ecological and practical importance for local communities.

Food-related species (F)

Edible macrofungi comprised a meaningful portion of the recorded taxa, particularly those belonging to saprotrophic and lignicolous guilds. *Auricularia auricula-judae* and *A. nigricans*, both marked as food species (F), are among the most widely consumed wild mushrooms in Indonesia and globally. Their gelatinous texture and rich polysaccharide content contribute to their popularity, and previous studies highlight their potential in immune modulation and dietary fiber supplementation (Miles and Chang 2004; Mayra et al. 2024). *Termitomyces* sp. also categorized as edible-holds exceptionally high cultural and economic value, as members of this genus are regarded as delicacies with substantial protein content and antioxidant activity (Boa 2004; Sitotaw et al. 2020).

A few species from the genus *Mycena* have been reported to contain bioactive pigments and aromatic compounds, suggesting potential as functional food or natural colorants, although their edibility remains species-specific and requires further verification. The presence of edible taxa in upstream and middle zones indicates that riparian environments may serve as accessible foraging sites, particularly during humid months that support abundant fruiting.

Medicinally important species (M)

Medicinal macrofungi were relatively well represented in the Samin River dataset. *Ganoderma* sp., *P. sanguineus*, and *C. unicolor* are notable examples, each marked as medicinal (M) in Table 2 and widely studied for pharmacologically active compounds. *Ganoderma* species are renowned for triterpenoids, polysaccharides, and immunomodulatory agents with documented anticancer, antiviral, and hepatoprotective properties (Bibi et al. 2023). *Pycnoporus sanguineus* is a potent source of laccase and other ligninolytic enzymes used in bioremediation, textile processing, and biodegradation of phenolic pollutants (Huang et al. 2023). Similarly, *C. unicolor* produces bioactive metabolites with antimicrobial and antioxidant activity, and its enzymatic repertoire makes it a candidate for biotechnological applications in the green industry and waste decomposition (Sondej et al. 2025). The presence of these medicinal taxa across multiple habitat zones suggests that riparian wood resources support stable populations of pharmaceutically valuable fungi, highlighting opportunities for conservation-based sustainable utilization.

Toxic and inedible species (P)

Species categorized as poisonous (P) include *I. geophylla*, *Tetrapyrgos nigripes*, and *Peziza* sp., all of which are known to contain toxic alkaloids or irritant compounds (Benjamin 1995: Madsen and Crook 2021). *I. geophylla* is widely recognized as a muscarine-rich species associated with severe cholinergic poisoning. *Tetrapyrgos* *nigripes* and several *Peziza* species are also reported to cause gastrointestinal distress. These toxic taxa highlight the need for careful identification in potential foraging activities, especially in areas where edible species co-occur with morphologically similar toxic forms.

Local and biotechnological relevance

The macrofungal community of the Samin River includes species with substantial potential for food security, traditional medicine, and modern biotechnology. Edible taxa may support community-based harvesting programs, while medicinal and enzyme-producing species could be explored for pharmaceutical development, organic waste management, and environmental remediation. The coexistence of edible, medicinal, and toxic species underscores the ecological richness of the riparian corridor and emphasizes the value of accurate species documentation for sustainable resource utilization.

Discussion

Drivers of macrofungal diversity in riparian habitats

The interplay of microclimatic stability, substrate availability, and riparian hydrological dynamics strongly shapes macrofungal diversity in the Samin River corridor. Although species richness in the upstream section was comparable to that of the middle section (41 species each), the upstream zone exhibited the highest ecological diversity as indicated by the Shannon–Wiener and Margalef Indices (H' = 3.03, R = 6.40), a pattern that corresponds closely with the cooler temperatures, persistently high humidity (85-91%), and dense canopy structure characteristic of montane riparian ecosystems (Table 4). Numerous studies have shown that macrofungi respond sensitively to moisture and shade, which are critical for sporocarp formation, mycelial extension, and substrate decomposition rates (Lodge et al. 2004; Miles and Chang 2004). Similar environmental controls were reported from the Banyak Mountain Forest, Central Java, where macrofungal richness was closely associated with high humidity (67-80%), moderate temperatures (28-32°C), and shaded forest conditions (Nurzahra et al. 2025). In this study, the relatively stable humid microenvironment in the upstream zone created ideal conditions for various wood-decaying fungi. Genera such as *Xylaria, Crepidotus, Mycena,* and *Schizophyllum* were particularly abundant in these shaded, moisture-rich patches, likely because consistent moisture is essential for maintaining the enzymatic activity required for lignocellulose breakdown (Kumar et al. 2019; Fikri et al. 2023). Thus, the microclimatic buffering capacity of the upstream riparian forest appears to be a key driver sustaining both high ecological diversity and critical wood decomposition functions.

Light availability also played a significant role. The upstream canopy, with light intensity ranging only 4,000-9,000 lux, supports fungal communities that thrive under reduced irradiance. Shaded conditions slow substrate desiccation and enhance the persistence of fruiting bodies-particularly among taxa with delicate sporocarps such as *Marasmius*, *Hemimycena*, and several *Mycena* species. Similar patterns were documented in riparian forests in Vietnam (Le et al. 2022) and subtropical China, where low-light understories were associated with high basidiomycete richness. In forested ecosystems of Central Java, dense canopy cover was likewise linked to prolonged substrate moisture and the dominance of wood-inhabiting Basidiomycota, particularly Polyporales (Nurzahra et al. 2025). Conversely, in the downstream section of Samin River, elevated temperatures (31-33°C) and high light intensity (25,000-32,000 lux) likely contributed to lower fungal richness by accelerating substrate drying and reducing sporocarp longevity. This ecological gradient parallels observations by Muchane et al. (2021), who reported that macrofungal community indicators (abundance, species richness, and diversity) were lower in more open and degraded habitats than in more favorable habitats within riparian landscapes.

Hydrological dynamics further shape community composition. Riparian zones undergo periodic flooding and sediment deposition, processes known to influence the distribution of fungi associated with soil, litter, and woody debris. In the Samin River, periodic high-flow events in the middle and downstream areas result in substrate turnover and mechanical disturbance, potentially reducing habitat stability for fungi requiring long-term colonization, such as species of *Ganoderma*, *Cerrena*, and *Perenniporia* (Huang et al. 2023; Sondej et al. 2025). In contrast, the upstream segment-with its steeper slopes and faster drainage-experiences less substrate inundation, enabling sustained colonization by wood-decaying taxa. Studies from tropical riparian forests in Malaysia and the Philippines also highlight that stable, well-drained slopes foster richer macrofungal communities relative to more frequently disturbed lower reaches (Boa 2004).

Comparisons with other Indonesian macrofungal studies reveal both consistencies and distinctive patterns. Putra (2020) documented the dominance of Marasmiaceae and Mycenaceae in shaded forested habitats in Sumatra, a trend mirrored in the Samin dataset, where these families contained some of the highest species numbers (Figure 2). Similarly, Yusran et al. (2024) recorded a high abundance of *Auricularia* and *Termitomyces* in humid riparian-agroforestry mosaics in Sulawesi. However, the Samin River community is unique in its strong representation of both Ascomycota (*Xylaria*, *Peziza*, *Scutellinia*) and Basidiomycota, suggesting a mixed system where microhabitat heterogeneity-particularly diverse woody and litter substrates-supports a broad taxonomic profile. This differs from several lowland studies in Java and Bali, where Basidiomycota overwhelmingly dominate in more uniform forest conditions (Rahmi et al. 2021; Mahardhika et al. 2022).

Another driver of diversity is the mosaic of substrate types across the river sections. As later elaborated in Section 3.3, weathered logs (W) were the most prevalent substrate, and numerous species-such as *Xylaria longipes*, *S. commune*, *Mycena tenerrima*, and *C. mollis*-are well-adapted to colonize decomposing woody material. Substrate heterogeneity is widely acknowledged as a primary determinant of fungal richness (Ghosh et al. 2021), and the abundance of coarse woody debris in the upstream and middle zones likely contributed to higher species turnover and niche specialization.

In summary, macrofungal diversity along the Samin River is shaped by a combination of microclimatic gradients, substrate stability, canopy structure, and hydrological patterns. When compared with regional and global studies, the Samin River assemblage aligns with broader ecological principles governing fungal richness in humid riparian systems, while also displaying distinct features tied to its montane-to-lowland environmental transition.

Substrate ecology and functional interpretation

The dominance of weathered logs (W) as the primary substrate for macrofungi in the Samin River riparian area reflects a combination of ecological opportunity, microhabitat stability, and enzymatic specialization among lignicolous taxa. As shown in Figure 3, more than half of all recorded species occurred on W, including members of *Xylaria*, *Crepidotus*, *Mycena*, *Schizophyllum*, *Cerrena*, *Pycnoporus*, and *Ganoderma*. This pattern is consistent with global observations that riparian corridors with high humidity and moderate disturbance regimes accumulate Coarse Woody Debris (CWD), which supports rich communities of saprotrophic fungi (Boddy and Heilmann-Clausen 2008). In the upper Samin River, dense canopy cover and continuous litterfall further promote the formation of partially decomposed logs, creating long-lasting substrates that retain moisture throughout the year-conditions ideal for wood-decaying Basidiomycota.

Wood-inhabiting fungi play an essential role in carbon cycling, lignocellulose breakdown, and nutrient turnover. Genera such as *Xylaria* (Ascomycota) and *Crepidotus*, *Cerrena*, *Ganoderma*, and *Fomes* (Basidiomycota) possess enzyme systems capable of degrading cellulose, hemicellulose, and lignin (Kumar et al. 2019; Sondej et al. 2025). For example, *P. sanguineus* produces high levels of laccase, an oxidizing enzyme crucial in lignin decomposition, making it a cornerstone species in both natural and industrial biodegradation processes (Huang et al. 2023). Similarly, *S. commune* is known for its versatile ligninolytic activity and tolerance to fluctuating moisture, which explains its presence across all three river zones. These taxa exemplify the ecological importance of wood-decomposing fungi in maintaining riparian forest function, especially in systems with high organic input and variable hydrology.

The prevalence of wood substrates contrasts with the lower representation of soil (S), litter (L), tree bark (T), and animal dung (A). Soil fungi tend to require stable microenvironments and may be less likely to produce conspicuous fruiting bodies outside wetter seasons. Only a few species, such as *G. saccatum* and *H. miniata*, were restricted to soil substrates-a pattern consistent with studies from other tropical riparian forests (Amaral-Machado et al. 2020; Le et al. 2022). Leaf litter, although abundant along the Samin River, appears to support fewer specialists, dominated mainly by *Marasmius*, *Mycena*, and *Inocybe* species, which are known litter decomposers with relatively short-lived sporocarps (Patocka et al. 2021; Lodge and Cantrell 2023). Tree substrates (T) supported only a small subset of species, such as *P. hemitephrus* and *Phleogena* sp., consistent with their known preferences for living or recently dead woody tissues rather than fully decayed logs (Gilbert and Sousa 2002).

Animal dung (A) was the rarest substrate and hosted only two taxa, *B. coprophilus* and *Psilocybe* sp., mirroring patterns reported from Java, Sumatra, and Sulawesi, where dung fungi form small but ecologically distinct assemblages (Boa 2004; Yusran et al. 2024). Their presence indicates microhabitat heterogeneity within the riparian matrix and suggests that livestock movement contributes to organic micro-patches that foster niche specialists.

A notable feature of the Samin River macrofungal assemblage is the presence of multi-substrate species, such as *X. longiana* (W, L), *M. elegans* (L, W), *M. sullivantii* (L, W), *M. adscendens* (L, W), *M. chlorophos* (L, W), *M. fumosa* (L, W), *P. plicatilis* (L, W), and *P. multifida* (L, W), as documented in Table 2. Multi-substrate occupancy is generally interpreted as an indicator of ecological flexibility and adaptive foraging strategy by mycelial networks (Ovaskainen et al. 2013; Bässler et al. 2015; Shigyo and Hirao 2021). Species capable of colonizing both wood and litter may exploit transitional decay stages or microhabitats with shifting moisture levels-conditions typical of riparian slopes where periodic runoff redistributes organic material. This flexibility also enhances community resilience, as multi-substrate fungi can persist despite spatial or temporal fluctuations in substrate availability.

Comparisons with similar tropical studies reveal parallel trends. In Vietnam, Le et al. (2022) reported dominance of lignicolous taxa in humid riparian forests, while in West Java, Rahmi et al. (2021) observed that *Schizophyllum*, *Marasmius*, and *Mycena* thrived in mixed wood-litter substrates. The Samin River system aligns with these findings but further stands out because of its strong substrate gradient from upland to lowland sites, resulting in higher representation of lignicolous and flexible species in the upstream and middle zones.

The substrate ecology of the Samin River macrofungi underscores the functional importance of decaying wood as the backbone of fungal diversity in riparian ecosystems. The dominance of W, the presence of highly specialized lignicolous taxa, and the occurrence of multi-substrate species together highlight an ecologically dynamic system shaped by moisture, organic inputs, and microhabitat heterogeneity.

Comparison with other regions

Patterns of macrofungal diversity observed in the Samin River riparian area align with, yet also diverge in key ways from, studies conducted in other Indonesian landscapes and in tropical Asia. The dominance of Basidiomycota-particularly families such as Mycenaceae, Marasmiaceae, Polyporaceae, and Auriculariaceae-has also been reported in riparian or forest-edge environments elsewhere in Indonesia. For example, Putra (2020) documented

Marasmius, *Mycena*, and *Crepidotus* as the most common genera in West Java, reflecting similar ecological preferences for shaded, moist substrates rich in decomposing organic matter. Likewise, Yusran et al. (2024) noted strong representation of lignicolous taxa in Sulawesi's agroforestry-riparian mosaics, particularly *Auricularia*, *Termitomyces*, and *Ganoderma*, which mirrors the taxa recorded in Samin River (e.g., *A. auricula-judae*, *Termitomyces* sp., and *Ganoderma* sp.).

However, the Samin River assemblage exhibits a stronger association with weathered logs (W) compared to datasets from West Java and Sulawesi, where litter substrates (L) and soil (S) supported higher proportions of species. This may reflect differences in hydrological regime, canopy density, and organic input: the upland regions of Tawangmangu provide continuous wood debris deposition and stable humidity, conditions that promote extensive colonization by *Xylaria*, *Mycena*, *S. commune*, *C. unicolor*, and *P. sanguineus*-taxa consistently associated with high-moisture, high-lignin environments (Kumar et al. 2019; Sondej et al. 2025). In contrast, Putra's (2020) sites were dominated by mixed homegardens and secondary forest edges where leaf litter decomposition is the primary nutrient pathway.

At the regional scale, macrofungal surveys across Southeast Asia show similar structural patterns but with notable biogeographical variation. Studies in Thailand, Vietnam, Peninsular Malaysia, and the Philippines frequently report Mycenaceae and Polyporaceae as dominant families, consistent with the Samin River patterns (Hyde et al. 2018; Dell et al. 2020; Le et al. 2022). In Vietnam, Le et al. (2022) documented extensive colonization of decomposing logs by *Mycena*, *Marasmius*, and *Fomes* species in humid riparian forests, paralleling the strong wood-dependence observed in Samin River. In contrast, studies in seasonal tropical forests of Thailand and Northern Laos found a larger proportion of soil-associated taxa such as *Russula*, *Lactarius*, and *Amanita*, likely due to more pronounced dry seasons and higher rates of ectomycorrhizal activity (Dai et al. 2006; Li et al. 2018).

Globally, the macrofungal diversity structure of the Samin River riparian corridor aligns strongly with patterns recorded in other humid riparian or temperate-tropical transition zones. Riparian forests in the Pacific Northwest, Amazonia, and parts of East Africa similarly show a strong dominance of lignicolous fungi driven by abundant coarse woody debris and stable microclimates (Boddy and Heilmann-Clausen 2008; Guerin-Laguette et al. 2014). The representation of multi-substrate species such as *M. elegans*, *M. adscendens*, *P. plicatilis*, and *P. multifida* reflects broad functional strategies comparable to those reported in Costa Rican and Brazilian Atlantic forests, where microhabitat heterogeneity drives community resilience (Teixeira-Silva et al. 2024).

Despite these similarities, the Samin River system is distinctive for its sharp environmental gradient across relatively short spatial scales. Elevation shifts from >1,100 masl in the upstream to <100 masl in the downstream zone, accompanied by major changes in humidity, canopy cover, substrate availability, and anthropogenic pressure. This degree of environmental contrast-paired with the persistence of moisture-retaining woody substrates-appears to enhance overall macrofungal richness compared to more environmentally homogeneous riparian systems in Southeast Asia. While the macrofungal assemblage of Samin River is broadly consistent with regional and global patterns of tropical riparian mycobiota, it also displays unique features shaped by its elevational gradient, substrate composition, and landscape mosaic. These findings emphasize the ecological value of Javanese riparian corridors as biodiversity reservoirs within increasingly human-modified ecosystems.

Implications for conservation and utilization

The macrofungal diversity documented along the Samin River underscores the importance of riparian corridors as ecological refugia within increasingly fragmented landscapes. Riparian systems-characterized by consistently higher humidity, moderated temperatures, and periodic nutrient deposition-serve as stable microhabitats that buffer fungal communities against environmental fluctuations (Naiman and Décamps 1997; Fischer et al. 2019). The presence of 100+ macrofungal species across only six sampling stations suggests that even narrow riparian strips can sustain remarkably high taxonomic and functional diversity. This is especially relevant in Java, where forest cover outside protected areas is limited, and riparian vegetation often forms the last remaining continuum of semi-natural habitat. The strong dominance of lignicolous taxa such as *Xylaria*, *Mycena*, *Schizophyllum*, and *Cerrena* further indicates that riparian wood debris plays a critical conservation role, acting as a long-term reservoir for enzymatically specialized saprotrophs.

The Samin River findings support a broader recognition that fungi are foundational components of riparian ecosystem resilience through their contributions to organic matter decomposition, soil formation, and nutrient cycling (Kumar et al. 2019; Miles and Chang 2004). In particular, multi-substrate species such as *M. elegans*, *M. chlorophos*, and *P. plicatilis* signal functional redundancy and adaptive capacity within the community, traits that enhance ecosystem stability in the face of changing hydrological regimes or human disturbance (Ovaskainen et al. 2013; Bässler et al. 2015; Shigyo and Hirao 2021).

Beyond their ecological functions, several macrofungal taxa recorded here hold significant potential for food, medicinal applications, and biotechnology. Species categorized as edible (F) in Table 2-including *A. auricula-judae*, *A. nigricans*, and *Termitomyces* sp.-are widely consumed in Asia and valued for their nutritional content, antioxidant activity, and polysaccharide profiles (Boa 2004; Yusran et al. 2024). Their natural occurrence in humid wood-litter microhabitats suggests potential for community-based cultivation in semi-wild or agroforestry systems, as demonstrated in mushroom domestication efforts elsewhere in Indonesia (Kusters and Belcher 2004). The detection of *Termitomyces*, in particular, indicates the presence of well-established termite-fungus interactions in the Samin landscape, opening avenues for managed harvesting or symbiotic cultivation approaches.

Medicinally important species also feature prominently in the assemblage. *Ganoderma* sp., *P. sanguineus*, *C. unicolor*, and *Neofavolus alveolaris* have documented antimicrobial, antioxidant, and immunomodulatory properties (Le et al. 2022; Huang et al. 2023; Sondej et al. 2025). *Ganoderma* species are globally recognized for bioactive triterpenoids and polysaccharides (Karunarathna et al. 2025), while *Pycnoporus* is a source of industrially valuable laccases and secondary metabolites (Lesage-Meessen et al. 2011). The presence of these taxa within a relatively small riparian corridor highlights the biotechnological potential embedded in local fungal communities, many of which remain underutilized and understudied.

Conversely, species classified as poisonous (P), including *I. geophylla*, *T. nigripes*, and *Peziza* sp., underscore the need for caution in local utilization practices. Misidentification is a well-documented risk in tropical regions, where edible and toxic species may exhibit similar macromorphological traits (Li et al. 2025). Thus, conservation strategies should incorporate community education on mushroom identification, sustainable harvesting guidelines, and the promotion of safe, culturally informed foraging practices.

From a management perspective, maintaining and restoring riparian vegetation along the Samin River is essential for sustaining fungal diversity. Conservation measures such as limiting wood removal, retaining coarse woody debris, and reducing land-use conversion near riverbanks will preserve the substrate continuity necessary for lignicolous fungal communities (van der Linde et al. 2012). Additionally, microhabitat-specific cultivation-such as log-based cultivation of *Auricularia* or shaded-litter beds for *Marasmius* species-could offer sustainable livelihood opportunities while supporting in situ conservation. The riparian corridor of the Samin River represents both a biodiversity reservoir and a socioeconomic resource. Its fungal diversity provides ecological services, cultural value, and biotechnological potential that merit stronger integration into local conservation planning and sustainable-use frameworks.

In conclusion, this study provides a comprehensive assessment of macrofungal diversity in Java's tropical riparian Samin River, revealing it as a key refugium supporting 98 species across 38 families and 13 orders, with Basidiomycota, especially Mycenaceae, Polyporaceae, and Marasmiaceae, dominating as key decomposers. Spatial diversity patterns showed upstream zones with the highest richness (H′ = 3.03, R = 6.40) and downstream zones with lower values (H′ = 2.29, R = 3.88), reflecting gradients in humidity, light, and substrate availability. Multi-substrate species like *M. elegans* and *M. adscendens* demonstrated ecological flexibility, while edible, medicinal, and toxic taxa highlighted the community's practical relevance. Although limited by single-season, morphology-based identification, the findings underscore the need to conserve riparian vegetation and woody debris to maintain fungal-driven ecosystem functions. Future studies should integrate multi-season sampling, DNA barcoding, and functional assays to better understand temporal dynamics and species roles in this heterogeneous riparian landscape.

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Waterbird diversity and ecological characteristics of montane wetlands in Dieng Plateau, Central Java, Indonesia

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Abstract. *Agustina AT, Nugroho CKA, Damayanti JT, Dewi R, Yap CK, Iskandar J, Setyawan AD. 2025. Waterbird diversity and ecological characteristics of montane wetlands in Dieng Plateau, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 103-120.* This study examined waterbird diversity and habitat relationships across three montane wetlands of the Dieng Plateau, Central Java, Indonesia-Telaga Menjer, Telaga Merdada, and Telaga Cebong-during the dry season (June-September 2024), using standardized point count and transect walk methods to document species composition, habitat use, and foraging behavior. A total of 25 waterbird species belonging to 13 families were recorded, with assemblages dominated by Ardeidae, Rallidae, and Alcedinidae. Species richness varied among lakes, being highest at Telaga Menjer (21 species), followed by Telaga Merdada (18 species) and Telaga Cebong (15 species), reflecting gradients of habitat heterogeneity, lake size, and disturbance intensity. Diversity indices indicated moderate Shannon-Wiener values (H′ = 2.18-2.65) and high evenness (E = 0.83-0.91), suggesting relatively balanced community structures across sites. Piscivores (40%) and insectivores (36%) constituted the dominant feeding guilds, highlighting the importance of aquatic prey availability and structurally complex littoral zones. Community similarity analysis revealed moderate overlap among lakes, with Sørensen similarity values ranging from 0.61 to 0.72, and species turnover emerging as the primary component of beta diversity, driven by environmental filtering and spatial isolation. The presence of species of conservation concern, including *Aerodramus vulcanorum* (Near Threatened and endemic to Java) and *Gallinula chloropus*, underscores the ecological significance of these wetlands as refugia for both resident and migratory birds. Maintaining littoral vegetation, water quality, and habitat heterogeneity is therefore essential for sustaining avian diversity. Overall, these findings provide the first quantitative baseline for montane wetland avifauna in Java and offer a foundation for integrated management strategies that link habitat protection, sustainable tourism, and community-based monitoring to enhance long-term ecological resilience.

Keywords: Conservation management, Dieng Plateau, habitat heterogeneity, montane wetland, waterbird diversity

INTRODUCTION

Wetlands represent one of the most productive and ecologically significant ecosystems on Earth, functioning as vital habitats for a wide range of aquatic and semi-aquatic organisms, including birds that depend on shallow waters for feeding, breeding, and migration (Purify et al. 2020; Xu et al. 2024). In tropical regions, wetlands sustain complex food webs, regulate hydrological cycles, and serve as biological filters that maintain water quality (Odum 1993; Whitten et al. 1996). Among their faunal components, waterbirds occupy a key ecological position as consumers, dispersers, and bioindicators of wetland health (Şekercioğlu 2006; Taylor et al. 2020). The spatial and temporal diversity of waterbirds is strongly influenced by habitat structure, resource availability, and climatic gradients that determine their occurrence and abundance across ecosystems (Whittaker 1972; Magurran 2004).

Indonesia, an archipelago with extensive coastal, floodplain, and montane wetland systems, harbors a remarkable diversity of bird species with high endemism (MacKinnon et al. 2010; Kurnia et al. 2021). While lowland and coastal wetlands have been extensively studied, the ecological characteristics of montane wetlands, particularly crater lakes and high-altitude ponds, remain poorly documented (Tabalujan et al. 2024). In Java, montane wetlands are typically small and isolated, often situated above 1,500 meters above sea level (masl), where cooler temperatures and limited vegetation reduce overall biodiversity (Whitten et al. 1996; Lama et al. 2022). Despite their relatively small size, these ecosystems play a crucial role as refugia for highland species and as temporary habitats for migratory waterbirds (Ferreira et al. 2024). The Dieng Plateau, located in Central Java, is one of Indonesia's most prominent volcanic highlands, hosting a network of crater lakes such as Telaga Warna, Telaga Merdada, Telaga Cebong, and Telaga Menjer that together form a mosaic of montane wetland habitats (van Bemmelen

1949; Whitten et al. 1996).

Waterbird assemblages in such environments reflect not only ecological adaptation to cold and oligotrophic conditions but also the resilience of species to increasing anthropogenic pressure. Agricultural expansion, particularly potato cultivation and tourism development in Dieng, has transformed the wetland landscape and reduced the extent of littoral vegetation critical for nesting and foraging (Michon and de Foresta 1995; Perfecto and Vandermeer 2010). Furthermore, the combination of habitat fragmentation and eutrophication poses a significant threat to aquatic biodiversity, leading to local declines of sensitive bird populations (Süel et al. 2021; Zakia et al. 2024). Previous studies in Central Java have mainly addressed avifaunal diversity in agroforestry or lowland systems (Kurnia et al. 2021; Marshall et al. 2021; Putri et al. 2021), leaving a substantial knowledge gap on highland waterbird communities. As a result, there remains a limited understanding of how montane wetlands function as habitats for water-dependent birds under strong climatic and anthropogenic constraints.

Birds are particularly sensitive to environmental variations across altitudinal gradients, and changes in their community structure often mirror ecological processes operating at multiple spatial scales (Koleff et al. 2003; Vellend 2010). Studies from Southeast Asia and other tropical mountains have shown that species richness generally declines with elevation, while the composition of bird assemblages shifts toward habitat generalists and cold-tolerant taxa (Kissling et al. 2007; Lama et al. 2022). In montane wetlands, such as those of the Dieng Plateau, low primary productivity and narrow littoral zones limit available resources for foraging guilds, leading to smaller yet functionally specialized communities (Whittaker 1972; Sulai et al. 2022). Nevertheless, these communities often include migratory herons, rails, and grebes, whose presence indicates the persistence of ecological connectivity between highland and lowland wetlands (Ferreira et al. 2024; Xu et al. 2024).

Beyond ecological value, the study of waterbirds in montane environments has practical implications for conservation and sustainable land management. Waterbirds are widely recognized as bioindicators of ecosystem integrity due to their dependence on multiple trophic levels and their sensitivity to disturbance (Thiollay 2007; Şekercioğlu 2010). Understanding their diversity patterns and habitat associations is therefore essential for evaluating the conservation status of montane wetlands and guiding future management strategies. In Indonesia, where legal protection for wetland habitats remains limited (Nijman et al. 2022; Setiawan 2024), such ecological assessments are critical to prevent further degradation of high-altitude ecosystems that support unique avian assemblages.

This study aims to analyze the diversity, composition, and ecological characteristics of waterbirds inhabiting the montane wetlands of the Dieng Plateau, Central Java. Specifically, it seeks to (i) document the species richness and guild structure of waterbird communities around crater lakes, (ii) assess how environmental and habitat characteristics influence their distribution, and (iii) discuss the conservation significance of montane wetlands in maintaining regional avian diversity. The results are expected to contribute baseline data for the long-term monitoring of bird populations in highland aquatic ecosystems and to inform integrative wetland management in one of Java's most ecologically fragile landscapes.

MATERIALS AND METHODS

Study area

The research was conducted in the Dieng Plateau, located in Central Java, Indonesia, approximately between 7°11′-7°15′ S and 109°52′-109°56′ E. The plateau is a volcanic highland complex situated at elevations ranging from 1,500 to 2,100 m asl, covering parts of Banjarnegara and Wonosobo districts (van Bemmelen 1949; Whitten et al. 1996). This area represents one of the few montane wetland systems on Java, characterized by a cluster of small crater lakes formed by ancient volcanic activity. The climate is typically cool and humid, with mean annual temperatures of 14-20 °C and rainfall exceeding 2,500 mm yr^{-1}, producing a distinctive montane microclimate that supports hydrophytic vegetation and specialized avifauna.

Three main crater lakes were selected as representative sampling sites: Telaga Merdada (25 ha), Telaga Cebong (12 ha), and Telaga Menjer (70 ha). Telaga Merdada and Telaga Cebong are located on the Dieng Plateau at elevations of approximately 2,000 masl and 2,100 masl, respectively, whereas Telaga Menjer, used as a comparative site, is situated at a lower elevation of around 1,200 masl. These lakes differ in size, elevation, and degree of human disturbance, providing a natural gradient for evaluating waterbird assemblages.

Telaga Cebong, located near Sikunir Hill, is a shallow montane wetland surrounded by agricultural terraces and remnant marsh vegetation, providing pronounced edge habitats for semi-aquatic and insectivorous birds. Telaga Merdada was selected due to its accessibility and contrasting ecological condition as a shallow montane lake characterized by advanced sedimentation and extensive macrophyte coverage dominated by *Eichhornia crassipes*, allowing assessment of waterbird assemblages under reduced open-water conditions. Telaga Menjer represents the largest water body in the Dieng Plateau and functions as a multipurpose reservoir for hydropower and irrigation, with a relatively deepwater column and well-developed littoral vegetation suitable for waterbird surveys. In contrast, Telaga Warna (2,100 masl, 40 ha) was not included because it is designated as a protected nature reserve (Cagar Alam Telaga Warna), where research access requires special permits, and its sulphuric and geothermal limnological conditions differ markedly from the other crater lakes, limiting ecological comparability.

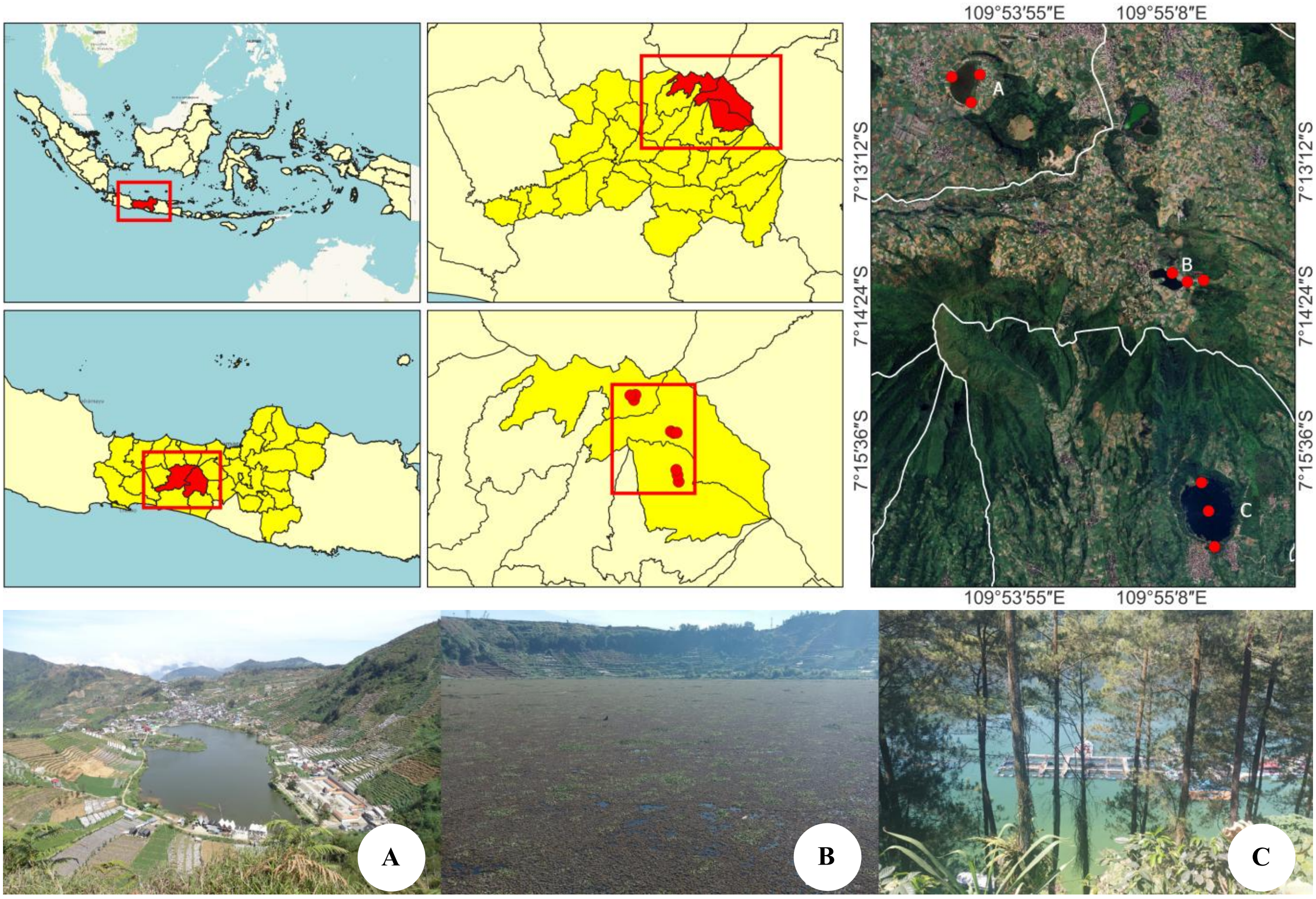


Figure 1. Location of the study area in the Dieng Plateau, Central Java, Indonesia, showing the three surveyed crater lakes: A. Telaga Cebong, B. Telaga Merdada, and C. Telaga Menjer

The ecological setting of these wetlands is highly dynamic due to the interaction between natural processes and anthropogenic pressure. Expansion of potato cultivation, uncontrolled tourism infrastructure, and increasing settlement density have led to partial sedimentation, nutrient enrichment, and fragmentation of wetland habitats (Michon and de Foresta 1995; Perfecto and Vandermeer 2010). Vegetation clearance along the lakeshores reduces habitat complexity and limits the availability of safe nesting areas for herons, rails, and grebes. Nevertheless, the combination of open water, vegetated margins, and surrounding agro-ecosystems still supports a mosaic of ecological niches that sustain both resident and migratory waterbirds (Whitten et al. 1996; Kurnia et al. 2021).

Geologically and ecologically, the Dieng wetlands represent a unique montane ecosystem that functions as an upland refuge for aquatic biodiversity in Java. A schematic map of the study sites and their spatial relationships within the plateau is provided in Figure 1.

Data collection

Bird sampling methods

Field observations were carried out from June to September 2024, representing the dry-season period. This season was strategically selected for sampling because the water levels in the Dieng crater lakes were relatively stable, and waterbirds were more easily detectable along the exposed littoral zones. Additionally, the dry season provides better visibility and safer field conditions compared to the wet season, which is characterized by persistent heavy fog and rainfall that can severely impede bird observation and identification. The primary techniques used were the point count and transect walk methods, which are widely adopted for avian population surveys in both tropical and temperate wetlands (Ralph et al. 1995; Sutherland 2006).

Each of the three lakes (Telaga Merdada, Telaga Cebong, and Telaga Menjer) was visited three times during the study period, with surveys spaced approximately one month apart to account for intra-seasonal variation. At each lake, a series of five to eight observation points was systematically established along the accessible shoreline, spaced at least 200 m apart to minimize double-counting of individual birds. Each point covered an estimated radius of 50 m, encompassing both open water and marginal vegetation. Observations were conducted twice daily, during early morning (05:30-09:00) and late afternoon (15:30-17:30), corresponding to peak bird activity periods when foraging and vocalization are most frequent (Kroodsma and Miller 1996).

Each observation session lasted 10-15 minutes per point, during which all individuals seen or heard were recorded. Binoculars (8×42) and a DSLR camera equipped with a telephoto lens were used to ensure accurate identification and to document rare or ambiguous species. Species were identified in the field using MacKinnon and Phillipps (1993) and MacKinnon et al. (2010) as standard field guides. Vocal cues were also used for species recognition, especially for cryptic or nocturnal taxa such as rails and bitterns. For each record, data on species name, number of individuals, behavior (foraging, resting, flying, or nesting), and microhabitat type were noted.

Only water-dependent and semi-aquatic species were included in the final dataset. These include members of families such as Ardeidae (herons and egrets), Anatidae (ducks), Rallidae (rails and moorhens), and Alcedinidae (kingfishers). Terrestrial birds occasionally found near the lakes were excluded unless they showed strong dependence on aquatic habitats. This criterion followed international standards for wetland avifauna studies (Şekercioğlu 2006; Sodhi et al. 2010). To ensure sampling consistency, the total effort-expressed as the number of observation points multiplied by duration per point-was maintained equally across the three lakes, providing comparable detection probabilities.

Habitat and environmental measurements

To complement bird data, environmental parameters were measured concurrently at each observation point to characterize habitat structure and ecological conditions. Vegetation cover was estimated within a 10 × 10 m quadrat adjacent to each point count location, recording the dominance of emergent aquatic plants such as *Typha angustifolia*, *Cyperus malaccensis*, *Scirpus grossus*, and *Phragmites karka*. These species form dense stands that offer nesting substrates, roosting cover, and invertebrate prey resources for waterbirds (Whitten et al. 1996).

Basic limnological parameters were measured at the littoral zone using portable instruments: water depth (cm) with a measuring pole, temperature (°C) with a digital thermometer, and turbidity (NTU) using a Secchi disk. These factors influence prey availability and visibility conditions that affect bird foraging efficiency (Xu et al. 2024).

Land-use intensity surrounding the lakes was categorized visually based on dominant human activities within a 100 m buffer zone (e.g., agriculture, settlements, or tourism facilities), and distance from the nearest road or village was measured with a handheld GPS unit. Habitat types were further described according to their microhabitat features, including (i) open water, (ii) vegetated margin, (iii) mudflat, and (iv) agro-edge. The proportion of each habitat type was estimated visually and used for subsequent ecological interpretation of bird-habitat associations.

All field data were recorded on standardized datasheets to ensure comparability among sites. The combination of avian census and environmental measurements provides a robust baseline for analyzing waterbird diversity patterns in relation to habitat heterogeneity and human influence in the montane wetland ecosystems of Dieng.

Data analysis

Diversity indices

Waterbird diversity across the three lakes was quantified using several standard ecological indices that describe community composition and structure. Species richness (S) was determined as the total number of species observed per site. The Shannon-Wiener diversity index (H′) was calculated to incorporate both species richness and the relative abundance of each species, using the formula $H\prime = -\sum p_i \ln p_i$, where *pi* represents the proportion of individuals belonging to the *i*th species (Magurran 2004). To assess the distribution of individuals among species, evenness (E) was derived as $E = \frac{H\prime}{\ln S}$, indicating the degree to which species are evenly represented within the community (Whittaker 1972). The dominance index (C), derived from Simpson's index, was used to detect the presence of dominant taxa that may disproportionately influence ecosystem function.

Comparative analyses were performed to evaluate spatial variation in diversity among Telaga Merdada, Telaga Cebong, and Telaga Menjer, providing insight into how habitat size, water depth, and human disturbance affect waterbird assemblages. Differences in diversity values were examined descriptively and visualized through bar plots. This multimetric approach allows a comprehensive understanding of how environmental heterogeneity shapes montane wetland avifauna.

Functional guild classification

To explore ecological roles within the waterbird community, species were grouped into functional feeding guilds following the EltonTraits database (Wilman et al. 2014) and verified through regional ecological accounts (Whitten et al. 1996; Hothem et al. 2020; Taylor et al. 2020). Each species was assigned to one of the major trophic categories based on its dominant diet and foraging behavior, namely: piscivores (species feeding primarily on fish, such as herons and kingfishers), insectivores (species feeding mainly on aquatic or aerial insects, such as swallows, swifts, and wagtails), omnivores (species consuming mixed diets of invertebrates and plant material, such as rails and some passerines), granivores (species feeding predominantly on seeds or grains, such as munias), and carnivores (opportunistic predators feeding on small vertebrates or large invertebrates, such as shrikes). This classification facilitated comparison of trophic composition and functional diversity among the surveyed wetlands.

Additionally, habitat dependence was classified into three categories to interpret the ecological association of each species with aquatic environments. Strict waterbirds are species whose activities are confined to aquatic habitats for both feeding and nesting, such as herons and grebes. Semi-aquatic species utilize both wetland and adjacent terrestrial areas, moving between water edges and surrounding vegetation for foraging and roosting. Terrestrial associates, on the other hand, are birds that frequent lakes primarily for feeding but nest and spend most of their time in nearby drylands. This classification framework helps link feeding behavior and habitat use along environmental gradients, providing a functional interpretation of biodiversity patterns in montane wetland systems (Şekercioğlu 2010; Sulai et al. 2022).

Similarity and assemblage structure

Community composition among the three lakes was compared using the Sørensen similarity index (IS) (Sørensen 1948), which measures the proportion of shared species between two sites according to the formula IS=2C/(A+B)IS = 2C/ (A + B)IS=2C/(A+B), where *C* is the number of species common to both sites, and *A* and *B* represent total species at each site. Values close to 1 indicate high similarity, while values near 0 denote distinct assemblages.

To assess overall species turnover, beta diversity (β) was computed following the method of Koleff et al. (2003), partitioning differences in community composition into components of turnover and nestedness. Beta diversity analysis reveals the extent to which each lake contributes unique species to the regional pool, an important parameter in conservation prioritization. A cluster dendrogram based on Sørensen distances was used to visualize assemblage similarity among sites, indicating patterns of spatial clustering influenced by elevation, habitat complexity, and human disturbance.

To test the relationship between vegetation cover and waterbird species richness, a Pearson correlation analysis was performed using IBM SPSS Statistics 26. Mean vegetation cover (%) at each observation point ($n = 15$) was correlated with the number of species recorded at the same points. Data normality was checked prior to analysis. The correlation coefficient ($r = 0.82$, $p < 0.05$) indicated a strong positive association, confirming that higher vegetation cover supported greater species richness in the surveyed wetlands.

Conservation assessment

The conservation significance of each species was determined by cross-referencing its global and national protection status. The IUCN Red List (IUCN 2024) was used to classify species into conservation categories such as Least Concern (LC) and Near Threatened (NT). In parallel, the Indonesian Ministry of Environment and Forestry Regulation (Permen LHK No. 106/2018) (KLHK 2018a) was used to identify species protected under national law. Migratory status was also recorded, distinguishing resident, migrant, and vagrant species based on the IOC World Bird List and regional field guides (MacKinnon and Phillipps 1993; MacKinnon et al. 2010; Gill et al. 2024).

Species richness and composition were interpreted in light of these conservation categories to determine the ecological importance of each lake. Lakes hosting protected or migratory species were considered to have higher conservation value, warranting long-term habitat monitoring and management. This assessment framework aligns with the broader objectives of biodiversity conservation in tropical montane ecosystems, emphasizing the role of small crater wetlands as refuges for aquatic and migratory birds (Ferreira et al. 2024; Xu et al. 2024).

Ethical considerations

All field procedures followed established ethical guidelines to minimize disturbance to birds and their habitats. Observations were conducted from a safe distance using binoculars and telephoto lenses, avoiding approach during breeding or nesting activity. Playback calls and artificial attractants were not used to prevent behavioral alteration. The study adhered to the ethical principles outlined in Newing (2011) for wildlife research, ensuring respect for both ecological integrity and local community norms. Coordination was maintained with local authorities and communities surrounding each lake to obtain access permission and ensure compliance with existing environmental regulations. No specimens were collected or handled during the study, and all data were obtained through non-invasive visual and auditory methods.

RESULTS AND DISCUSSION

Waterbird species composition and richness across lake sites

A total of 25 waterbird species belonging to 13 families were recorded from the three surveyed lakes in the Dieng Plateau: Telaga Merdada, Telaga Cebong, and Telaga Menjer. Most species were aquatic or semi-aquatic, with several terrestrial associates occasionally observed along the lake margins. Species richness varied slightly among sites, with Telaga Menjer hosting the highest number of species (21), followed by Telaga Merdada (18) and Telaga Cebong (15) (Table 2). This pattern reflects differences in habitat size, vegetation cover, and degree of anthropogenic disturbance among the three crater lakes.

The avifauna recorded in the crater lake wetlands was dominated by species belonging to the families Ardeidae, Rallidae, Alcedinidae, and Hirundinidae, represented by *Ardea cinerea*, *Ardeola bacchus*, *Ardeola speciosa*, *Nycticorax nycticorax*, *Butorides striata*, *Ixobrychus cinnamomeus* (Ardeidae); *Gallinula chloropus* and *Amaurornis phoenicurus* (Rallidae); *Halcyon cyanoventris* and *Todiramphus chloris* (Alcedinidae); and *Hirundo tahitica* (Hirundinidae). These taxa constitute key functional components of wetland ecosystems, encompassing piscivorous, insectivorous, and omnivorous feeding guilds that contribute to the regulation of aquatic and semi-aquatic trophic processes. Several species, including *Tachybaptus ruficollis*, *A. phoenicurus*, and *A. speciosa*, were recorded across multiple habitat types within the surveyed crater lakes, indicating broad ecological tolerance. In contrast, *A. vulcanorum* and *N. nycticorax* were associated with more specific habitat features, such as rocky cliffs and dense emergent vegetation, reflecting habitat specialization rather than numerical dominance.

Terrestrial associates, such as *Passer montanus*, *Lanius schach*, and *Dendrocopos analis*, were frequently recorded near agroforestry margins and settlements surrounding the lakes. Although not strictly aquatic, their presence indicates the close ecological connectivity between wetland and terrestrial habitats in this montane landscape. The co-occurrence of these guilds suggests that small crater lakes in Dieng act as biodiversity refugia that sustain mixed avifaunal assemblages characteristic of montane Java.

Table 1 presents the complete list of waterbird species recorded during the survey, including family affiliation, feeding guild, habitat dependence, and conservation status according to the IUCN (2024) and the Indonesian national protection list (Permen LHK No. 106/2018) (KLHK 2018b). The recorded species were classified only under the Least Concern (LC) and Near Threatened (NT) categories of the IUCN Red List. No species categorized as Vulnerable (VU) or Endangered (EN) were detected in the surveyed wetlands. Most species were categorized as Least Concern (LC), while *A. vulcanorum*, a Javan endemic, was identified as Near Threatened (NT) due to its restricted distribution and specialized habitat requirements.

The species composition revealed that strict waterbirds dominated the avifaunal assemblage with 9 species (36%), followed closely by 10 semi-aquatic species (40%). Terrestrial associates, including species utilizing wetland margins, adjacent farmland, and cliff environments, comprised 6 species (24%). Consequently, a combined 76% of all recorded species were either strictly water-dependent or semi-aquatic, emphasizing the central role of aquatic habitats in structuring the avifaunal community.

This composition indicates a structurally diverse assemblage despite the limited spatial extent of the montane wetlands. The high representation of piscivorous and insectivorous species reflects the ecological productivity of these crater lakes, particularly in supporting aquatic and aerial prey resources. In contrast, the presence of granivorous and omnivorous species highlights the influence of surrounding agricultural landscapes and terrestrial habitats on bird assemblages. The results suggest that the Dieng crater lakes collectively sustain a moderately rich waterbird community for a montane environment, where cool climatic conditions, elevation, and habitat isolation often constrain aquatic biodiversity.

Diversity indices and community structure

Quantitative analysis of community structure revealed moderate diversity levels among the three surveyed lakes of the Dieng Plateau. The calculated Shannon-Wiener diversity index (H′) ranged from 2.18 to 2.65, while evenness (E) values were relatively high (0.83-0.91), indicating that most species were fairly evenly represented in the assemblages (Table 2). Dominance (C) values were low (<0.15), suggesting that no single species overwhelmingly dominated the waterbird community.

Table 1. Waterbird species recorded from three crater lakes in the Dieng Plateau, Central Java, Indonesia

Scientific name	English name	Indonesian name	Family	Feeding guild	Habitat type	Conservation status (IUCN/ Permen LHK No. 106/2018)
Aerodramus vulcanorum	Volcano Swiftlet	*Walet jawa*	Apodidae	Insectivore	Terrestrial associate	NT/ Protected
Apus affinis	Little Swift	*Kapinis rumah*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Collocalia esculenta	Glossy Swiftlet	*Walet sarang-putih*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Collocalia linchi	Cave Swiftlet	*Walet linci*	Apodidae	Insectivore	Semi-aquatic	LC/ -
Ardea cinerea	Grey Heron	*Cangak abu*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Ardeola bacchus	Chinese Pond Heron	*Blekok cina*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Ardeola speciosa	Javan Pond Heron	*Blekok sawah*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Butorides striata	Striated Heron	*Kokokan laut*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Ixobrychus cinnamomeus	Cinnamon Bittern	*Bambangan merah*	Ardeidae	Piscivore	Strict waterbird	LC/ -
Nycticorax nycticorax	Black-crowned Night Heron	*Kowak malam abu*	Ardeidae	Piscivore	Strict waterbird	LC/ Protected
Halcyon cyanoventris	Javan Kingfisher	*Cekakak jawa*	Alcedinidae	Piscivore	Semi-aquatic	LC/ Protected
Todiramphus chloris	Collared Kingfisher	*Cekakak sungai*	Alcedinidae	Piscivore	Semi-aquatic	LC/ -
Cacomantis merulinus	Plaintive Cuckoo	*Wiwik kelabu*	Cuculidae	Insectivore	Semi-aquatic	LC/ -
Cacomantis variolosus	Brush Cuckoo	*Wiwik lurik*	Cuculidae	Insectivore	Semi-aquatic	LC/ -
Lonchura leucogastroides	Javan Munia	*Bondol jawa*	Estrildidae	Granivore	Terrestrial associate	LC/ -
Hirundo tahitica	Pacific Swallow	*Layang-layang batu*	Hirundinidae	Insectivore	Semi-aquatic	LC/ -
Lanius schach	Long-tailed Shrike	*Bentet kelabu*	Laniidae	Carnivore	Terrestrial associate	LC/ -
Motacilla cinerea	Grey Wagtail	*Kicuit batu*	Motacillidae	Insectivore	Semi-aquatic	LC/ -
Passer montanus	Eurasian Tree Sparrow	*Burung gereja erasia*	Passeridae	Omnivore	Terrestrial associate	LC/ -
Dendrocopos analis	Freckle-breasted Woodpecker	*Pelatuk dada-bintik*	Picidae	Insectivore	Terrestrial associate	LC/ -
Tachybaptus novaehollandiae	Australasian Grebe	*Podang australis*	Podicipedidae	Piscivore	Strict waterbird	LC/ -
Tachybaptus ruficollis	Little Grebe	*Podang kecil*	Podicipedidae	Piscivore	Strict waterbird	LC/ -
Pycnonotus aurigaster	Sooty-headed Bulbul	*Cucak kutilang*	Pycnonotidae	Omnivore	Terrestrial associate	LC/ -
Amaurornis phoenicurus	White-breasted Waterhen	*Kareo padi*	Rallidae	Omnivore	Strict waterbird	LC/ -
Gallinula chloropus	Common Moorhen	*Mandar biasa*	Rallidae	Omnivore	Strict waterbird	LC/ -

Table 2. Diversity indices and abundance summary of waterbird communities across three crater lakes in the Dieng Plateau, Central Java, Indonesia

Lake site	Total species (S)	Total individuals (n)	Shannon-Wiener Index (H′)	Evenness (E)	Dominance (C)	Remarks
Telaga Menjer	21	186	2.65	0.91	0.11	Highest diversity, extensive vegetation, and low disturbance
Telaga Merdada	18	154	2.43	0.88	0.13	Moderate diversity; influenced by tourism activity
Telaga Cebong	15	127	2.18	0.83	0.14	Lowest diversity; small area and higher human pressure
Mean ± SD	-	-	2.42 ± 0.19	0.87 ± 0.04	0.13 ± 0.02	-

Among the three surveyed sites, Telaga Menjer exhibited the highest diversity (H′ = 2.65) and evenness (E = 0.91), which corresponded with its larger surface area, deeper water column, and extensive aquatic vegetation that supported a wide range of foraging microhabitats. Telaga Merdada showed moderately high diversity (H′ = 2.43), while Telaga Cebong recorded the lowest diversity (H′ = 2.18) and slightly higher dominance (C = 0.14). These spatial patterns indicate that variations in habitat heterogeneity and disturbance intensity play crucial roles in shaping the organization and stability of waterbird communities in these montane wetlands.

The relatively high evenness across all sites indicates ecological balance, with resource competition spread among multiple species and feeding guilds. The low dominance index further supports the notion that the Dieng lakes maintain a structurally stable waterbird community despite their small size and surrounding anthropogenic pressures. These findings align with previous studies reporting that moderate diversity with high evenness is typical of small, isolated wetlands in tropical highlands where space and food availability are limited but stable (Whittaker 1972; Magurran 2004; Lama et al. 2022).

The diversity structure of the Dieng waterbird community demonstrates a balanced assemblage dominated by small to medium-sized piscivores and insectivores. Despite the modest richness compared to lowland wetlands, the high evenness values suggest functional complementarity among species and minimal ecological monopolization. These results reinforce the importance of small montane lakes as stable, self-sustaining habitats supporting diverse avifauna under constrained environmental conditions.

Functional feeding guilds and habitat dependence

The recorded avifauna of the Dieng Plateau lakes represented a broad range of ecological functions, encompassing five major feeding guilds: piscivores, insectivores, omnivores, carnivores, and granivores. Guild classification was based on species' predominant foraging behavior and dietary characteristics following the EltonTraits database (Wilman et al. 2014) and field observations. Among the 25 recorded species, piscivores were the most dominant guild (40%, n=10), followed closely by insectivores (36%, n=9), omnivores (16%, n=4), while carnivores and granivores each comprised 4% (n=1) (Table 3, Figure 2.A).

Piscivorous species-primarily members of the families Ardeidae, Podicipedidae, and Alcedinidae-occupied open-water and shallow-vegetated habitats where small fish and aquatic invertebrates were abundant. Representative species such as *A. speciosa*, *T. ruficollis*, and *H. cyanoventris* were frequently observed foraging in pairs or small groups, indicating stable prey availability. The dominance of this guild (10 species, 40%) suggests that these montane wetlands sustain productive aquatic food webs despite their small size and cool temperature regimes.

Insectivores comprised 9 species (36%), consisting of swifts, swallows, cuckoos, and wagtails that forage on aerial insects or small invertebrates near the water surface and surrounding areas. Their prevalence reflects both the abundance of emergent aquatic vegetation that supports insect larvae and the adjacent terrestrial vegetation that shelters adult insects.

The omnivore guild included 4 species (16%), such as *A. phoenicurus* and *G. chloropus*, which displayed high adaptability by exploiting both aquatic and terrestrial food resources, including seeds, mollusks, and detritus. In contrast, both granivores and carnivores were each represented by a single species (4% each): *Lonchura leucogastroides* foraged on grass seeds in the terrestrial margins, while *L. schach* hunted small vertebrates in the surrounding scrubland.

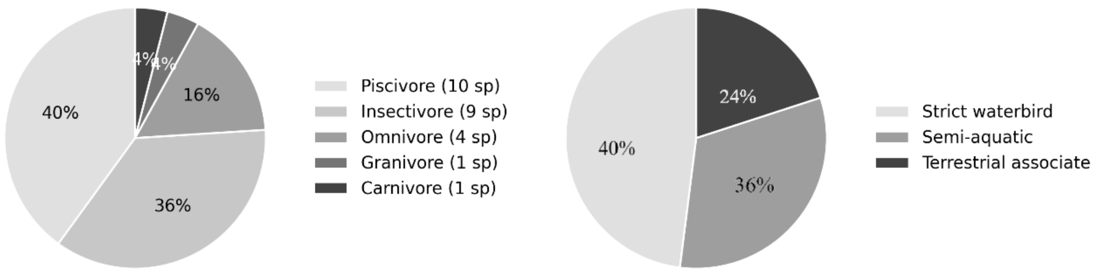
When categorized by habitat dependence, strict waterbirds comprised 9 species (36%), semi-aquatic species accounted for 10 species (40%), and terrestrial associates-including species utilizing wetland margins, adjacent farmland, and cliff habitats-totaled 6 species (24%) (Table 3, Figure 2.B). This pattern indicates that habitat heterogeneity-characterized by a mosaic of open water, shallow littoral zones, and emergent vegetation-facilitates the coexistence of multiple ecological guilds within relatively confined crater lake basins.

The community structure was dominated by predator guilds (piscivores and insectivores), which together accounted for 76% of all species, indicating a trophic structure heavily reliant on aquatic and aerial prey. This was complemented by omnivores and the single granivorous and carnivorous species, demonstrating a degree of resource partitioning in small but stable montane wetland ecosystems. These findings align with prior observations that high habitat heterogeneity and vegetation complexity enhance niche differentiation and reduce interspecific competition (Schoener 1971; Sulai et al. 2022).

Table 3. Functional feeding guilds and habitat dependence of waterbird species recorded from Dieng Plateau lakes, Central Java, Indonesia

Feeding guild	Representative families/ species	No. of species	Percentage (%)	Habitat dependence (dominant)
Piscivore	Ardeidae (*Ardea cinerea, Ardeola bacchus, Ardeola speciosa, Nycticorax nycticorax, Butorides striata, Ixobrychus cinnamomeus*); Alcedinidae (*Halcyon cyanoventris, Todiramphus chloris*); Podicipedidae (*Tachybaptus ruficollis, T. novaehollandiae*)	10	40.0	Strict waterbird
Insectivore	Apodidae (*Collocalia esculenta, C. linchi, Apus affinis, Aerodramus vulcanorum*); Cuculidae (*Cacomantis merulinus, C. variolosus*); Hirundinidae (*Hirundo tahitica*); Motacillidae (*Motacilla cinerea*); Picidae (*Dendrocopos analis*)	9	36.0	Semi-aquatic
Omnivore	Rallidae (*Amaurornis phoenicurus, Gallinula chloropus*); Pycnonotidae (*Pycnonotus aurigaster*); Passeridae (*Passer montanus*)	4	16.0	Semi-aquatic/ terrestrial associate
Granivore	Estrildidae (*Lonchura leucogastroides*)	1	4.0	Terrestrial associate
Carnivore	Laniidae (*Lanius schach*)	1	4.0	Terrestrial associate
Total		25	100.0	-

Note: Omnivorous species were assigned to habitat categories based on dominant habitat use: *Amaurornis phoenicurus* and *Gallinula chloropus* as semi-aquatic, and *Pycnonotus aurigaster* and *Passer montanus* as terrestrial associates



A B

Figure 2. Proportion of (A) waterbird feeding guilds (piscivore, insectivore, omnivore, carnivore) and (B) habitat dependence categories (strict waterbird, semi-aquatic, terrestrial associate) across Dieng Plateau lakes, Central Java, Indonesia (n=25 spesies) %

The balanced composition between strict waterbirds (40%) and semi-aquatic species (36%) demonstrates that montane crater lakes in Dieng sustain both obligate wetland specialists and generalist bird species. The persistence of diverse insectivores and omnivores underscores the cross-ecosystem connectivity between open water, vegetated littoral zones, and adjacent agricultural mosaics. These results imply that maintaining vegetation diversity and hydrological stability around crater lakes is critical for preserving functional guild diversity and ecosystem resilience. Degradation of littoral zones or conversion of surrounding farmland into intensive tourism areas may disproportionately affect semi-aquatic guilds that depend on edge habitats.

Similarity and beta diversity among lake sites

Community similarity analysis using the Sørensen index (Sørensen 1948) revealed moderate overlap in waterbird composition among the three surveyed lakes (Table 4). Pairwise similarity values ranged from 0.61 to 0.72, indicating that while several core species were shared among all sites, each lake also harbored a number of unique taxa. The highest similarity occurred between Telaga Menjer and Telaga Merdada (S = 0.72), reflecting their comparable habitat conditions-broad water surfaces, vegetated margins, and moderate human activity. Telaga Cebong showed similar and lower similarity values with both Menjer and Merdada (S = 0.61), likely due to its smaller size, higher elevation, and more limited littoral vegetation.

Partitioning of beta diversity following Koleff et al. (2003) indicated that species turnover (mean = 0.23 ± 0.06) contributed more strongly to overall beta diversity than nestedness (mean = 0.12 ± 0.01). This suggests that species replacement across sites-rather than mere loss or gain of subsets-was the main driver of compositional differences among the Dieng lakes. The relatively high turnover reflects environmental heterogeneity, differences in disturbance regimes, and spatial isolation between lake basins separated by steep terrain.

A cluster dendrogram (Figure 3) based on Sørensen similarity grouped Telaga Menjer and Telaga Merdada closely together, while Telaga Cebong formed a separate branch, confirming its distinct community structure. This pattern corresponds with field observations showing that Menjer and Merdada support broader aquatic habitats dominated by herons, grebes, and rails, whereas Cebong sustains fewer strictly aquatic species and is dominated by aerial insectivores and edge-dwelling birds.

The analysis demonstrates moderate differentiation in waterbird assemblages among the crater lakes of Dieng, driven by ecological specialization and spatial isolation. These results are consistent with the general principle that small montane wetlands exhibit higher beta diversity due to limited connectivity and strong local environmental filters (Vellend 2010; Süel et al. 2021).

The overall pairwise Sørensen similarity averaged 0.65 ± 0.06, indicating that approximately two-thirds of the species were shared between any two lakes. Beta diversity was primarily driven by turnover rather than nestedness, underscoring the role of environmental filtering and local adaptation in structuring bird assemblages across the Dieng Plateau's fragmented montane wetlands.

From a conservation standpoint, the relatively high turnover implies that protecting a single lake would not suffice to conserve regional waterbird diversity. Instead, integrated management of multiple lake habitats is necessary to preserve complementary species pools and maintain ecosystem-level diversity.

Habitat and environmental characteristics

The three surveyed lakes in the Dieng Plateau exhibited clear variation in physical conditions, vegetation structure, and surrounding land-use intensity, which collectively shaped the observed waterbird assemblages (Table 5). The habitats were composed of three primary microhabitat types: open water zones, mudflats, and vegetated margins. Open-water areas dominated Telaga Menjer and Telaga Merdada, while Telaga Cebong, being smaller and shallower, featured extensive vegetated edges and periodically exposed mudflats.

Telaga Menjer, the largest and deepest lake, possessed wide open-water surfaces fringed by emergent macrophytes such as *Cyperus*, *Phragmites*, and *Typha* species. These vegetated margins provided nesting and foraging sites for herons (Ardeidae) and grebes (Podicipedidae), resulting in high waterbird diversity. The water column was relatively clear (turbidity < 10 NTU) and deep (mean depth ≈ 24 m), maintaining stable temperature profiles and supporting a persistent aquatic invertebrate community.

Telaga Merdada exhibited intermediate ecological characteristics. Although smaller than Menjer, it had complex littoral vegetation interspersed with exposed mudflats during dry periods, supporting insectivores and wading birds such as *A. phoenicurus* and *G. chloropus*. However, human disturbance was moderate to high due to tourism infrastructure along the shoreline, contributing to elevated turbidity (≈ 14 NTU) and reduced vegetation continuity.

In contrast, Telaga Cebong-located at a higher elevation 2,100 masl)-was shallow (mean depth ≈ 6 m) and heavily influenced by nearby vegetable farming and human settlements. The littoral zone was dominated by grasses and sedges with limited macrophyte cover, while domestic runoff occasionally entered the lake, increasing nutrient load and turbidity. Despite this, its high vegetation density along the banks provided refuge for semi-aquatic species such as *Cacomantis merulinus* and *Hirundo tahitica*.

The overall pattern indicated that species richness increased with vegetation cover and habitat complexity, while high disturbance and turbidity corresponded to lower diversity. This positive correlation between habitat heterogeneity and bird diversity ($r = 0.82$, $p < 0.05$) supports the notion that structural complexity enhances resource diversity and ecological niches for both aquatic and semi-aquatic guilds (Figure 4).

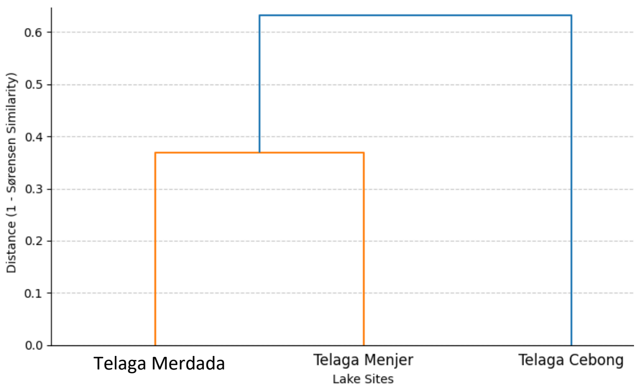


Figure 3. Cluster dendrogram of waterbird assemblages across crater lakes in the Dieng Plateau, Central Java, Indonesia

Table 4. Pairwise Sørensen similarity index and beta diversity components (turnover and nestedness) among three crater lakes in the Dieng Plateau, Central Java, Indonesia

Comparison	Shared species	Sørensen similarity (S)	Beta diversity (β_{total})	Turnover	Nestedness	Interpretation
Menjer - Merdada	14	0.72	0.28	0.17	0.11	Highest similarity; both large and vegetated lakes
Menjer - Cebong	11	0.61	0.39	0.26	0.13	Moderate dissimilarity driven by elevation and lake size
Merdada - Cebong	10	0.61	0.39	0.27	0.12	Moderate dissimilarity dominated by species turnover
Mean ± SD	-	0.65 ± 0.06	0.35 ± 0.06	0.23 ± 0.06	0.12 ± 0.01	Turnover dominates assemblage differentiation

Note: Species turnover was the dominant component of beta diversity across all lake pairs

Table 5. Environmental parameters and land-use intensity at three crater lakes in the Dieng Plateau, Central Java, Indonesia

Parameter	Telaga Menjer	Telaga Merdada	Telaga Cebong	Remarks
Elevation (masl)	1,200	2,000	2,100	Increases with decreasing lake size
Surface area (ha)	70	25	12	Larger lakes sustain greater habitat diversity
Mean depth (m)	24	10	6	Deeper lakes have lower seasonal fluctuation
Water temperature (°C)	21.4 ± 0.7	20.1 ± 0.9	18.3 ± 1.2	Cooler temperatures at higher elevations
Turbidity (NTU)	9.5 ± 2.1	14.3 ± 2.8	18.7 ± 3.2	Higher in disturbed and shallow lakes
Vegetation cover (%)	65.4 ± 5.2	53.8 ± 4.9	42.1 ± 6.3	Positively correlated with species richness.
Dominant plant families	Cyperaceae, Typhaceae, Poaceae	Cyperaceae, Poaceae	Poaceae, Asteraceae	Reflects habitat zonation and altitude
Land-use intensity (qualitative)	Low	Moderate	High	Based on tourism, settlement, and agriculture
Species richness (no. of species)	21	18	15	Corresponds to the vegetation and disturbance gradient

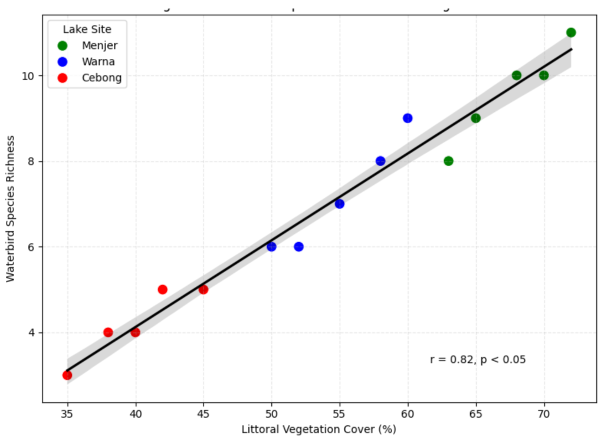


Figure 4. Relationship between vegetation cover and bird species richness across crater lakes in the Dieng Plateau, Central Java, Indonesia

The relationship between vegetation cover and bird diversity demonstrates that structurally complex shorelines promote greater foraging and nesting opportunities. The abundance of emergent macrophytes and aquatic-edge vegetation around Telaga Menjer and Telaga Merdada explains their higher diversity indices compared to Telaga Cebong. Conversely, reduced vegetation and intensive land use were associated with community simplification and lower evenness. These findings emphasize the importance of maintaining littoral vegetation and controlling shoreline disturbance to sustain ecological integrity and avian diversity in montane wetland ecosystems.

Conservation status and ecological significance

The waterbird assemblages of the Dieng Plateau include species of varying conservation concern at both global and national levels. Based on assessments by the IUCN (2024) and the Indonesian protected species list (Permen LHK No. 106/2018) (KLHK 2018b), most recorded species were classified as Least Concern (LC), reflecting their relatively stable global populations. However, several taxa possess regional or national importance due to endemism, restricted distribution, or specialized habitat requirements (Table 6, Figure 5).

A total of five species (20%) were listed under Indonesia's national protection regulation: *Aerodramus vulcanorum*, *H. cyanoventris*, *A. cinerea*, *A. speciosa*, and *N. nycticorax*. Among them, *A. vulcanorum*-the Javan Volcano Swiftlet-is also categorized as Near Threatened (NT) by IUCN (2024), being a montane endemic species confined to volcanic cliffs above 1,000 masl. Its occurrence near Telaga Cebong and the steep escarpments of the Dieng caldera highlights the site's importance as a refuge for range-restricted taxa.

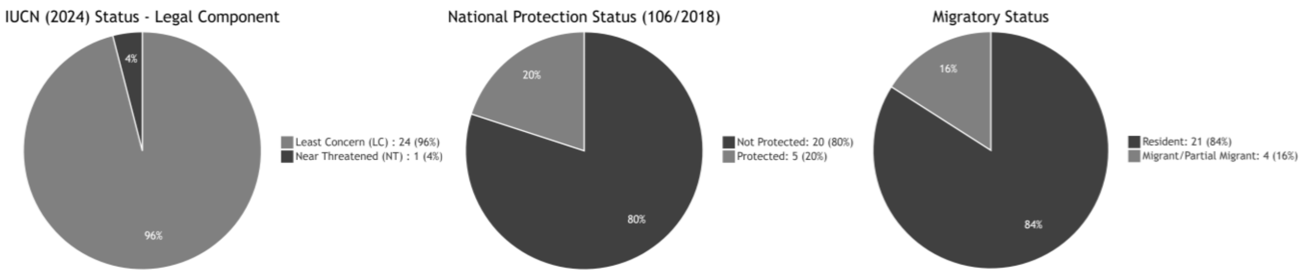
Of the recorded species, 24 were classified as Least Concern (LC), indicating that the majority of the assemblage currently faces relatively low extinction risk. The remaining protected species, primarily from the Ardeidae and Alcedinidae families, function as apex or mid-trophic predators in wetland food webs, thus serving as ecological indicators of water quality and prey availability. Their sustained presence in Telaga Menjer and Telaga Merdada suggests that these lakes maintain sufficient ecological integrity and trophic productivity to support higher-level consumers.

In terms of migratory status, four species (16%)-including *G. chloropus*, *Motacilla cinerea*, *Tachybaptus novaehollandiae*, and *N. nycticorax*-were identified as migratory visitors or partially resident migrants, occurring seasonally or during post-breeding dispersal periods. The remaining majority were resident species typical of montane Java, emphasizing the Dieng Plateau's role as a year-round habitat rather than a transient stopover site.

When assessed by conservation value, Telaga Menjer ranked highest owing to its richness of protected and migratory species, followed by Telaga Merdada and Telaga Cebong. The occurrence of legally protected species in all three lakes, however, highlights their collective potential as significant habitats for regional biodiversity. This potential is vulnerable to emerging threats from the continued expansion of tourism, agricultural encroachment, and water pollution. These pressures warrant proactive, adaptive management that integrates targeted conservation actions, community awareness programs, and carefully regulated sustainable ecotourism initiatives.

Table 6. Conservation categories and migratory status of waterbird species recorded in the Dieng Plateau, Central Java, Indonesia

Species	IUCN (2024) Status	National Protection (106/2018)	Migratory status	Remarks
Aerodramus vulcanorum	NT	Protected	Resident (endemic)	Montane cliffs, limited range
Halcyon cyanoventris	LC	Protected	Resident	Endemic to Java
Ardea cinerea	LC	Protected	Partial migrant	Wide distribution
Ardeola speciosa	LC	Protected	Resident	Common wader in Java
Nycticorax nycticorax	LC	Protected	Migrant/ Resident	Nocturnal forager
Ardeola bacchus	LC	-	Resident	Occasional visitor to Dieng
Tachybaptus novaehollandiae	LC	-	Partial migrant	Breeding confirmed in Menjer
Gallinula chloropus	LC	-	Migrant	Seasonal visitor (Oct-Mar)
Motacilla cinerea	LC	-	Migrant	Common in high-altitude wetlands
Amaurornis phoenicurus	LC	-	Resident	Stable population
Tachybaptus ruficollis	LC	-	Resident	Dominant piscivore species
Lanius schach	LC	-	Resident	Terrestrial predator
Cacomantis merulinus	LC	-	Resident	Semi-aquatic cuckoo
Hirundo tahitica	LC	-	Resident	Aerial insectivore
Collocalia linchi	LC	-	Resident	Common swiftlet
Passer montanus	LC	-	Resident	Common urban associate
Collocalia esculenta	LC	-	Resident	Widespread swiftlet
Apus affinis	LC	-	Resident	Common in open areas
Pycnonotus aurigaster	LC	-	Resident	Terrestrial generalist
Lonchura leucogastroides	LC	-	Resident	Granivore in grasslands
Todiramphus chloris	LC	-	Resident	Coastal and inland waters
Cacomantis variolosus	LC	-	Resident	Forest edge, semi-aquatic
Butorides striata	LC	-	Resident	Mangroves and freshwater
Ixobrychus cinnamomeus	LC	-	Resident	Secretive in dense reeds
Dendrocopos analis	LC	-	Resident	Woodlands and forests
25 species	1 NT, 24 LC	5 Protected (20%)	4 Migratory (16%)	-



A B C

Figure 5. Proportion of protected and threatened waterbird species across the three study sites based on IUCN (2024) (A) and national protection status (B), and migratory status (C) across Telaga Menjer, Telaga Merdada, and Telaga Cebong in the Dieng Plateau, Central Java, Indonesia

The conservation evaluation shows that the Dieng wetland complex contributes significantly to the protection of highland bird diversity in Central Java. The coexistence of endemic, migratory, and legally protected species within a limited area highlights its ecological and biogeographical uniqueness. Effective management should therefore focus on habitat protection, pollution control, and community-based conservation to prevent local population declines.

Representative species and field observations

Field observations in the three crater lakes of the Dieng Plateau revealed several ecologically significant and characteristic waterbird species representing distinct trophic and behavioral groups. Among these, *T. ruficollis* (Little Grebe), *G. chloropus* (Common Moorhen), and *N. nycticorax* (Black-crowned Night Heron) were the most notable due to their consistent presence, distinct ecological roles, and behavioral adaptations to montane wetland environments.

The Little Grebe (*T. ruficollis*) was the most frequently encountered diving bird across all lakes, particularly abundant in Telaga Menjer and Telaga Merdada. Individuals were commonly observed foraging solitarily or in pairs on open-water surfaces, diving repeatedly to capture small fish and aquatic invertebrates. Their compact body size and dense plumage enable effective thermoregulation in the cool montane climate. Floating nests composed of aquatic vegetation were detected along the sheltered vegetated edges of Telaga Menjer, suggesting local breeding activity. These behavioral patterns indicate stable resident populations supported by high prey availability and low predation pressure.

The Common Moorhen (*G. chloropus*), observed mainly in Telaga Merdada and occasionally in Telaga Menjer, exhibited territorial and cautious behavior. Individuals were typically seen foraging near emergent vegetation or mudflats, consuming aquatic plants, small crustaceans, and insects. During the observation period (June-August), adults with fledglings were recorded, confirming successful reproduction in situ. This species' dependence on dense emergent vegetation underscores the importance of maintaining littoral macrophyte zones, which provide both nesting cover and food resources.

The Black-crowned Night Heron (*N. nycticorax*) was recorded primarily in Telaga Menjer during late afternoon observations (16:30-17:30). Its crepuscular and nocturnal habits made it less frequently visible than diurnal herons, yet repeated sightings suggest resident individuals or small roosting groups. Foraging activity was concentrated along shaded lake margins where the birds preyed upon small fish and amphibians. This species' persistence indicates the continued presence of structurally complex habitats offering both prey and roosting sites.

In addition to these key species, other representative taxa such as *A. speciosa*, *H. cyanoventris*, and *H. tahitica* illustrated the ecological versatility of the Dieng avifauna. *A. speciosa* (Javan Pond Heron) displayed adaptive foraging in both shallow and disturbed habitats, including agricultural ditches adjoining Telaga Cebong. The endemic *H. cyanoventris* (Javan Kingfisher), characterized by vivid blue plumage and loud territorial calls, was occasionally observed perched along open banks of Telaga Merdada, preying on small aquatic organisms-signifying the persistence of suitable riparian microhabitats despite tourism activity. Meanwhile, *H. tahitica* (Pacific Swallow) was abundant above all lakes, capturing aerial insects in open air columns, often in association with *Collocalia linchi* (Glossy Swiftlet).

Direct observations also recorded several interspecific interactions, including mixed foraging groups of *A. speciosa* and *A. phoenicurus* exploiting receding shorelines, and occasional competitive displacement between *T. ruficollis* and *G. chloropus* when foraging territories overlapped. Such interactions indicate a dynamic balance among sympatric species occupying overlapping trophic niches, facilitated by the structural heterogeneity of the wetland habitat mosaic.

Photographic documentation of key species and habitat conditions (Figure 6) illustrates the ecological diversity of the Dieng wetland complex-from open pelagic zones inhabited by diving birds to vegetated littoral zones supporting omnivores and waders. The combination of endemic, resident, and partially migratory species observed during the field period provides empirical evidence that these small montane lakes sustain a functionally rich and ecologically stable waterbird community.

Figure 6. Bird species found in the Dieng Plateau wetlands, Central Java, Indonesia. A. *Lanius schach*, B. *Pycnonotus aurigaster*, C. *Dendrocopos analis*, D. *Ardeola speciosa*, E. *Ardeola speciosa* (nonbreeding/immature), F. *Gallinula chloropus*, G. *Nycticorax nycticorax*, H. *Halcyon cyanoventris*, I. *Amaurornis phoenicurus*, J. *Tachybaptus novaehollandiae*, K. *Butorides striata*, L. *Motacilla cinerea*, M. *Passer montanus*, N. *A. bacchus* (nonbreeding/immature), O. *Lonchura leucogastroides*, P. *Ixobrychus cinnamomeus*

Discussion

Patterns of waterbird diversity in montane wetlands

The moderate species richness of waterbirds recorded in the Dieng Plateau (25 species) aligns with the typically depauperate nature of montane wetlands when compared to lowland systems across Southeast Asia. While lowland wetlands in Java, such as mangrove complexes, can host over 40 species due to higher primary productivity and greater habitat heterogeneity (Purify et al. 2020; Fabrina and Faizah 2022), high-altitude systems are inherently constrained. The Dieng avifauna's richness is comparable to other isolated montane lakes, such as those in North Sulawesi (Tabalujan et al. 2024) and Western Nepal (Lama et al. 2022), where communities comprise fewer than 30 species. This recurrent pattern underscores the powerful filtering effects of elevation-driven factors, including cooler temperatures (18-21°C), reduced aquatic primary productivity, and limited habitat area, which collectively restrict the availability of trophic resources and nesting sites for waterbirds (Sodhi et al. 2010; Süel et al. 2021). Furthermore, the intrinsic biogeographical isolation of the Dieng crater lakes, separated by steep volcanic topography, exacerbates these limitations by hindering dispersal and recolonization, thereby sustaining smaller, more isolated populations than those in interconnected lowland wetlands.

Elevation is among the most influential factors shaping avian diversity (Sodhi et al. 2010; Süel et al. 2021). The Dieng Plateau lies between 1,300-1,850 masl, where temperature, oxygen concentration, and primary productivity are substantially lower than in the lowlands. Cooler temperatures (18-21°C) restrict the diversity of aquatic prey such as insects and small fish, thereby limiting the carrying capacity for piscivorous and insectivorous birds. In addition, the reduced surface area and volume of the crater lakes, particularly Telaga Cebong, impose spatial constraints on breeding and foraging territories. As indicated by the intermediate diversity index (H′ = 2.42), these montane wetlands maintain stable but species-limited communities adapted to narrow environmental gradients.

Another important determinant of species richness is ecosystem isolation. The Dieng wetlands form discrete water bodies separated by steep volcanic ridges, resulting in limited inter-lake dispersal and weak connectivity to lowland habitats. Such geographic isolation reinforces stochastic colonization dynamics and turnover-dominated species replacement, as reflected in the moderate Sørensen similarity values (0.61-0.72). Comparable patterns of spatial segregation have been documented in montane lakes of Borneo (Ab Razak et al. 2019) and Luzon (Mabugat et al. 2024), where isolation restricts recolonization after local extinctions, maintaining distinct community assemblages at each site.

Despite the constraints of elevation and size, the Dieng lakes still support a functionally diverse waterbird community, including piscivores, insectivores, and omnivores, indicative of moderate ecosystem productivity. These results emphasize that montane wetlands, though species-poor compared to lowland systems, play a crucial role as refugia for specialized and endemic taxa adapted to highland conditions, thus representing key components of Java's regional biodiversity network.

Habitat heterogeneity and its role in supporting species richness

Habitat heterogeneity emerged as a key driver of waterbird diversity in the Dieng Plateau wetlands. The observed pattern of higher species richness in Telaga Menjer and Telaga Merdada, compared to Telaga Cebong, corresponds strongly with differences in vegetation cover, water depth, and microhabitat diversity. Lakes with wider littoral zones and greater proportions of emergent vegetation supported more species and guilds, especially those dependent on structured habitats for foraging and nesting. This strong positive relationship between vegetation cover and species richness underscores the importance of structural complexity in maintaining avian assemblages under montane conditions.

Vegetation along lake margins, primarily composed of Cyperaceae, Typhaceae, and Poaceae, provides multiple ecological functions: substrate for nesting (e.g., *T. ruficollis*, *G. chloropus*), shelter against predators, and foraging grounds for wading birds and insectivores. Dense stands of *Cyperus* and *Typha* create microhabitats that support aquatic invertebrates, small fish, and amphibians, which in turn sustain piscivorous species such as *A. speciosa* and *H. cyanoventris*. Similar findings have been reported by Sulai et al. (2022) in Malaysian floodplain systems, where structural diversity of emergent vegetation and hydrological variability explained up to 70% of the variance in avian taxonomic and functional diversity. In contrast, Telaga Cebong's reduced vegetation cover and shallow water limit both prey availability and nesting substrate, resulting in lower evenness and dominance of aerial insectivores rather than true aquatic specialists.

Water depth further modulates community composition by influencing prey accessibility and thermal conditions. Deep and stable lakes such as Menjer offer pelagic niches for diving birds (Podicipedidae), while shallow margins of Telagas' Merdada and Cebong attract waders and rails that exploit ephemeral mudflats. This spatial mosaic mirrors the general principle proposed by Xu et al. (2024), who demonstrated that moderate hydrological fluctuations and mixed depth profiles in China's Shengjin Lake promote higher functional redundancy and resilience of waterbird communities.

Species in the Dieng wetlands display adaptive strategies to narrow habitat gradients imposed by montane topography. Small body size, flexible foraging behavior, and tolerance to cooler climates enable persistence in limited spaces. For instance, *A. phoenicurus* and *T. ruficollis* utilize vegetated microhabitats both for nesting and feeding, while *H. tahitica* and *C. linchi* exploit aerial niches above open water. These behavioral adaptations enhance coexistence within confined crater basins, reinforcing the notion that even small, isolated wetlands can sustain complex ecological networks when structural heterogeneity is maintained.

Collectively, these results indicate that habitat complexity-not area alone-governs species richness and functional stability in montane wetlands. Conservation actions that preserve shoreline vegetation, regulate water-level fluctuations, and minimize disturbance from tourism and agriculture are therefore critical to maintaining avian diversity and ecological integrity in the Dieng Plateau ecosystem.

Functional guild composition and trophic structure

The trophic organization of waterbird assemblages in the Dieng Plateau wetlands is characterized by a clear dominance of piscivores and insectivores, which together accounted for over 60% of the recorded species (Table 3). This dominance pattern reflects the energy pathways and prey availability typical of small montane aquatic systems, where fish and aquatic insects form the core trophic resources. Piscivores such as *A. speciosa*, *B. striata*, and *T. ruficollis* perform a crucial ecological role as top predators that regulate prey populations and maintain food-web stability. Their presence also indicates the persistence of functional aquatic networks, since piscivores are sensitive to fluctuations in prey density and water quality. Similarly, insectivores, including *H. cyanoventris, Cacomantis merulinus,* and *H. tahitica,* exploit both aquatic and aerial niches, linking aquatic productivity with surrounding terrestrial ecosystems.

The prevalence of these two guilds suggests that the Dieng wetlands sustain a balanced trophic structure despite their limited area and isolation. According to Şekercioğlu (2006), insectivorous and piscivorous birds enhance ecological stability through top-down control mechanisms, reducing trophic oscillations and promoting nutrient turnover. Their consistent representation across all three lakes supports the view that montane wetlands, though species-poor, can maintain high functional efficiency when dominant guilds are well-represented.

Omnivorous and generalist species, such as *G. chloropus*, *A. phoenicurus*, and *P. montanus*, also play pivotal roles in resource recycling and disturbance resilience. Their dietary flexibility allows them to exploit fluctuating food resources, from aquatic vegetation to small invertebrates, thereby sustaining energy flow during periods of prey scarcity. In disturbed habitats near agricultural or touristic zones, omnivores often serve as ecological buffers, mitigating community instability caused by environmental fluctuations. This aligns with findings from Lama et al. (2022) in Himalayan wetlands, where omnivores dominated in human-influenced sites, contributing to functional redundancy and overall system resilience.

When compared with other tropical highlands, the Dieng assemblage mirrors the functional convergence observed in Lake Sebu (Philippines) and the Kinabalu highlands (Borneo), where insectivores and omnivores dominate due to low aquatic productivity and narrow trophic niches (Ab Razak et al. 2019; Mabugat et al. 2024). The relatively low proportion of strict herbivores or detritivores underscores the oligotrophic nature of crater lakes, where nutrient input is minimal, and vegetation is sparse.

The dominance of piscivorous and insectivorous guilds, supplemented by omnivores with broad ecological plasticity, reflects an efficient but compact trophic architecture that allows Dieng's montane wetlands to remain functionally stable despite spatial and climatic constraints. Maintaining this guild balance through protection of prey habitats and reduction of anthropogenic disturbance is essential to preserving the ecological integrity of these high-altitude wetland systems.

Beta diversity and spatial differentiation among lakes

Patterns of beta diversity among the Dieng Plateau wetlands reveal that species composition varies substantially between lakes, with Sørensen similarity values ranging from 0.61 to 0.72 (Table 4). This moderate similarity reflects a combination of shared generalist taxa and distinct site-specific assemblages, leading to turnover-dominated species differentiation across the three sites. Most compositional dissimilarity was attributed to species replacement rather than nestedness, indicating that each lake supports a partially unique subset of the regional avifauna rather than representing a simple gradient of species loss. Such differentiation underscores the ecological individuality of the crater lakes, shaped by physical isolation, habitat heterogeneity, and varying degrees of anthropogenic influence.

Environmental filtering plays a primary role in structuring these assemblages. Each lake possesses distinct environmental attributes-Telaga Menjer is deep with steep margins, Telaga Merdada has intermediate depth and complex vegetated edges, while Telaga Cebong is shallow and surrounded by agricultural plots. Species adapted to particular microhabitats or prey conditions selectively occupy these sites; for instance, *T. ruficollis* and *B. striata* dominate deeper lakes with abundant fish prey, while *A. phoenicurus* and *G. chloropus* prefer shallow, vegetated wetlands. This pattern corresponds with the niche partitioning model proposed by Whittaker (1972), in which environmental filtering along physical gradients drives community differentiation more strongly than stochastic processes.

In addition, dispersal limitation contributes significantly to spatial turnover among lakes. The crater lakes of Dieng are separated by steep volcanic ridges and cultivated valleys, which restrict avian movement, especially for species with low mobility or narrow habitat preferences. This physical fragmentation reduces colonization rates and promotes local differentiation. Comparable processes were described by Ab Razak et al. (2019) in Borneo's montane lakes and Xu et al. (2024) in subtropical China, where isolation limited interchange among wetlands and maintained distinct assemblages despite geographic proximity.

From a conservation standpoint, these results highlight the importance of multi-site conservation strategies in fragmented montane landscapes. Because no single lake encompasses the full spectrum of waterbird diversity, effective management should consider the entire lake network as a metacommunity. Conservation interventions should thus focus on maintaining ecological connectivity, protecting vegetated corridors, and preventing excessive eutrophication or land-use intensification around each lake. Recognizing the complementary value of individual wetlands ensures that conservation efforts in the Dieng Plateau sustain not only alpha diversity within sites but also beta diversity across the landscape, thereby enhancing the resilience of the region's highland wetland ecosystems.

Conservation significance and management implications

The waterbird assemblages of the Dieng Plateau wetlands hold substantial conservation significance within Java's montane ecosystems. Although species richness is moderate, the presence of legally protected and highland-restricted taxa such as *A. vulcanorum* (Volcano Swiftlet) and *H. cyanoventris* (Javan Kingfisher) highlights the area's unique ecological value. *A. vulcanorum* is an endemic montane swiftlet confined to volcanic regions of Java above 1000 m elevation (Eaton et al. 2021), while *H. cyanoventris* is a near-endemic kingfisher species protected under Permen LHK No. 106/2018 (KLHK 2018b) due to its declining population linked to habitat degradation (Kurnia et al. 2021). Their occurrence across the Dieng wetlands reinforces the plateau's function as a dry-season refugium for highland specialists that are increasingly rare in lowland areas transformed by agriculture and urbanization (Nijman et al. 2022).

From a regional perspective, the presence of species with known migratory populations, such as *G. chloropus* (migrant) and *A. cinerea* (partial migrant), suggests the potential of these crater lakes to act as seasonal stopover habitats, though year-round monitoring is needed to confirm their full role in maintaining connectivity along the East Asian-Australasian Flyway (Ferreira et al. 2024). Protection of these habitats, therefore, contributes not only to national biodiversity objectives but could also support international migratory bird conservation commitments under the IUCN and Ramsar frameworks. Despite their small size, these montane wetlands may provide critical resting and feeding sites that sustain bird populations during high-altitude transits, similar to patterns observed in other tropical highland wetlands (Lama et al. 2022; Xu et al. 2024).

All recorded species were native or long-established residents, with no invasive taxa detected in the assemblages. *Passer montanus*, although historically introduced from Eurasia, is now fully naturalized and poses negligible ecological risk to native waterbirds. The absence of invasive species indicates that these montane wetlands remain ecologically intact and relatively isolated from biological invasions common in disturbed lowland wetlands. Maintaining this biosecurity integrity should be prioritized through regular surveillance and community-based awareness programs on invasive species prevention.

Sustainable conservation of these ecosystems requires integration of habitat protection, tourism management, and community participation. Ecotourism activities around Telaga Merdada and Telaga Menjer have grown rapidly, offering economic opportunities but also increasing disturbance through noise, litter, and shoreline modification (Setiawan 2024). Effective management should include zoning schemes that restrict intensive tourism near critical breeding sites, promote low-impact visitor facilities, and involve local communities in habitat monitoring and interpretation programs. The participatory models successfully implemented in Ciletuh-Palabuhanratu Geopark (Iskandar et al. 2021) demonstrate that local stewardship enhances long-term conservation compliance.

These management recommendations are supported by our findings, which recorded five nationally protected species and a community structure dominated by insectivores and piscivores that are highly dependent on habitat quality. The moderate to high beta diversity among the lakes further underscores the need for a landscape-scale approach to conservation, ensuring the protection of complementary habitats across the plateau (Koleff et al. 2003; Süel et al. 2021).

Policy recommendations aligned with Permen LHK No. 106/2018 emphasize the enforcement of species protection and habitat integrity, while IUCN (2024) guidelines encourage site-based monitoring integrated with adaptive management. The Dieng wetlands should be incorporated into broader highland biodiversity management plans under the Central Java Provincial Environmental Agency, ensuring continuous data collection on species population trends, water quality, and habitat condition. Strengthening coordination among research institutions, tourism operators, and local governments would further support the establishment of a Dieng Wetland Conservation Network, aimed at harmonizing scientific conservation goals with socio-economic realities (Perfecto and Vandermeer 2010; Marshall et al. 2021). Safeguarding the Dieng Plateau wetlands demands a multi-dimensional approach-legal protection of key species, regulation of human activities, and community-based conservation-to ensure the persistence of these high-altitude aquatic ecosystems as vital components of Java's montane biodiversity heritage.

Ecological and biogeographical context of the Dieng Plateau

The wetlands of the Dieng Plateau occupy a unique ecological and biogeographical position within the central mountain chain of Java. Situated between 1,300-1,850 masl, these crater lakes represent relict ecosystems formed by ancient volcanic activity (van Bemmelen 1949) and now function as refugia for montane waterbirds adapted to cooler, oligotrophic, and structurally confined habitats. In a landscape increasingly fragmented by agriculture and tourism, these wetlands provide isolated yet stable habitats that buffer sensitive species from the rapid land-use changes dominating lowland regions (Nijman et al. 2022; Setiawan 2024). The persistence of highland endemics such as *A. vulcanorum* and *H. cyanoventris*, together with montane-adapted species like *T. ruficollis* and *A. phoenicurus*, underscores the Dieng Plateau's role as a climatic sanctuary within the broader biogeographical mosaic of Java (Eaton et al. 2021).

When compared with other Javan highlands-such as Tawangmangu (Mount Lawu), Pangrango, and Bromo-Tengger-the Dieng wetlands exhibit a distinct avian assemblage characterized by higher proportions of aquatic and semi-aquatic guilds. Highland forests of Pangrango, for instance, are dominated by canopy insectivores and frugivores (van Balen et al. 1999; Putra et al. 2020), whereas Dieng supports a trophic structure centered on lentic systems and emergent macrophytes. In Bromo's crater ponds and Tawangmangu's upper catchments, avian diversity is typically constrained by extreme elevation (>2000 m) and limited vegetation cover, resulting in fewer aquatic specialists (Whitten et al. 1996). Dieng's intermediate altitude, coupled with moderate precipitation and hydrological stability, thus provides optimal conditions for maintaining mixed assemblages of resident and migratory waterbirds-a pattern consistent with mid-elevation diversity peaks described by Rahbek (1995) and subsequently confirmed in Southeast Asian montane systems (Süel et al. 2021; Lama et al. 2022).

From a biogeographical perspective, the Dieng Plateau serves as a stepping-stone habitat linking the central and western Javan highlands. Its lakes support seasonal migrants that connect continental flyways to insular ecosystems, enhancing regional gene flow and ecological connectivity (Ferreira et al. 2024). However, this connectivity is increasingly threatened by habitat loss, pollution, and climate-driven hydrological shifts (Xu et al. 2024). Predicted warming and reduced precipitation could accelerate eutrophication and contraction of littoral vegetation, diminishing habitat suitability for species dependent on shallow water zones, as observed in other tropical montane wetlands (Lama et al. 2022).

Given these dynamics, the Dieng wetlands offer a valuable natural laboratory for long-term eco-hydrological monitoring. Regular surveys integrating ornithological, limnological, and vegetation data would provide early indicators of ecosystem change (Şekercioğlu 2006). Collaborative research initiatives could apply remote sensing and acoustic monitoring to assess temporal shifts in species composition and habitat structure (Sutherland 2006). Such sustained observation is critical for understanding how montane wetlands respond to environmental stressors and for developing adaptive management frameworks applicable across the Javan volcanic highlands (Sulai et al. 2022). The Dieng Plateau not only represents an ecological enclave of significant ornithological interest but also a biogeographical keystone for understanding the resilience of montane wetland biodiversity under changing climatic and anthropogenic regimes.

Limitations and future research directions

This study acknowledges several limitations that constrain the generalization of its findings. Observations were conducted within a limited temporal window during the dry season, which may not fully capture seasonal variation in species occurrence, particularly for migratory taxa. The reliance on presence-absence data without systematic abundance measurements restricts the quantitative assessment of population dynamics and habitat preferences. In addition, habitat parameters such as water chemistry, nutrient load, and vegetation productivity were only measured descriptively, leaving potential cause-and-effect relationships between environmental variables and bird assemblages unexplored. Future research should therefore implement year-round monitoring to document phenological shifts and migration cycles, coupled with repeated point counts and acoustic recording to estimate abundance and detectability. Integrating eco-hydrological data with multivariate modeling would help elucidate functional links between habitat heterogeneity and avian community structure. Finally, establishing community-based biodiversity monitoring programs-involving local residents, students, and birdwatching groups-would not only generate long-term datasets but also enhance local stewardship and awareness of montane wetland conservation in the Dieng Plateau. In conclusion, the present study provides the first comprehensive assessment of waterbird diversity and ecological characteristics of montane wetlands in the Dieng Plateau, Central Java. Across the three crater lakes-Telaga Menjer, Telaga Merdada, and Telaga Cebong-we recorded 25 waterbird species representing multiple feeding guilds, reflecting the combined influence of habitat heterogeneity, elevation, and climatic conditions on avian assemblages. Despite their limited spatial extent, these wetlands act as crucial refugia for both endemic and migratory species, underscoring their conservation importance within Java’s montane ecosystems. Species diversity was moderate (H′ = 2.18-2.65) and evenness was high (E = 0.83-0.91), indicating relatively balanced assemblages dominated by piscivorous and insectivorous birds that depend on stable aquatic prey and structurally complex littoral vegetation. These findings emphasize that integrating habitat protection, sustainable tourism management, and local community participation is essential to ensure long-term ecosystem resilience. Continued ecological monitoring and interdisciplinary research are therefore recommended to strengthen the role of Dieng’s highland wetlands in regional biodiversity conservation and climate adaptation strategies. To safeguard the long-term ecological integrity of these wetlands, management actions should include the establishment of ecological zoning around each lake, designation of core conservation zones in areas with dense littoral vegetation and high species use, and restriction of intensive tourism and infrastructure development to clearly defined buffer zones.

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Spatio-temporal changes in mangrove density and cover in Sriwulan and Pasar Banggi-Tireman, Central Java, Indonesia

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Abstract. *Khawarizmi IA, Syahrani LPW, Luthfia, Fadhilah RN, Hapsari KS, Pradhan P, Sutomo, Setyawan AD. 2025. Spatio-temporal changes in mangrove density and cover in Sriwulan and Pasar Banggi-Tireman, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 121-129.* Mangrove ecosystems play a critical role in maintaining coastal stability and supporting ecological functions in tropical regions. However, mangrove dynamics often involve subtle internal changes that may not be captured by area-based assessments alone. This study analyzed spatio-temporal changes in mangrove density and land cover in Sriwulan Village (Demak District) and Pasar Banggi-Tireman Villages (Rembang District), Central Java, Indonesia, during the period 2019-2024 using Sentinel-2 satellite imagery. Mangrove distribution and density were assessed through Normalized Difference Vegetation Index (NDVI) classification, and changes were quantified by overlaying spatial data from both observation years. Mangrove density was categorized into low, medium, and high classes, and classification accuracy was supported by ground observations. The results show that total mangrove area in Sriwulan Village increased slightly from 16.75762 ha in 2019 to 16.77258 ha in 2024, representing a net gain of 0.01496 ha (0.09%). This change was accompanied by a marked increase in medium-density mangrove, while low- and high-density classes declined. In contrast, total mangrove area in Pasar Banggi-Tireman Villages decreased marginally from 51.13480 ha to 51.05880 ha, corresponding to a net loss of 0.07600 ha (0.15%). Despite this slight decline, medium- and high-density mangrove areas increased, whereas low-density mangrove decreased substantially. These findings indicate that mangrove ecosystems in both study sites remained spatially stable but underwent internal restructuring of canopy density. The study demonstrates that density-based analysis provides critical additional insight beyond total area change and offers a robust approach for evaluating mangrove dynamics and supporting local-scale monitoring and management.

Keywords: Mangrove density, NDVI, remote sensing, Sentinel-2, Spatio-temporal analysis

INTRODUCTION

Mangrove ecosystems are among the most productive coastal habitats in tropical and subtropical regions, providing essential ecological functions and socio-economic benefits. They play critical roles in shoreline stabilization, sediment trapping, nutrient cycling, and carbon sequestration, while also serving as nursery grounds for fish and invertebrates that support coastal fisheries (Alongi 2014; Friess et al. 2019). In densely populated coastal zones, mangroves further contribute to disaster risk reduction by attenuating wave energy and reducing the impacts of coastal erosion and storm surges (Barbier et al. 2011).

Despite their importance, mangrove ecosystems are under persistent pressure from anthropogenic and natural drivers. Coastal development, aquaculture expansion, land conversion, and infrastructure construction have historically contributed to mangrove loss in Southeast Asia (Hamilton and Casey 2016; Richards and Friess 2016). Climate-related factors, including sea-level rise, altered sediment supply, and increasing coastal abrasion, further influence mangrove stability and regeneration (Lovelock et al. 2015; Ward et al. 2016). In Indonesia, which hosts one of the largest mangrove extents globally, patterns of degradation and recovery vary substantially among regions due to differences in geomorphology, management practices, and disturbance regimes (Giri et al. 2011; Ilman et al. 2016; Worthington and Spalding 2018).

Recent studies suggest that large-scale mangrove loss has slowed or stabilized in some coastal areas following rehabilitation initiatives and increased recognition of ecosystem services (Friess et al. 2020). However, stability in total mangrove area does not necessarily indicate ecological resilience, as internal changes in stand structure and canopy condition may still occur (Alongi 2008; Osland et al. 2017). Consequently, reliance on area-based indicators alone may obscure important internal dynamics, highlighting the need for approaches that capture structural change within mangrove stands.

Remote sensing has become a widely used tool for monitoring mangrove distribution, condition, and temporal dynamics across spatial scales. Satellite-based observations enable repeated and consistent measurements of vegetation cover, facilitating the detection of long-term trends and short-term fluctuations (Blasco et al. 2001). Medium-resolution sensors such as Sentinel-2 are particularly suitable for mangrove studies because their spatial resolution and revisit frequency allow effective monitoring of dynamic coastal environments (Li et al. 2011; Pham et al. 2019).

Among vegetation indices, the Normalized Difference Vegetation Index (NDVI) is commonly applied to assess vegetation greenness, canopy density, and photosynthetic activity. NDVI-based analyses have been widely used to classify mangrove density, identify degradation patterns, and evaluate rehabilitation outcomes (Lucas et al. 2007; Kuenzer et al. 2011; Giri and Long 2016; Pham et al. 2019). Changes in NDVI values reflect variations in canopy closure, biomass, and stand maturity, making density-based classification a valuable complement to total area assessments (Zhu and Woodcock 2014). Nevertheless, NDVI interpretation in coastal environments is subject to limitations related to tidal inundation, background reflectance, mixed pixels, and potential saturation in high-density stands (Heumann 2011). These constraints necessitate cautious interpretation and support from ground observations and accuracy assessment (Congalton and Green 2009).

The northern coast of Central Java, Indonesia, exemplifies the interaction between mangrove ecosystems and human activities, including settlement, fisheries, and rehabilitation programs (Setyawan 2005; Kusmana 2011). Sriwulan Village (Demak District) and Pasar Banggi–Tireman Villages (Rembang District) represent contrasting coastal settings shaped by differences in shoreline morphology, exposure to abrasion, and management interventions. Sriwulan Village is characterized by chronic coastal abrasion and shoreline instability, whereas Pasar Banggi–Tireman Villages have experienced more intensive rehabilitation and relatively stable mangrove belts (Fikriyani and Mussadun 2014; Ain et al. 2025). Despite numerous studies documenting mangrove extent and rehabilitation outcomes in Central Java (Sasmito et al. 2019), analyses focusing on spatio-temporal changes in canopy density at the village scale remain limited.

This gap is critical because minor net changes in mangrove area may conceal substantial internal restructuring of mangrove stands, potentially leading to misinterpretation of management effectiveness (Friess and Webb 2014). Therefore, a spatially explicit NDVI-based assessment integrating both total area and density-class changes is required. Based on this rationale, this study hypothesizes that mangrove ecosystems in Sriwulan Village and Pasar Banggi–Tireman Villages exhibit minimal net changes in total area but significant spatio-temporal redistribution among canopy density classes. Accordingly, this study aims to analyze spatio-temporal changes in mangrove density and land cover between 2019 and 2024 using Sentinel-2 imagery, quantify changes in total mangrove area and density classes, and compare mangrove dynamics between the two sites to support local-scale mangrove monitoring and management.

MATERIALS AND METHODS

Study area

This study was conducted in two coastal villages along the northern coast of Central Java, Indonesia, namely Sriwulan Village (6°56′19″S 110°28′48″E) in Demak District and Pasar Banggi (6°42′23″S 111°23′16″E)-Tireman (6°42′30″S 111°22′14″E) Villages in Rembang District (Figure 1). Both locations are situated within low-lying coastal plains that are directly influenced by tidal dynamics, sediment transport, and shoreline processes typical of the Java Sea coast. Mangrove ecosystems in these areas are distributed along estuarine margins and open coastlines, forming narrow to moderately wide belts adjacent to coastal settlements and aquaculture ponds. Field visits were conducted in both villages during late 2024 to support spatial interpretation.

Sriwulan Village is located in a coastal zone that has experienced long-term shoreline changes, including erosion and land subsidence, which have influenced mangrove distribution and stability. In contrast, Pasar Banggi-Tireman Villages represent a coastal setting where mangrove rehabilitation initiatives have been implemented alongside existing natural stands. Differences in coastal morphology, exposure to wave action, and sediment availability contribute to spatial variation in mangrove structure between the two sites.

Both study areas are characterized by mixed mangrove stands dominated by typical Indo-West Pacific species and are subject to ongoing human activities related to fisheries, coastal protection, and settlement expansion. These contrasting environmental and management contexts provide a suitable basis for comparative analysis of mangrove density and land cover dynamics using remote sensing approaches (Alongi 2014).

Data sources and satellite imagery

Mangrove mapping and change analysis were conducted using multispectral satellite imagery acquired from the Sentinel-2 mission of the European Space Agency. Sentinel-2 provides optical imagery with a spatial resolution of 10-20 m and a revisit time suitable for monitoring dynamic coastal environments. In this study, cloud-free Sentinel-2 images representing conditions in 2019 and 2024 were selected to enable multi-temporal comparison of mangrove density and spatial extent.

Satellite data were obtained from publicly accessible archives and processed using standard pre-processing procedures. Images were atmospherically corrected and geometrically aligned to ensure spatial consistency between observation years. To minimize spectral interference from clouds and cloud shadows, only scenes with minimal cloud cover over the study areas were used. The selected images represent comparable acquisition periods to reduce the influence of seasonal variability on vegetation reflectance.

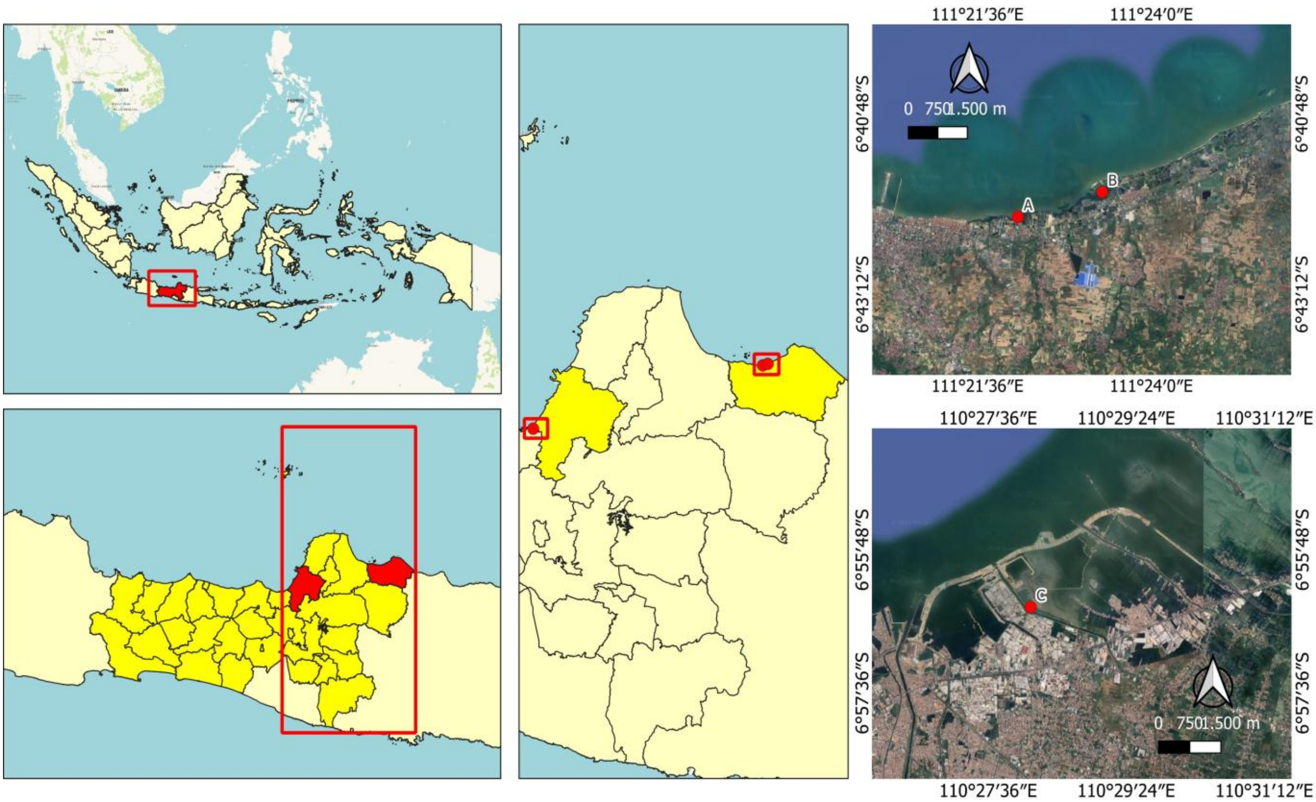

Figure 1. Location of the study area in Pasar Tireman (A)-Banggi (B) Villages, Rembang District, and Sriwulan Village (C), Demak District, Central Java, Indonesia

Sentinel-2 imagery was chosen because its spectral bands in the visible and near-infrared regions are well suited for vegetation analysis, including the calculation of vegetation indices such as NDVI. Previous studies have demonstrated the suitability of Sentinel-2 data for mangrove mapping and condition assessment at local to regional scales (Drusch et al. 2012; Pham et al. 2019). The use of consistent satellite data sources across both time points ensures that observed changes in mangrove density and cover reflect actual spatial dynamics rather than sensor-related differences.

NDVI calculation and density classification

Mangrove vegetation density was assessed using the Normalized Difference Vegetation Index (NDVI), which is widely applied to evaluate vegetation greenness and canopy condition based on spectral reflectance properties. NDVI was calculated from Sentinel-2 imagery using the Near-Infrared (NIR) and red bands according to the standard formula: NDVI = (NIR − Red) / (NIR + Red). Higher NDVI values generally indicate denser and healthier vegetation cover, while lower values correspond to sparse or degraded vegetation.

Following NDVI calculation, mangrove areas were classified into three density classes: low, medium, and high density. The classification thresholds were defined based on NDVI values as follows: low-density mangrove (NDVI 0.30-0.45), medium-density mangrove (NDVI 0.45-0.60), and high-density mangrove (NDVI > 0.60). Classification thresholds were applied consistently across both observation years to ensure comparability of density patterns between 2019 and 2024. This density-based classification approach allows the detection of internal structural changes within mangrove stands that may not be evident from total area measurements alone.

NDVI-based density classification has been widely used in mangrove studies to examine spatial heterogeneity, rehabilitation outcomes, and temporal dynamics of canopy structure (Kuenzer et al. 2011; Pham et al. 2019). However, NDVI interpretation in coastal environments requires caution due to potential influences of tidal inundation, background reflectance, and mixed pixels at mangrove–water interfaces. To address these limitations, NDVI results were evaluated in conjunction with visual interpretation and subsequent accuracy assessment, ensuring that density classes reasonably represented on-ground mangrove conditions (Huete et al. 2002).

Change detection and spatial analysis

Spatial changes in mangrove density and land cover between 2019 and 2024 were analyzed using a post-classification comparison approach. NDVI-based mangrove density maps from each observation year were spatially overlaid to identify changes in both total mangrove area and density-class distribution. This method allows for direct comparison of classified maps from different time periods and is commonly applied in vegetation change analysis due to its conceptual simplicity and interpretability.

For each study site, the spatial extent of mangrove density classes was calculated in hectares based on pixel counts and the spatial resolution of Sentinel-2 imagery. Changes in mangrove cover were quantified as absolute differences in area between the two observation years, while relative changes were calculated with reference to baseline conditions in 2019. This approach enables the identification of both net changes in mangrove area and internal shifts among density classes.

Spatial analysis was conducted using Geographic Information System (GIS) tools to ensure consistent projection, alignment, and area calculation across datasets. By applying identical analytical procedures to both study sites, differences in mangrove dynamics could be attributed to spatial and temporal variation rather than methodological inconsistencies. Post-classification comparison has been widely used in land cover change studies, including mangrove ecosystems, to assess spatio-temporal patterns in vegetation structure and extent (Singh 1989).

Accuracy assessment

The accuracy of mangrove density classification derived from NDVI was evaluated through ground-based validation (Table 1). A total of 30 observation points were collected in each study site, representing different mangrove density conditions. These points were used to verify the correspondence between NDVI-derived density classes and on-site mangrove characteristics. Field observations focused on canopy cover and vegetation condition to ensure consistency with the low-, medium-, and high-density categories identified from satellite imagery.

Classification accuracy was assessed by comparing NDVI-based class assignments with ground observation data. Overall accuracy was calculated to quantify the proportion of correctly classified points, indicating the reliability of the density maps used for subsequent spatial analysis. The classification achieved an overall accuracy of 84.67% with a Kappa coefficient of 0.78, indicating good agreement between NDVI-based density classes and field observations. This validation approach is commonly applied in vegetation mapping studies to assess the performance of remote sensing-based classification, particularly when high-resolution reference data are limited.

The accuracy assessment procedure was integrated into the overall methodological workflow to ensure that mangrove density classification results were sufficiently robust for change detection analysis (Figure 2). Although field sampling was limited in number, the use of evenly distributed observation points across density classes supports the credibility of the classification results (Congalton and Green 2009).

Table 1. Accuracy assessment results of NDVI-based mangrove density classification

Metric	Value
Overall accuracy (%)	84.67
Kappa coefficient	0.78

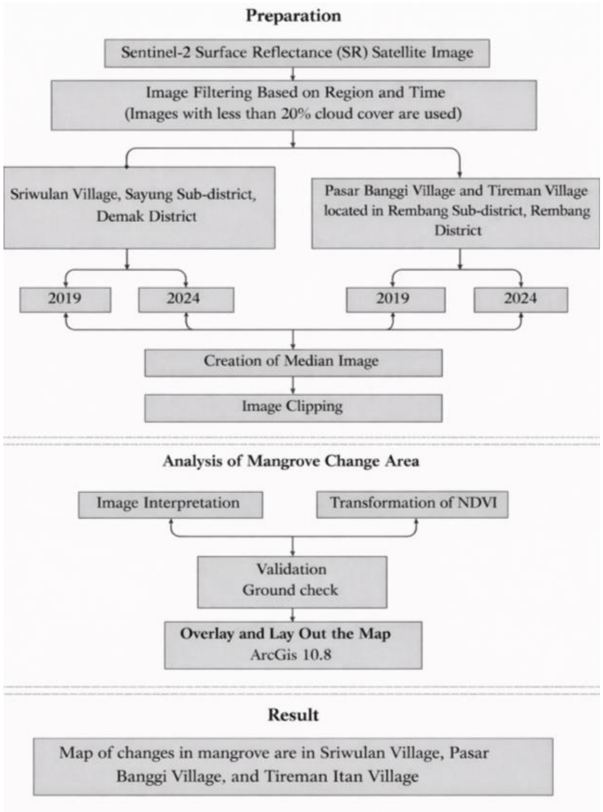

Figure 2. Flowchart of the research methodology for mangrove density and land cover analysis using Sentinel-2 imagery and NDVI classification

RESULTS AND DISCUSSION

Changes in mangrove density and area in Sriwulan Village

Analysis of Sentinel-2 imagery indicates that mangrove cover in Sriwulan Village remained largely stable between 2019 and 2024, with only minor changes in total area and noticeable redistribution among density classes (Table 2; Figure 3.A). In 2019, the total mangrove area in Sriwulan Village was recorded at 16.75762 ha. By 2024, this area increased slightly to 16.77258 ha, representing a net gain of 0.01496 ha or a relative increase of 0.09% over the five-years. Given the validated classification accuracy (Table 1), spatio-temporal changes in mangrove density are considered reliable. Given the satisfactory overall classification accuracy (84.67%) and Kappa coefficient (0.78), these minor net changes are considered robust and not attributable to classification uncertainty.

At the density-class level, contrasting trends were observed. Low-density mangrove area decreased from 2.23652 ha in 2019 to 1.55919 ha in 2024. A similar decline was recorded for high-density mangrove, which decreased from 12.53340 ha to 11.58300 ha. In contrast, medium-density mangrove exhibited a marked increase, expanding from 1.98770 ha in 2019 to 3.63039 ha in 2024. This redistribution among density classes reflects internal structural adjustment within existing mangrove stands rather than artefacts of NDVI-based classification. These changes indicate internal restructuring of mangrove stands rather than substantial spatial expansion or loss.

Spatial patterns derived from NDVI classification show that increases in medium-density mangrove were primarily concentrated adjacent to existing mangrove stands, suggesting gradual changes in canopy condition rather than the establishment of new mangrove areas. Despite reductions in low- and high-density classes, the near-constant total mangrove area suggests that mangrove cover in Sriwulan Village remained relatively stable during the study period. The consistency between spatial patterns, quantitative area estimates, and validated classification accuracy confirms that density-based analysis provides reliable additional insight into mangrove dynamics beyond total area measurements alone.

Table 2. Mangrove area by density class and total change in Sriwulan Village and Pasar Banggi-Tireman Villages, Central Java, Indonesia (2019-2024)

Mangrove density class	Area 2019 (ha)	Area 2024 (ha)
Sriwulan Village		
Low density	2.23652	1.55919
Medium density	1.98770	3.63039
High density	12.53340	11.58300
Total mangrove area	16.75762	16.77258
Net change (2019-2024)		+0.01496
Relative change (%)		+0.09
Pasar Banggi-Tireman Villages		
Low density	11.78290	7.86450
Medium density	16.48810	17.08110
High density	22.86380	26.11320
Total mangrove area	51.13480	51.05880
Net change (2019-2024)		-0.07600
Relative change (%)		-0.15

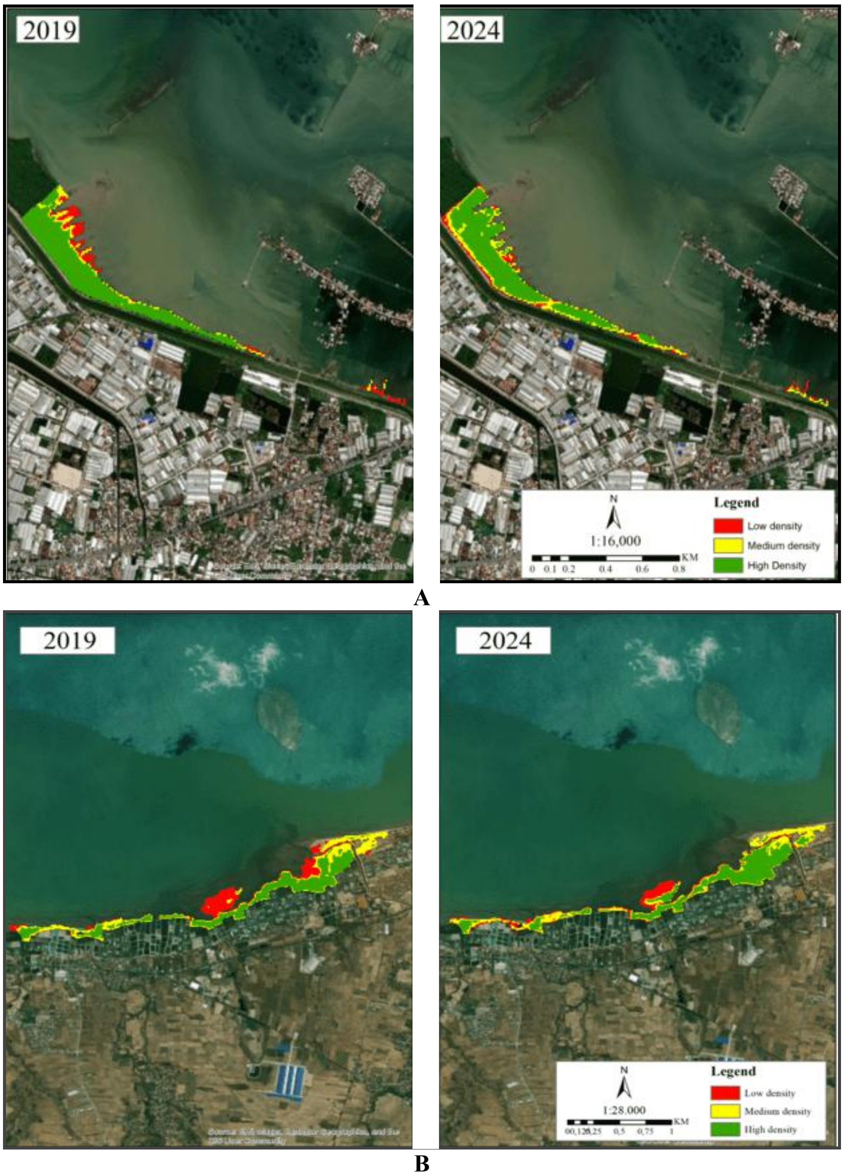

Figure 3. Mangrove density distribution in Central Java, Indonesia. A. Sriwulan Village and B. Pasar Banggi-Tireman Villages in 2019 and 2024 based on NDVI classification

Changes in mangrove density and area in Pasar Banggi-Tireman Villages

Results from NDVI-based analysis indicate that mangrove dynamics in Pasar Banggi-Tireman Villages between 2019 and 2024 differed from those observed in Sriwulan Village, particularly in terms of density-class redistribution (Table 2; Figure 3.B). In 2019, the total mangrove area in Pasar Banggi-Tireman Villages was 51.13480 ha. By 2024, this area decreased slightly to 51.05880 ha, corresponding to a net loss of 0.07600 ha or a relative decrease of 0.15% over the five-years.

At the density-class level, substantial changes were recorded. Low-density mangrove area declined markedly from 11.78290 ha in 2019 to 7.86450 ha in 2024. In contrast, medium-density mangrove increased from 16.48810 ha to 17.08110 ha during the same period. The most notable increase was observed in high-density mangrove, which expanded from 22.86380 ha in 2019 to 26.11320 ha in 2024. These opposing trends among density classes indicate internal structural changes within the mangrove ecosystem rather than large-scale spatial loss.

Spatial distribution patterns show that areas of high-density mangrove were concentrated within existing mangrove belts, suggesting improved canopy closure or stand development in certain zones. Despite the slight reduction in total mangrove area, the increase in medium- and high-density classes highlights localized improvements in mangrove condition. The results demonstrate that mangrove dynamics in Pasar Banggi-Tireman Villages during the study period were characterized by density enhancement accompanied by minimal net area change.

Comparative patterns between study sites

Comparison of mangrove dynamics between Sriwulan Village and Pasar Banggi-Tireman Villages reveals contrasting patterns in density-class redistribution despite similarly small net changes in total mangrove area. In Sriwulan Village, total mangrove cover increased marginally by 0.01496 ha (0.09%) between 2019 and 2024, whereas Pasar Banggi-Tireman Villages experienced a slight net decrease of 0.07600 ha (0.15%) during the same period (Table 2). These values indicate that, at the landscape scale, mangrove extent in both locations remained largely stable over the five-year interval.

At the density-class level, the two sites exhibited different trajectories. Sriwulan Village showed a pronounced increase in medium-density mangrove accompanied by declines in both low- and high-density classes. In contrast, Pasar Banggi-Tireman Villages displayed substantial reductions in low-density mangrove alongside increases in medium- and high-density classes. These patterns suggest that internal structural changes occurred differently across the two sites, even though overall mangrove extent changed only slightly.

Spatially, density-class shifts in both villages were primarily concentrated within existing mangrove areas rather than along new coastal fronts. This indicates that changes were dominated by redistribution among density classes rather than by expansion into previously non-mangrove areas. The comparative results highlight that similar levels of net area stability can be associated with distinct internal dynamics of mangrove density and structure at the local scale.

Discussion

Stability of mangrove cover and implications of minor net changes

The results demonstrate that mangrove cover in both Sriwulan Village and Pasar Banggi-Tireman Villages remained largely stable between 2019 and 2024, with net changes of less than 0.2% of total area. Such minor net changes indicate that, at the landscape scale, neither extensive mangrove expansion nor large-scale degradation occurred during the study period. Similar patterns of relative stability have been reported in several coastal regions where mangrove loss has slowed following rehabilitation efforts or natural stabilization processes (Worthington and Spalding 2018; Friess et al. 2019).

The observed stability contrasts with earlier reports of rapid mangrove decline in parts of Southeast Asia during previous decades (Richards and Friess 2016), suggesting that recent dynamics may reflect shifts in management practices, coastal protection measures, or geomorphological constraints. In Indonesia, regional-scale analyses have shown that mangrove extent can remain stable even under continued anthropogenic pressure, particularly where degradation and recovery processes occur simultaneously in different locations (Giri et al. 2011; Ilman et al. 2016).

Importantly, the small magnitude of net change highlights the limitations of using total area alone as an indicator of mangrove ecosystem condition. Studies have emphasized that stable mangrove extent does not necessarily imply ecological resilience, as internal structural changes, species composition shifts, or canopy degradation may still take place (Alongi 2014; Duke et al. 2017). In this study, density-class redistribution observed in both sites underscores that mangrove dynamics were occurring internally rather than through extensive spatial gain or loss.

From a monitoring perspective, these findings align with research advocating for density- or structure-based indicators to complement area-based assessments (Kuenzer et al. 2011; Pham et al. 2019). Minor net changes, when interpreted alongside density dynamics, can still provide meaningful insights into ecosystem processes and management outcomes. Therefore, the apparent stability of mangrove cover in the study area should be understood as a dynamic equilibrium rather than a static condition, emphasizing the need for continuous, multi-dimensional monitoring approaches.

Density-class shifts as indicators of structural dynamics

Shifts among mangrove density classes observed in both study sites indicate that internal structural dynamics played a more prominent role than net spatial change during the study period. In Sriwulan Village, the expansion of medium-density mangrove alongside reductions in low- and high-density classes suggests gradual canopy reorganization, potentially reflecting transitions between growth stages rather than abrupt disturbance. Similar density-class transitions have been reported in mangrove systems undergoing stand development, where young or recovering stands gradually increase canopy closure before reaching mature structural conditions (Bosire 2008; Duke et al. 2017).

In Pasar Banggi-Tireman Villages, the marked decrease in low-density mangrove accompanied by increases in medium- and high-density classes points to localized improvements in canopy structure within existing mangrove belts. Such patterns are consistent with findings from NDVI-based mangrove assessments that document density enhancement without substantial areal expansion, particularly in areas influenced by rehabilitation or natural regeneration processes (Kuenzer et al. 2011; Pham et al. 2019). These internal shifts may reflect improved vegetation vigor, increased biomass, or enhanced canopy continuity rather than changes in spatial extent.

Density-class analysis provides an important proxy for mangrove structural condition, as canopy density is closely linked to ecological functions such as habitat provision, sediment trapping, and shoreline stabilization (Alongi 2014). However, NDVI-derived density classes should be interpreted as indicators of relative structural change rather than direct measures of biomass or species composition. Factors such as tidal inundation, background reflectance, and mixed pixels may influence spectral responses, particularly at mangrove-water interfaces (Heumann 2011).

The density-class shifts documented in this study reinforce the value of integrating structural indicators into mangrove monitoring frameworks. By capturing internal changes within stable spatial extents, density-based metrics offer a more nuanced understanding of mangrove ecosystem dynamics than total area measurements alone, supporting previous recommendations for multi-dimensional assessments of mangrove condition (Kairo et al. 2001; Simard et al. 2019).

Site-specific processes influencing mangrove dynamics

The contrasting density-class trajectories observed between Sriwulan Village and Pasar Banggi-Tireman Villages highlight the influence of site-specific environmental and anthropogenic processes on mangrove dynamics. Although both locations exhibited minimal net changes in total mangrove area, differences in canopy density redistribution suggest that local conditions play a critical role in shaping mangrove structural development. Such site-dependent dynamics are commonly reported in mangrove ecosystems, where geomorphology, sediment supply, and hydrodynamic exposure interact to influence vegetation structure (Lovelock et al. 2015; Friess et al. 2019).

Sriwulan Village is situated in a coastal zone that has experienced long-term shoreline instability, including erosion and land subsidence, which may constrain mangrove stand development and promote internal restructuring rather than outward expansion. In environments affected by chronic physical stress, mangrove systems often exhibit gradual shifts in canopy density as stands adjust to changing substrate conditions and inundation regimes (Duke et al. 2017). These processes may contribute to the observed redistribution among density classes without substantial changes in overall mangrove extent.

In contrast, Pasar Banggi-Tireman Villages has been the focus of mangrove rehabilitation and coastal protection initiatives, which may have supported improvements in canopy density within existing mangrove areas. Studies have shown that rehabilitation efforts can lead to increased canopy closure and structural maturation without necessarily producing large gains in total mangrove area, particularly in space-limited coastal settings (Kodikara et al. 2017; Worthington and Spalding 2018). At the same time, localized losses may still occur due to natural disturbance or land-use pressures, resulting in overall area stability accompanied by internal structural change.

These site-specific patterns emphasize the importance of localized assessments when evaluating mangrove condition and management outcomes. Even within the same regional coastline, mangrove dynamics may differ substantially depending on physical setting and intervention history, underscoring the need for spatially explicit monitoring approaches tailored to local contexts.

Implications for mangrove monitoring and management

The findings of this study underscore the importance of integrating density-based indicators into mangrove monitoring and management frameworks. The observed stability in total mangrove area, coupled with notable shifts among density classes, demonstrates that area-based metrics alone may be insufficient to capture meaningful ecological changes. Similar conclusions have been drawn in previous studies, which emphasize that structural attributes such as canopy density and stand condition are critical for assessing mangrove ecosystem health and functionality (Alongi 2014; Friess et al. 2019).

From a monitoring perspective, the use of NDVI-derived density classification provides a practical and cost-effective approach for tracking internal changes within mangrove stands over time. Such methods are particularly valuable for local-scale assessments in data-limited contexts, where repeated field-based measurements may be logistically challenging. Remote sensing-based density metrics can support early detection of canopy degradation or recovery by revealing transitions among density classes before substantial changes in total mangrove area become apparent, thereby enabling more responsive and preventive management interventions (Lucas et al. 2007; Giri and Long 2016).

In terms of management, density-based information allows for spatially differentiated rehabilitation strategies. Areas classified as low-density mangrove should be prioritized for targeted rehabilitation actions, such as enrichment planting, improvement of hydrological connectivity, or protection from ongoing physical disturbance. Medium-density stands represent transitional conditions where management efforts should focus on supporting natural growth trajectories and preventing further degradation, rather than introducing excessive planting that may disrupt stand development. In contrast, high-density mangrove areas indicate relatively mature or closed-canopy conditions and should be managed primarily through protection and regular monitoring to maintain long-term stability.

The contrasting density dynamics observed between the two study sites further highlight the need for site-specific management approaches. Locations exhibiting stable mangrove extent but internal restructuring may benefit more from strategies aimed at improving stand quality and resilience than from spatial expansion alone. Accordingly, rehabilitation success should be evaluated not only by increases in mangrove area but also by measurable improvements in canopy density and structural condition, as recommended in recent mangrove management frameworks (Worthington and Spalding 2018).

Integrating spatial extent and density-based indicators provides a more comprehensive basis for evaluating mangrove management outcomes. Such an approach supports adaptive management strategies that are sensitive to local environmental pressures and management histories, ensuring that monitoring and rehabilitation efforts address both the stability and internal dynamics of mangrove ecosystems.

Methodological considerations and limitations

Several methodological considerations should be acknowledged when interpreting the results of this study. NDVI-based classification provides a useful proxy for mangrove canopy density and vegetation condition; however, it does not directly measure biomass, species composition, or structural complexity. Spectral responses in coastal environments can be influenced by tidal inundation, sediment background, and water reflectance, particularly at mangrove–water interfaces, potentially affecting density-class assignment (Heumann 2011).

Beyond these environmental influences, uncertainty in NDVI-based density classification represents an inherent methodological limitation. NDVI values integrate canopy greenness but may overlap across density classes due to variations in canopy structure, species composition, understory exposure, and substrate conditions. In abrasion-prone coastal settings, sparse canopies and exposed sediments can produce intermediate NDVI values that blur the distinction between low- and medium-density classes. Nevertheless, the satisfactory overall classification accuracy (84.67%) and substantial Kappa coefficient (0.78) obtained in this study indicate that such spectral overlap is unlikely to substantially bias the observed spatio-temporal patterns of mangrove density change.

The moderate spatial resolution of Sentinel-2 imagery may also limit the detection of fine-scale changes in narrow or fragmented mangrove stands. Mixed pixels can obscure subtle transitions between density classes, particularly along mangrove edges and in heterogeneous canopy patches. Although these limitations are inherent to medium-resolution satellite data, the use of ground-based validation and accuracy assessment supports the overall reliability of the classification results for comparative and change detection purposes. Some degree of uncertainty nevertheless remains inherent in satellite-based analyses and should be considered when interpreting localized density changes (Congalton and Green 2009).

Temporal resolution represents an additional limitation. The use of two observation years, while sufficient for identifying medium-term trends, may not capture short-term disturbances, episodic events, or seasonal variability in mangrove canopy condition. Tidal stage differences at the time of image acquisition may further influence NDVI responses by altering the proportion of exposed substrate and inundated vegetation surfaces. Long-term monitoring using multi-year time series and complementary field data would improve the robustness of change detection and support more detailed assessments of mangrove dynamics (Friess et al. 2019). Despite these limitations, the applied methodology provides a consistent, validated, and replicable framework for local-scale mangrove monitoring, particularly when results are interpreted as indicative spatial patterns rather than exact measurements of mangrove structural attributes.

In conclusion, this study demonstrates that mangrove ecosystems in Sriwulan Village and Pasar Banggi–Tireman Villages between 2019 and 2024 exhibited a high degree of spatial stability, with only minor net changes in total mangrove area. Mangrove cover in Sriwulan Village increased marginally from 16.76 ha to 16.77 ha (net gain of 0.015 ha; 0.09%), while Pasar Banggi-Tireman Villages experienced a slight decrease from 51.13 ha to 51.06 ha (net loss of 0.076 ha; 0.15%). Despite these minimal net changes, pronounced redistribution among mangrove density classes was observed at both sites, indicating that meaningful internal structural dynamics can occur without substantial spatial expansion or loss. The application of NDVI-based density classification proved effective for capturing these internal changes in canopy structure. By distinguishing shifts among low-, medium-, and high-density classes, this approach provided critical additional insight into canopy reorganization and stand development that would not have been evident from total area metrics alone. Density-based indicators therefore offer a practical and complementary tool for local-scale mangrove monitoring in dynamic coastal environments. From a management perspective, the findings suggest that mangrove conservation and rehabilitation efforts should not be evaluated solely on the basis of areal gain. Improvements in canopy density and structural condition within existing mangrove stands represent important indicators of ecosystem recovery and functionality. Several limitations should be acknowledged, including the indirect nature of NDVI as a proxy for canopy structure and the use of two observation years, which may not capture short-term disturbances or seasonal variability. Future research should prioritize longer-term, multi-temporal monitoring and integration of field-based measurements to strengthen the assessment of mangrove dynamics and support adaptive, evidence-based coastal management strategies.

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Structural sustainability imbalances in community-managed mangrove ecosystems in Central Java, Indonesia

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Abstract. *Iftitani MA, Dewi MPS, Sheliana MS, Hapsari M, Wahyuni T, Yap CK, Setyawan AD. 2025. Spatio-temporal changes in mangrove density and cover in Sriwulan and Pasar Banggi-Tireman, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 130-139.* Mangrove ecosystems play a strategic role in supporting ecological integrity, coastal protection, and socio-economic resilience in tropical coastal landscapes by providing essential ecosystem services such as shoreline stabilization, biodiversity support, and livelihood resources for coastal communities. Despite their importance, mangrove systems continue to face sustainability challenges driven by anthropogenic pressures, including land-use conversion, aquaculture expansion, and weak governance arrangements. Existing assessments of mangrove sustainability have predominantly adopted sectoral approaches that emphasize either ecological or socio-economic dimensions in isolation, limiting the ability to diagnose cross-dimensional interactions and structural conditions in which progress in one dimension coexists with persistent constraints in others. As a result, structural sustainability imbalances remain insufficiently examined, particularly in community-managed mangrove systems. This study diagnoses structural sustainability imbalance in a community-managed mangrove ecosystem in Kartika Jaya Village, Central Java, Indonesia, using a cross-sectional, single-site design. A multidimensional assessment was conducted using the Rapid Appraisal for Mangrove Forest (RAP-MForest) method, applying Multidimensional Scaling, leverage analysis, and Monte Carlo simulation. Rather than functioning solely as an evaluative index, RAP-MForest was applied as a diagnostic framework to examine relative performance and sensitivity across ecological, economic, and social dimensions. The results indicate that the ecological (68.16) and social (73.87) dimensions exhibit fairly sustainable conditions, supported by moderate ecosystem resilience and strong community awareness and participation. In contrast, the economic dimension (41.93) shows substantially weaker performance, reflecting limited economic utilization, funding constraints, and weak integration with local development. This cross-dimensional disparity produces a clear structural sustainability imbalance, in which economic underperformance constrains overall system coherence. Conceptually, this study advances sustainability assessment by framing sustainability as a configuration of interacting dimensions rather than an average composite score. Practically, the findings highlight the need for management and policy interventions that prioritize economic leverage points to consolidate existing ecological recovery and social capital within community-based mangrove management.

Keywords: Community-based management, mangrove, multidimensional sustainability, RAP-MForest, structural sustainability imbalance

INTRODUCTION

Mangrove ecosystems represent complex socio-ecological systems that integrate ecological functions with social and economic processes in tropical coastal landscapes. Ecologically, mangroves provide critical services such as shoreline stabilization, wave attenuation, sediment trapping, and the maintenance of coastal water quality, thereby reducing vulnerability to erosion and extreme weather events (Barbier 2019; Friess et al. 2019). Mangrove forests are also globally recognized as highly efficient blue carbon ecosystems, storing substantial amounts of carbon in both biomass and sediments and playing a significant role in climate change mitigation (Hamilton and Friess 2018; Arnaud et al. 2023). In addition, mangroves support high biodiversity by functioning as nursery habitats for fish, crustaceans, and other coastal fauna, contributing to broader marine productivity (Carugati et al. 2018).

Beyond their ecological importance, mangrove ecosystems sustain diverse social and economic functions. Coastal communities depend on mangroves for fisheries, aquaculture, fuelwood, non-timber forest products, and emerging livelihood opportunities such as ecotourism (Walters et al. 2008; Malik et al. 2015). These ecosystem services contribute not only to household income but also to food security and social resilience, particularly in developing tropical countries. Community-based mangrove management has therefore emerged as a widely promoted approach to balance conservation and livelihood needs by fostering local participation, stewardship, and adaptive governance (Kongkeaw et al. 2019; Macamo et al. 2024).

Despite their multifunctionality, tropical mangrove ecosystems remain highly vulnerable. Rapid coastal development, aquaculture expansion, land-use conversion, pollution, and weak institutional coordination continue to drive mangrove degradation across Southeast Asia and other tropical regions (Utami et al. 2024; Apriani and

Delistiani 2025). These pressures disrupt ecological integrity while simultaneously undermining the socio-economic foundations of mangrove-dependent communities, highlighting the need for sustainability assessments that explicitly consider interactions among ecological, economic, and social dimensions rather than treating them in isolation.

Research on mangrove sustainability has expanded considerably over the past two decades; however, much of this literature remains sectoral in nature. Numerous studies emphasize biophysical indicators such as mangrove cover change, species composition, biomass, and carbon stocks (Pham et al. 2019; Sunkur et al. 2024), while social and economic studies tend to focus on participation, perceptions, or valuation of ecosystem services (Afonso et al. 2022; Bakri et al. 2023). This separation constitutes a critical analytical gap, as sustainability is often inferred from improvements within individual dimensions without examining how uneven performance across dimensions may constrain overall system coherence.

An increasing body of evidence indicates that sustainability challenges in mangrove systems are frequently structural rather than uniform. Structural sustainability imbalance refers to a condition in which certain dimensions—typically ecological and social—exhibit relatively strong performance, while others, particularly the economic dimension, remain persistently weak and act as systemic constraints (Kusmana 2011; Sabrina et al. 2022; Ramadhani et al. 2025). Such patterns have been documented in community-managed mangrove systems across Indonesia and Southeast Asia, where successful rehabilitation and high community awareness coexist with limited funding, weak market integration, and low economic returns (Hidayah et al. 2024; Kamakuala et al. 2025). These observations underscore the novelty of framing sustainability not as a composite score, but as a configuration of interacting dimensions characterized by structural imbalance.

The Rapid Appraisal for Mangrove Forest (RAP-MForest) method, adapted from the Rapid Appraisal for Fisheries (RAPFISH) framework, offers a multidimensional diagnostic approach based on Multidimensional Scaling (MDS) that evaluates ecological, economic, and social dimensions separately (Pitcher and Preikshot 2001; Pitcher et al. 2013). When applied diagnostically, RAP-MForest enables the identification of cross-dimensional disparities and leverage attributes that shape sustainability configurations, rather than merely ranking overall performance. However, its explicit use to diagnose structural sustainability imbalance at the community-management scale remains limited in the peer-reviewed literature (Sabrina et al. 2022; Ramadhani et al. 2025).

Based on this perspective, this study hypothesizes that in a community-managed mangrove system, the economic sustainability dimension exhibits lower performance than the ecological and social dimensions, resulting in a structural sustainability imbalance that constrains overall system coherence. Accordingly, this study applies the RAP-MForest approach to a community-managed mangrove ecosystem in a tropical coastal landscape with three objectives: (i) to assess sustainability indices across ecological, economic, and social dimensions; (ii) to identify key leverage attributes contributing to structural sustainability imbalance; and (iii) to derive management- and policy-relevant insights to support integrated community-based mangrove sustainability strategies.

MATERIALS AND METHODS

Study area and community-managed mangrove context

The study was conducted in Kartika Jaya Village, Kendal District, located along the northern coast of Central Java, Indonesia (6°52′6″S, 110°12′22″E). This coastal area represents a typical tropical lowland shoreline characterized by shallow waters, muddy substrates, and tidal dynamics that support mangrove vegetation. The mangrove ecosystem in this village is managed predominantly through community-based initiatives involving local residents, fishers, aquaculture farmers, and village-level organizations. Management activities include small-scale rehabilitation, monitoring, and limited utilization of mangrove resources for livelihoods. Despite ongoing conservation efforts, the system remains exposed to anthropogenic pressures such as land conversion, aquaculture expansion, and infrastructure development, making it a relevant case for sustainability assessment. This study adopts a cross-sectional, single-site design, with Kartika Jaya Village serving as a representative case of a community-managed mangrove system within a broader tropical coastal landscape where ecological functions, economic activities, and social institutions interact closely (Figure 1).

Data collection and respondent selection

Data were collected through a combination of field observation, semi-structured interviews, and questionnaire surveys to capture ecological conditions, management practices, and community perspectives related to mangrove sustainability. Field observations were conducted to document mangrove vegetation condition, signs of degradation, rehabilitation activities, and human use patterns within the study area. These observations provided contextual information to support the interpretation of sustainability attributes.

Interviews and questionnaires were administered to key community members involved in mangrove use and management, including fishers, aquaculture farmers, community leaders, and members of local mangrove conservation groups. The survey instruments were designed to capture respondents' perceptions of ecological conditions, economic benefits, institutional arrangements, and participation in mangrove management.

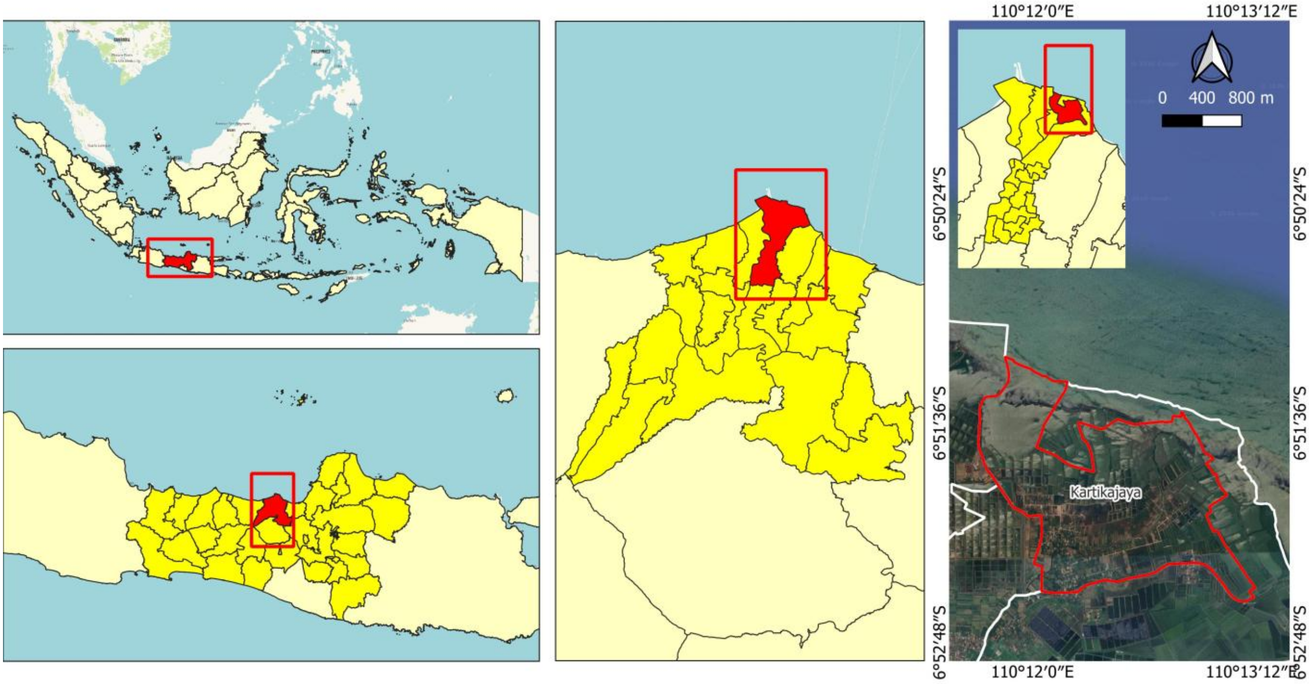

Figure 1. Study area of a community-managed mangrove system in the tropical coastal zone of Central Java, Indonesia

Respondents were selected using purposive sampling to ensure that participants had direct experience and knowledge relevant to mangrove management in the study area. A total of 97 respondents were included, proportionally distributed across the hamlets within Kartika Jaya Village. This sampling approach is appropriate for sustainability assessments that rely on informed stakeholder perspectives rather than statistical generalization. Participation in the study was voluntary, and informed consent was obtained from all respondents prior to interviews and questionnaire administration. To ensure ethical research practice, respondents' identities were kept anonymous, and all information was treated confidentially and used solely for academic purposes. Overall, the respondent profile reflects the primary stakeholder groups whose activities and decisions directly influence the sustainability of the community-managed mangrove system.

Sustainability dimensions and attribute architecture

Sustainability assessment in this study was structured around three interrelated dimensions: ecological, economic, and social, which together represent the core components of community-managed mangrove systems (Table 1). The ecological dimension reflects biophysical integrity, ecosystem functioning, and regenerative capacity of mangrove forests. The economic dimension captures the extent to which mangrove ecosystems contribute to livelihoods, funding availability, and sustainable resource use. The social dimension represents institutional arrangements, community awareness, participation, and governance mechanisms supporting mangrove management.

Attributes within each dimension were selected based on literature review, field observations, and relevance to local management contexts. Rather than functioning as isolated indicators, these attributes collectively represent the internal structure of the mangrove sustainability system. This attribute architecture allows sustainability to be interpreted diagnostically, enabling the identification of cross-dimensional imbalances and leverage points that shape overall system performance.

Each attribute was scored using an ordinal scale following the RAP-MForest framework, in which attribute scores were assigned along a graded continuum from unfavorable to favorable conditions based on field observations and respondent assessments. Specifically, attributes were scored using a standardized ordinal scale ranging from 0 to 4, where lower scores (0-1) represent unfavorable or less sustainable conditions and higher scores (3-4) indicate more favorable or sustainable conditions, following the standard RAP-MForest/RAPFISH procedure. Lower ordinal scores represent poorer or less sustainable conditions, whereas higher ordinal scores indicate better or more sustainable conditions within each dimension.

In the Multidimensional Scaling (MDS) ordination, hypothetical "good" and "bad" reference points were used to anchor the sustainability space, allowing observed attribute scores to be positioned relative to ideal and undesirable conditions. Sustainability indices were subsequently derived by standardizing ordination scores along this continuum, enabling comparative interpretation across ecological, economic, and social dimensions.

Table 1. Structural architecture of ecological, economic, and social attributes used to diagnose sustainability imbalances in community-managed mangrove ecosystems

Dimension	Attrib. code	Attribute description
Ecological	E1	Mangrove species diversity
Ecological	E2	Habitat variation
Ecological	E3	Water quality
Ecological	E4	Mangrove pressure (e.g., land conversion, logging, pollution)
Ecological	E5	Fauna diversity
Ecological	E6	Mangrove rehabilitation activities
Ecological	E7	Seedling availability and natural regeneration
Ecological	E8	Presence of endemic or native mangrove species
Economic	Ec1	Economic utilization of mangrove resources
Economic	Ec2	Availability of management funding
Economic	Ec3	Land-use zoning and spatial allocation
Economic	Ec4	Support for rehabilitation and conservation activities
Economic	Ec5	Contribution of mangroves to household income
Economic	Ec6	Integration of mangrove management with local development
Social	S1	Institutional coordination among stakeholders
Social	S2	Existence and enforcement of local regulations
Social	S3	Community awareness of mangrove functions
Social	S4	Community participation in mangrove management
Social	S5	Attitude toward sustainability and conservation
Social	S6	Role of community leaders and non-governmental organizations

RAP-MForest analysis and sustainability indices

The sustainability status of the community-managed mangrove system was assessed using the Rapid Appraisal for Mangrove Forest (RAP-MForest) method, adapted from the RAPFISH framework and based on Multidimensional Scaling (MDS). This approach transforms multiple sustainability attributes into ordination scores that represent the relative position of the system along a continuum between ideal ("good") and undesirable ("bad") reference conditions. Each attribute was scored on an ordinal scale and subsequently standardized to produce sustainability indices ranging from 0 to 100.

Sustainability indices were classified into three consistent categories applied throughout this study: less sustainable (<50), fairly sustainable (50-75), and sustainable (>75), allowing direct comparison across ecological, economic, and social dimensions. These categories are used solely as interpretative thresholds rather than absolute benchmarks of sustainability. Rather than being interpreted as absolute measures, the resulting indices function as relative diagnostic indicators that reflect comparative performance and internal structural configuration within the system. Differences among dimension-specific indices therefore indicate potential structural sustainability imbalances, where relatively strong dimensions may coexist with weaker ones.

By maintaining separate indices for each dimension, the RAP-MForest approach enables sustainability to be evaluated as a configuration of interacting components rather than as a single aggregated score. This diagnostic interpretation emphasizes relative positioning within the ordination space and provides a principled basis for identifying leverage attributes and priority areas for management intervention, rather than prescribing absolute sustainability status.

Leverage and Monte Carlo analysis

Leverage analysis was conducted to identify attributes that exert the greatest influence on sustainability indices within each dimension. The sensitivity of each attribute was quantified using the Root Mean Square (RMS) of changes in ordination scores resulting from systematic variation of attribute values. Attributes with higher RMS values were interpreted as key leverage factors, as small changes in these attributes produced relatively large shifts in the sustainability index. Importantly, leverage values reflect sensitivity within the ordination space rather than causal relationships, and therefore indicate relative influence rather than direct cause–effect mechanisms. These leverage factors, therefore, represent priority points for management intervention from a diagnostic perspective aimed at reducing structural sustainability imbalances.

To assess the robustness of the RAP-MForest results, a Monte Carlo analysis was applied. This procedure evaluates the potential effects of scoring uncertainty and random variation in respondent assessments on the stability of sustainability indices. Monte Carlo simulations showed minimal deviation between the original and simulated ordination scores, indicating that the derived sustainability indices were robust to scoring uncertainty. Consistency between original and simulated ordination results indicates that the derived indices are not strongly affected by random error. As the analysis is partly based on perception-derived ordinal scoring, the resulting indices should be interpreted as relative diagnostic indicators rather than precise quantitative measurements. Accordingly, the combined use of leverage and Monte Carlo analyses supports comparative assessment and decision-support applications, rather than inferential or predictive claims.

RESULTS AND DISCUSSION

Cross-dimensional sustainability indices

The RAP-MForest analysis revealed clear differences in sustainability performance across ecological, economic, and social dimensions of the community-managed mangrove system (Table 2). The ecological dimension achieved a sustainability index of 68.16, placing it within the fairly sustainable category. This score indicates that, despite ongoing pressures, core ecological functions such as vegetation condition, regeneration potential, and habitat quality remain moderately resilient. The social dimension recorded the highest sustainability index at 73.87, also categorized as fairly sustainable, reflecting relatively strong community awareness, participation, and institutional support for mangrove management.

In contrast, the economic dimension exhibited a substantially lower sustainability index of 41.93, classified as less sustainable. This result highlights limited economic benefits derived from mangrove management, constrained funding mechanisms, and weak integration between conservation activities and local economic development. The disparity between the economic dimension and the other two dimensions indicates that improvements in ecological condition and social engagement have not been accompanied by comparable economic performance.

When examined collectively, these dimension-specific indices reveal an asymmetric sustainability configuration rather than a balanced system. The coexistence of moderately strong ecological and social dimensions (68.16 and 73.87, respectively) with a lagging economic dimension (41.93) provides an initial indication of structural sustainability imbalance within the mangrove management system. Monte Carlo analysis confirmed that these cross-dimensional patterns were stable, as simulated ordination results showed minimal deviation from the original configuration, indicating robustness of the sustainability indices to scoring uncertainty. This imbalance suggests that overall sustainability is constrained not by ecological degradation alone, but by uneven performance across dimensions. All sustainability indices are reported using a consistent two-decimal precision throughout the Results, corresponding tables, and figures to ensure clarity and comparability.

Ecological sustainability structure and leverage attributes

The ecological dimension of the community-managed mangrove system exhibited a fairly sustainable condition, as reflected by its sustainability index and the overall ordination pattern. Field observations and scoring results indicate that mangrove vegetation remains relatively intact in several areas, supported by ongoing rehabilitation activities and the presence of natural regeneration. However, ecological conditions are not uniform across the study area, with localized degradation still evident in zones exposed to higher anthropogenic pressure.

Leverage analysis identified mangrove pressure as the most influential ecological attribute shaping sustainability outcomes, indicating that the intensity of human-induced disturbances primarily controls ecological performance. Water quality and seedling availability formed a second tier of sensitive attributes, reflecting their critical roles in maintaining regeneration processes and habitat suitability. Together, these attributes define a hierarchical sensitivity structure within the ecological dimension, where pressure acts as the dominant driver and regenerative capacity functions as a stabilizing mechanism.

Overall, ecological sustainability appears to be governed by the balance between ongoing pressures and the system's regenerative potential. While current conditions support moderate ecological resilience, persistent increases in pressure or declines in water quality and seedling availability would likely disrupt this balance and reduce ecosystem stability (Figure 2). When interpreted in conjunction with the cross-dimensional results, the ecological sustainability index of 68.16 contrasts with a substantially lower economic index of 41.93 and a higher social index of 73.87, indicating that ecological performance alone does not determine overall sustainability but forms part of a structurally imbalanced configuration that is synthesized in the subsequent section.

Economic constraints underlying sustainability imbalance

The economic dimension showed the weakest sustainability performance among the assessed dimensions, indicating a fundamental constraint within the mangrove management system. Limited economic returns from mangrove-related activities, combined with inadequate funding and weak integration with local development initiatives, restrict the capacity of the system to support sustainable livelihoods. These conditions suggest that economic processes have not evolved in parallel with ecological recovery and social engagement.

Table 2. Cross-dimensional sustainability indices revealing structural imbalances among ecological, economic, and social dimensions

Dimension	Sustainability index (%)	Sustainability category
Ecological	68.16	Fairly sustainable
Economic	41.93	Less sustainable
Social	73.87	Fairly sustainable

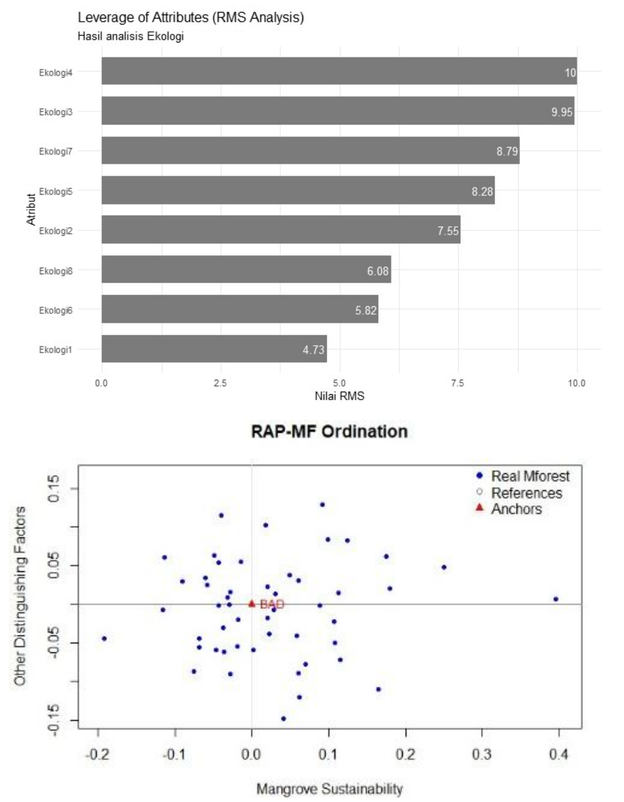

Figure 2. Ecological sustainability structure and leverage attributes shaping mangrove system resilience, derived from RAP-MForest Multidimensional Scaling (MDS) ordination and RMS-based leverage analysis

Leverage analysis revealed that economic utilization of mangrove resources constitutes the primary controlling attribute within the economic dimension. Management funding and support for rehabilitation formed additional high-sensitivity attributes, indicating that financial mechanisms strongly influence economic sustainability. This configuration reflects a structurally constrained economic subsystem, where limited incentives and resource flows restrict the translation of conservation efforts into tangible economic benefits.

As a result, the economic dimension functions as a systemic bottleneck. Despite favorable ecological conditions and strong social capital, economic limitations constrain overall sustainability by weakening feedbacks between conservation outcomes and livelihood improvement. This bottleneck position underscores the structural nature of the sustainability imbalance observed in the system, as illustrated by the RAP-MForest Multidimensional Scaling (MDS) ordination and leverage-based sensitivity output for the economic dimension (Figure 3).

Social drivers reinforcing sustainability

The social dimension exhibited a relatively high sustainability performance, indicating that social processes play a supportive role in maintaining mangrove management outcomes. High levels of community awareness regarding mangrove functions, coupled with active participation in conservation and rehabilitation activities, contribute positively to the overall sustainability profile. These social strengths reflect the presence of shared values, collective action, and local commitment to mangrove protection.

Leverage analysis identified community awareness and attitudes toward sustainability as the most sensitive social attributes influencing the sustainability index. Community participation and the role of local leaders and organizations also emerged as influential factors, indicating that institutional and informal governance structures help reinforce sustainable behavior. Changes in these attributes resulted in noticeable shifts in social ordination scores, underscoring their importance in shaping social resilience.

Despite these strengths, the social dimension operates within the constraints imposed by limited economic performance. Strong awareness and participation have not yet translated into adequate economic incentives or livelihood diversification. This contrast highlights a condition in which social capital supports conservation efforts but is insufficient to overcome economic limitations on its own, thereby reinforcing the cross-dimensional sustainability imbalance observed in the system (Figure 4).

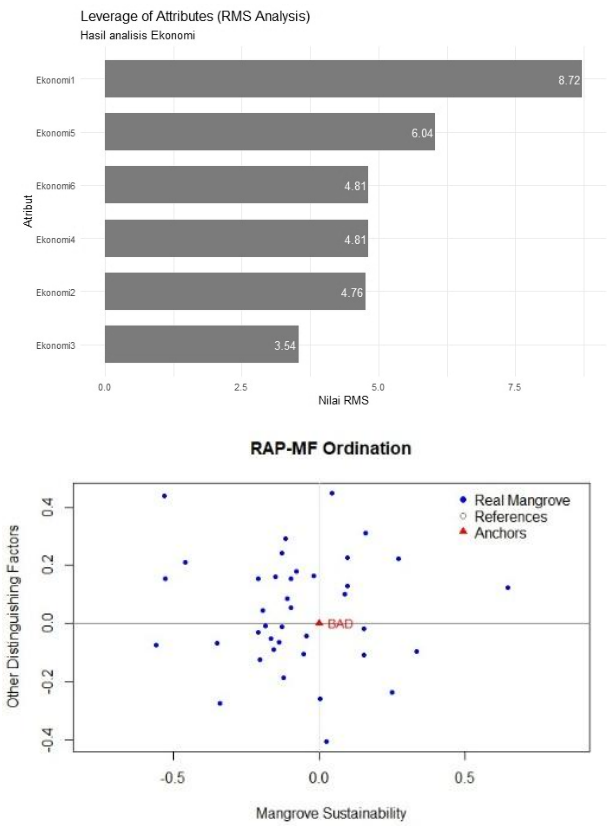

Figure 3. Economically driven constraints underlying the sustainability imbalance in mangrove management, derived from RAP-MForest Multidimensional Scaling (MDS) ordination and RMS-based leverage analysis of economic attributes

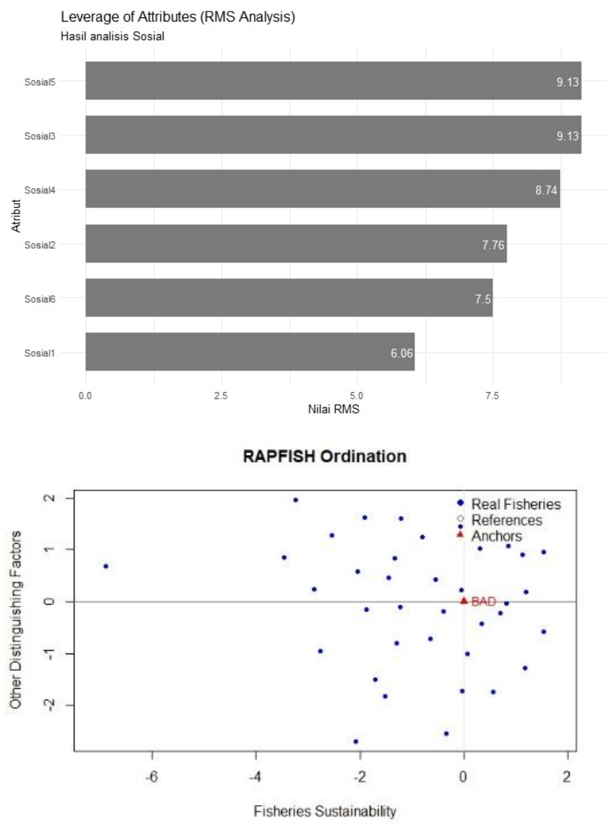

Figure 4. Social drivers reinforcing sustainability despite economic limitations in community-managed mangroves, derived from RAP-MForest Multidimensional Scaling (MDS) ordination and RMS-based leverage analysis of social attributes

Synthesis of structural sustainability imbalance

Integration of the ecological, economic, and social results reveals a clear pattern of structural sustainability imbalance within the community-managed mangrove system. The ecological dimension achieved a sustainability index of 68.16, and the social dimension reached 73.87, indicating fairly sustainable conditions supported by moderate ecosystem resilience, strong community awareness, and active participation. In contrast, the economic dimension recorded a substantially lower sustainability index of 41.93, consistently exhibiting weaker performance and limiting the system's ability to translate ecological recovery and social capital into sustainable livelihood outcomes.

This cross-dimensional configuration is effectively summarized through a kite diagram, which visualizes the asymmetric distribution of sustainability indices across dimensions. The pronounced contraction of the economic axis—corresponding to an index value of 41.93—relative to the more extended ecological (68.16) and social (73.87) axes illustrates how economic constraints structurally narrow the overall sustainability profile of the system (Figure 5). Rather than reflecting uniform underperformance across all dimensions, the diagram highlights imbalance as a defining structural characteristic, in which relatively strong ecological and social dimensions coexist with a persistently lagging economic dimension.

Within this configuration, the economic dimension emerges as the primary leverage and intervention point for rebalancing sustainability performance. While ecological integrity and social capacity provide a supportive foundation, strengthening economic mechanisms—such as improving sustainable resource utilization, funding availability, and linkage with local development—becomes essential to reduce structural imbalance and enhance overall system coherence.

Figure 5. Kite diagram summarizing structural sustainability imbalance among ecological, economic, and social dimensions based on RAP-MForest results

Discussion

Diagnosing structural sustainability imbalance in mangrove systems

The results of this study demonstrate that sustainability in community-managed mangrove systems is best understood as a structural sustainability imbalance rather than a uniform condition. The coexistence of moderately strong ecological and social dimensions with a comparatively weak economic dimension indicates that sustainability challenges are not driven by ecological degradation alone. Instead, they emerge from uneven interactions among system components, where persistent economic constraints and weak economic linkages constrain progress in certain dimensions. Similar patterns have been reported in mangrove systems across Southeast Asia, Africa, and Latin America, where rehabilitation success and high community engagement coexist with limited livelihood diversification and financial returns (Friess et al. 2019; Sunkur et al. 2023).

The concept of structural sustainability imbalance provides a useful lens to interpret these outcomes. Rather than treating sustainability as an average score derived from multiple indicators, this perspective emphasizes the relative configuration of dimensions and their internal coherence. In mangrove systems, ecological recovery may enhance habitat quality and carbon storage, while strong social capital promotes participation and compliance; however, in the presence of economic underperformance and financial limitations, these gains remain fragile. Studies from Vietnam, Bangladesh, and the Philippines similarly report that economic underperformance—manifested through limited market access, weak incentives, or insufficient funding— often undermines long-term sustainability despite ecological improvements (Portorreal et al. 2024; Ebeler et al. 2025).

Viewing sustainability as a configuration also aligns with broader socio-ecological systems theory, which highlights the importance of cross-scale interactions and feedback among ecological processes, governance structures, and economic drivers (Ostrom 2009; Berkes 2017). From this standpoint, imbalance is not an anomaly but a common system state arising from differential rates of adaptation across dimensions. The RAP-MForest results illustrate that ecological and social dimensions in the study area have adapted more rapidly—through rehabilitation and collective action—than the economic dimension, which remains constrained by structural financial and institutional limitations beyond local control.

This diagnostic interpretation has important implications. It suggests that improving sustainability does not necessarily require further ecological interventions or awareness campaigns, but rather targeted efforts to address economic constraints and weak economic linkages that inhibit system coherence. International experiences indicate that integrating mangrove conservation with sustainable value chains, payment for ecosystem services, or community-based enterprises can reduce such imbalances when supported by enabling governance and financing mechanisms (Locatelli et al. 2014; Zhang et al. 2024). Consequently, sustainability should be assessed and managed as a relational configuration, where balance among dimensions is as critical as performance within individual components.

Comparison with other tropical mangrove systems

The structural sustainability imbalance identified in this study is consistent with patterns reported from other tropical mangrove systems, particularly in Southeast Asia and deltaic coastal regions. Across Indonesia, Vietnam, Thailand, and the Philippines, numerous studies document situations in which mangrove rehabilitation and community participation have improved ecological conditions, while economic benefits for local communities remain limited or unevenly distributed (Friess and Webb 2014; Malik et al. 2015; Ebeler et al. 2025). These findings suggest that the imbalance observed in Kartika Jaya Village reflects a broader regional tendency rather than an isolated local condition.

In major delta systems such as the Mekong, Ganges–Brahmaputra, and Irrawaddy deltas, similar dynamics have been reported. Ecological restoration and regulatory enforcement have often succeeded in stabilizing mangrove cover, yet economic sustainability remains constrained by insecure tenure, restricted market access, and dependence on low-value resource use (Datta et al. 2012; Sunkur et al. 2023). Community-based management has strengthened social cohesion and awareness, but without complementary economic instruments, these systems continue to exhibit structural imbalance between conservation outcomes and livelihood resilience. From a diagnostic perspective, such cross-dimensional imbalances indicate the potential relevance of policy instruments that specifically target economic leverage points, including payment for ecosystem services schemes, development of sustainable mangrove-based value chains, rehabilitation financing mechanisms, or community-based enterprise models, without presupposing their current application in the studied systems.

Comparative evidence from tropical coastal communities in Africa and Latin America further reinforces this pattern. Studies from Mozambique, Kenya, and Ecuador indicate that strong local institutions and collective action can sustain mangrove protection, but economic incentives frequently lag, limiting long-term system coherence (Walters et al. 2008; Romañach et al. 2018). These cross-regional similarities underscore that economic underperformance is a recurrent bottleneck in community-managed mangrove systems globally.

Within this international context, the present study contributes by explicitly framing these disparities as a structural sustainability imbalance rather than as independent shortcomings of individual dimensions. By applying RAP-MForest as a diagnostic tool, this research advances the global discourse on mangrove sustainability from descriptive assessments toward configuration-based interpretations. This approach aligns with emerging calls in the literature to move beyond single-dimension success metrics and to evaluate how ecological, social, and economic components interact to shape long-term sustainability trajectories in tropical coastal systems (Ostrom 2009; Berkes 2017).

Governance and economic bottlenecks in community-based management

The findings of this study indicate that governance-related economic constraints constitute the principal structural limitation in community-based mangrove management within the specific context of the studied site. Although local institutions and community participation provide a strong social foundation, limited and unstable funding remains a persistent challenge. Community-based mangrove initiatives often rely on short-term project support, voluntary labor, or external assistance, which restricts the continuity and scalability of management activities. Similar funding constraints have been widely reported across Southeast Asian mangrove systems, where the absence of sustained financial mechanisms undermines long-term economic viability (Locatelli et al. 2014; Malik et al. 2015).

In addition to funding limitations, weak market integration represents a critical economic barrier. Mangrove-related products and services, such as sustainable fisheries, ecotourism, or non-timber forest products, frequently lack access to stable value chains and fair pricing mechanisms. As a result, conservation-compatible livelihoods remain marginal and insufficient to offset opportunity costs associated with land conversion or intensive aquaculture. Comparative studies from Vietnam, Bangladesh, and Indonesia consistently show that without market access and economic incentives, community engagement alone cannot sustain mangrove conservation efforts (Zhang et al. 2024; Ebeler et al. 2025).

Institutional coordination further shapes these economic outcomes. While community organizations often function effectively at the local level, coordination with higher-level government agencies, private sector actors, and financial institutions is frequently fragmented. This institutional disconnect limits access to technical support, legal recognition, and investment opportunities, reinforcing economic underperformance despite strong social capital (Friess et al. 2019; Portorreal et al. 2024). These governance gaps should be interpreted as diagnostic features of the studied community-managed mangrove system rather than as statistically generalizable conditions across all mangrove contexts.

Taken together, these conditions reflect a structural sustainability imbalance, rather than a lack of community commitment or ecological potential. Based on the diagnostic results of this single-site, cross-sectional assessment, improving mangrove sustainability requires governance arrangements that prioritize rebalancing economic performance relative to ecological and social dimensions, rather than expanding the indicator set. From a policy perspective, this implies targeted support for stable financing mechanisms and market-oriented instruments that can strengthen economic linkages without undermining existing community-based governance structures. Without addressing these structural economic constraints, community-based mangrove systems are likely to remain in a state of partial sustainability, where ecological and social gains cannot be fully consolidated into durable socio-economic outcomes.

Implications for sustainability diagnostics and management priorities

The findings of this study highlight the value of RAP-MForest not merely as an evaluative index but as a diagnostic tool for informing sustainability-oriented policy and management decisions. By disaggregating sustainability into ecological, economic, and social dimensions, RAP-MForest enables policymakers to identify structural imbalances that are often obscured by aggregated indicators. This diagnostic capacity is particularly relevant for mangrove systems, where apparent ecological success may mask underlying economic fragility. Similar calls for diagnostic rather than descriptive sustainability assessments have been emphasized in international socio-ecological literature (Ostrom 2009; Berkes 2017).

The leverage analysis provides a practical basis for prioritizing management interventions. Rather than allocating resources evenly across all dimensions, the results suggest that targeted interventions addressing high-sensitivity attributes can yield disproportionate improvements in overall sustainability. In the present case, economic attributes related to funding availability, resource utilization, and support mechanisms emerged as critical leverage points. International experiences demonstrate that addressing such leverage attributes through incentive-based instruments, such as payment for ecosystem services, sustainable value chains, or community-based enterprises, can significantly reduce structural imbalances in mangrove systems (Locatelli et al. 2014; Zhang et al. 2024).

From a broader policy perspective, the diagnostic insights generated by RAP-MForest are highly relevant for tropical coastal governance. Many coastal management policies continue to prioritize ecological indicators, such as mangrove cover or biomass, as proxies for sustainability. However, the results of this study reinforce the argument that long-term sustainability depends on balancing ecological recovery with economic viability and social capacity. Integrating diagnostic tools like RAP-MForest into coastal planning frameworks can help align conservation objectives with livelihood development, thereby enhancing policy coherence across sectors (Friess et al. 2019; Sunkur et al. 2023).

Ultimately, adopting a diagnostic approach shifts management priorities from short-term ecological targets toward structural coherence among dimensions. This shift is essential for designing adaptive, inclusive, and resilient mangrove management strategies in tropical coastal landscapes facing increasing environmental and socio-economic pressures.

Methodological considerations and limitations

Several methodological considerations should be acknowledged when interpreting the results of this study. First, the RAP-MForest assessment relies partly on perception-based scoring derived from interviews and questionnaires. Although respondents were purposively selected for their direct involvement and knowledge of mangrove management, subjective judgments may introduce bias. To mitigate this limitation, leverage and Monte Carlo analyses were applied to evaluate the sensitivity and robustness of sustainability indices, providing greater confidence in the observed patterns.

Second, the study adopts a cross-sectional design focused on a single community-managed mangrove system. As such, the results are not intended for statistical generalization across all tropical mangrove landscapes. Instead, the findings should be interpreted as a context-specific diagnosis that illustrates a broader structural pattern reported in comparable systems. Longitudinal data and multi-site comparisons would be valuable for capturing temporal dynamics and testing the persistence of structural imbalances over time.

Despite these limitations, the diagnostic strength of the approach represents a key contribution. By disaggregating sustainability into multiple dimensions and identifying leverage attributes, RAP-MForest enables a nuanced interpretation of system configuration rather than a simplistic performance ranking. This capacity makes the method particularly useful for decision-support and adaptive management in complex socio-ecological systems, where understanding structural relationships is as important as measuring outcomes.

In conclusion, this study demonstrates that sustainability in community-managed mangrove ecosystems is best interpreted as a structurally imbalanced configuration rather than a uniform condition. The RAP-MForest analysis shows that the ecological dimension reached a sustainability index of 68.16 and the social dimension 73.87, both indicating fairly sustainable performance, whereas the economic dimension recorded a substantially lower index of 41.93. This numerical disparity confirms that overall sustainability is constrained by cross-dimensional imbalance, in which relatively strong ecological and social conditions coexist with persistent economic underperformance. From a practical perspective, the results indicate that the economic dimension represents the primary leverage point for improving system coherence. Diagnostic leverage analysis suggests that targeted interventions focusing on funding availability, economic utilization of mangrove resources, and institutional support are more likely to strengthen overall sustainability than additional ecological rehabilitation or awareness-based initiatives alone. Strengthening economic mechanisms is therefore essential to consolidate existing ecological recovery and social capital within community-based mangrove management. Several limitations should be acknowledged. This assessment is based on a cross-sectional design, a single study site, and perception-based ordinal scoring, which restrict statistical generalization. Accordingly, the findings should be interpreted as diagnostic and context-specific. Future research should adopt longitudinal and multi-site comparative approaches to examine how structural sustainability imbalances evolve over time and across different mangrove management contexts, while maintaining a focus on rebalancing performance among sustainability dimensions rather than expanding indicator sets.

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