Species Diversity, Mangrove Density, and Socio-Ecological Resilience of Mangrove Ecosystems in East Seram Regency, Indonesia: Implications for Sustainable Management

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Abstract

The analysis of species diversity, stand density, and socio-ecological resilience of mangroves in East Seram Regency was conducted to assess the sustainability of biodiversity. Ecological data were collected using quadrat plots (10 × 10 m²), while social data were obtained through questionnaires and interviews with 135 respondents across four sites. The analysis included the Shannon-Wiener diversity index, vegetation density, recruitment index (RI), and the calculation of the Ecological Resilience Index (ERI), Social Resilience Index (SRI), and Integrated Socio-Ecological Resilience Index (SERI). The results revealed 16 mangrove species with varying levels of diversity among sites. The Shannon-Wiener diversity index (H′) ranged from 0.98 to 1.75, with evenness (E) values between 0.58 and 0.84. Stand density was highest in Tutuk Tolu (1,300 stands/ha) and loEast in Parang Island (791 stands/ha). Recruitment Index values were generally negative, indicating limited regeneration, except for certain species such as *Rhizophora apiculata* and *Sonneratia alba*. On the social dimension, most respondents demonstrated good understanding of mangrove functions and practiced non-destructive resource use, reflected in relatively high SRI values (0.61–0.73). The integration of both dimensions showed that three sites (DTW, DTT, and PI) were categorized as *Resilient* with SERI values greater than 0.61, while Akat Island was classified as *Moderate* (0.52). These findings highlight the need for socio-ecological system-based management through adaptive species restoration, strengthening of local regulations, and diversification of mangrove utilization via ecotourism.

Keywords: mangroves, species diversity, density, ecological resilience, socio-ecological resilience

Introduction

Mangroves are among the most productive coastal ecosystems in the world. Their presence provides substantial ecological benefits, such as protecting shorelines from erosion (Damastuti et al., 2023; Morris et al., 2023; van Hespen et al., 2023; Sunkur et al., 2023; Anu et al., 2024), sequestering significant amounts of carbon (Alongi, 2014; Murdiyarso et al., 2015; Rahman et al., 2024a), and serving as critical habitats for fish, mollusks, crustaceans, and birds (Rahman et al., 2024b). Beyond their ecological role, mangroves also hold high socio-economic value by supporting coastal livelihoods through fisheries, fuelwood, and ecotourism opportunities (Handayani et al., 2020; Rahman et al., 2024c). With these dual functions, mangroves stand as a vital pillar balancing ecological integrity and human well-being in coastal zones.

Indonesia holds a privileged position as the country with the largest and most diverse mangrove forests globally, covering more than 3.3 million hectares and comprising over 40 true mangrove species along with numerous associates (Rahman et al., 2024b; 2024d). However, this vast potential faces severe threats from deforestation, land conversion into aquaculture, coastal development, and population pressures (Ilman et al., 2016; Rahman et al., 2020). Degradation reduces not only the carbon sequestration capacity but also the resilience of coastal communities dependent on these ecosystems (Nyangoko et al., 2022; Choudhary et al., 2024).

Maluku, located within the Coral Triangle, harbors exceptional marine biodiversity, including mangroves (Rahman et al., 2024b; 2024d). East Seram Regency is among the regions with extensive mangrove distribution, yet information on community structure, species composition, and socio-ecological dynamics remains scarce (Rahman et al., 2025). Facing the Banda Sea, this region is both rich in resources and highly vulnerable to ecological and social pressures from climate change and human activities.

Most existing studies in Indonesia have focused predominantly on biophysical aspects, such as carbon storage, primary productivity, or rehabilitation techniques (Alongi, 2025; Kauffman et al., 2025). Research linking species diversity, stand density, and socio-ecological resilience remains rare, particularly in small island ecosystems like East Seram. Consequently, the adaptive capacity of mangroves in archipelagic contexts is not yet well understood, limiting evidence-based management.

Socio-ecological resilience offers a critical approach to assess system sustainability. Resilience is not only about ecological recovery from disturbances but also about the ability of local communities to adapt, utilize, and manage resources wisely (Sunkur et al., 2025). In mangrove contexts, resilience reflects a combination of ecological factors—such as species diversity and stand density—and social factors, including local knowledge, traditional practices, and patterns of resource use (Holmes et al., 2025).

The coastal zone of East Seram faces distinct pressures. Intensive fishing, land conversion for settlements, and climate change threats increasingly compromise mangrove sustainability. Yet, local communities maintain strong economic and cultural ties with mangroves. This dual relationship makes East Seram a critical site for understanding how ecosystems and communities co-shape socio-ecological resilience.

Species diversity and stand density were used to evaluate ecological conditions, while socio-ecological resilience was assessed through community interactions with mangroves. This integrative approach provides a comprehensive perspective on the adaptive capacity of mangrove ecosystems in East Seram. Such integration remains uncommon, thus offering both conceptual and practical novelty.

The key innovation of this study lies in bridging ecological and socio-ecological dimensions within a unified analytical framework. While previous studies often addressed only one aspect—either biodiversity or social factors—this research integrates both, emphasizing that mangrove sustainability cannot be understood in isolation but as an interconnected system.

The findings are expected to enrich academic knowledge on mangrove diversity and structure while offering practical insights for sustainable management. Information on dominant species, stand density, and socio-ecological resilience can guide local governments, conservation agencies, and communities in developing adaptive strategies. Thus, this research serves a dual purpose: strengthening the scientific foundation and informing actionable policies.

Accordingly, this study was designed to assess species diversity, stand density, and socio-ecological resilience of mangroves in East Seram. Through this integrated perspective, it aims to generate new insights into how ecological and social dimensions interact in shaping resilience and how such findings can support more sustainable coastal management in East Seram Regency.

Methods

Description of the study sites

The research was conducted in the coastal area of East Seram Regency, Maluku Province, from July to September 2025. This region is known for its extensive and diverse mangrove ecosystems, although comprehensive data remain limited. As part of the Maluku archipelagic landscape, the East Seram coastline faces the Banda Sea, which is rich in marine resources but also vulnerable to ecological pressures from climate change and human activities (Rahman et al., 2025). This geographical setting makes the study area a critical site for understanding the interactions between ecological and socio-economic factors that shape mangrove ecosystem resilience.

Ecologically, mangroves in East Seram play a strategic role in protecting coastlines, reducing erosion, and providing critical habitats for a wide range of aquatic and terrestrial organisms. Mangrove distribution is concentrated in several locations, namely Teluk Waru District (DTW), Tutuk Tolu District (DTT), Akat Island (AI), and Parang Island (PI) (Figure 1). The selection of these sites was based on the plan of the Indonesian Ministry of Marine Affairs and Fisheries to designate the area as a Regional Marine Conservation Zone.

From a socio-economic perspective, coastal communities in East Seram are highly dependent on mangroves. Utilization occurs through various practices, including capture fisheries, fuelwood collection, and timber for construction. The close relationship between communities and mangroves forms a dynamic socio-ecological system in which the sustainability of ecosystems strongly influences social resilience, and vice versa. This condition underscores the relevance of the study area for examining how ecosystem resilience is constructed through the interconnectedness of biophysical and social dimensions.

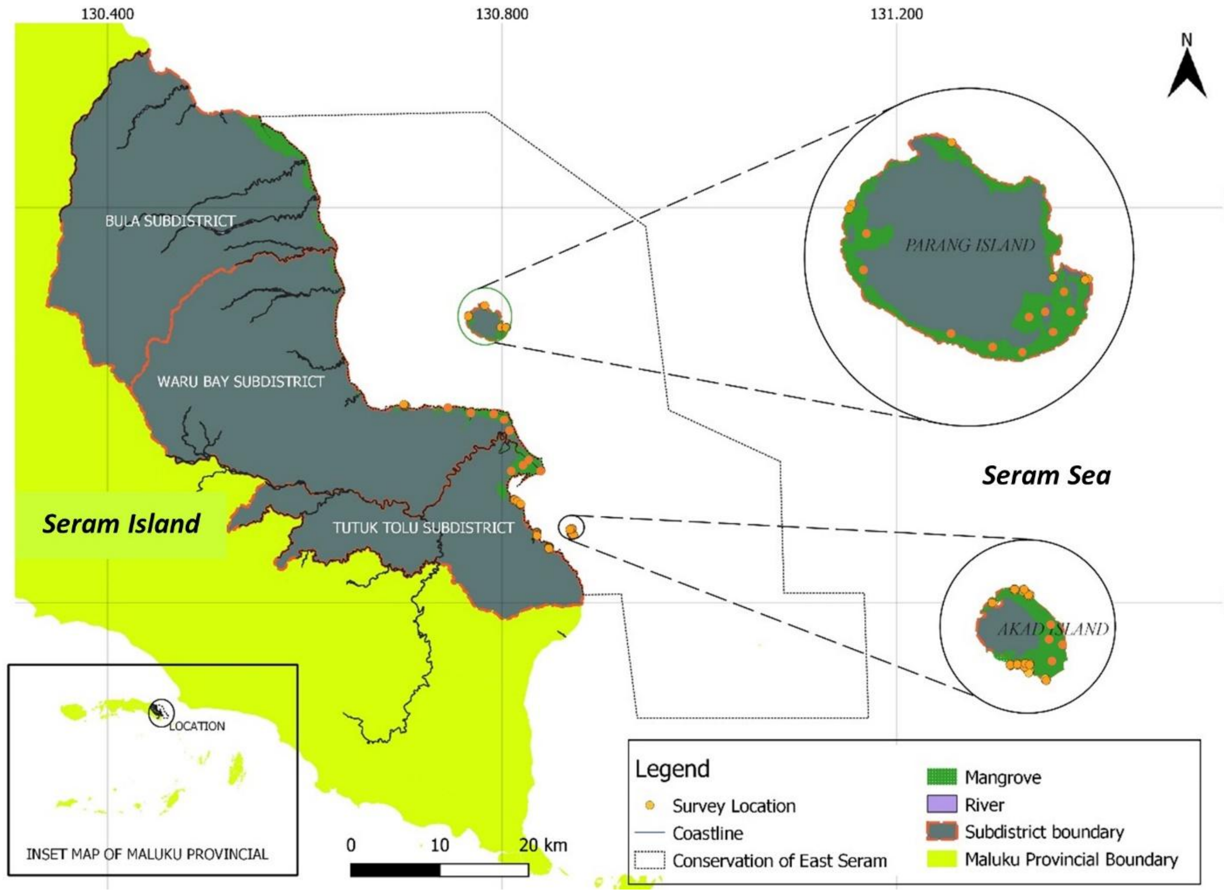

Figure 1. Map of the study sites

Data Collection

Mangrove Ecological Sampling

Ecological sampling of mangroves was conducted to obtain a comprehensive overview of the structure, composition, and environmental conditions of the ecosystem. Parameters measured included species richness, stand density, mangrove belt width, salinity variation, substrate characteristics, and recruitment index.

Mangrove species were identified directly in the field by recording key morphological traits, such as leaf, root, flower, and fruit characteristics. Species determination followed the mangrove identification guidelines developed by Noor et al. (2006). Stand density was determined using 10 × 10 m² quadrat plots (Bengen et al., 2022). Within each quadrat, all mangrove individuals were enumerated and their densities calculated in trees per hectare.

The mangrove belt width was measured from the landward margin to the seaward edge, or vice versa, depending on field accessibility. Spatial data on mangrove width were obtained through direct surveys combined with remote sensing image analysis. Spatial interpolation techniques were applied to estimate variations in mangrove width between plots, producing a more representative distribution map.

Water salinity surrounding the mangroves was measured using a hand refractometer. Measurements were taken at multiple points within each sampling location, repeated during different tidal phases (high and low tide) to capture temporal variation. Substrate characteristics were determined by collecting sediment samples using a 6 cm diameter and 100 cm long Peat Auger Set. Samples were extracted at depth intervals (e.g., 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm) and subsequently analyzed in the laboratory for texture, organic content, and dominant sediment fractions (Sasmito et al., 2020).

The recruitment index of mangroves was assessed based on vegetation density across three growth categories: tree, sapling, and seedling. Stand classification followed Rahman et al. (2024e), with criteria: (1) tree, diameter (D) > 5 cm; (2) sapling, 2 cm < D < 5 cm; and (3) seedling, D < 2 cm. These data were then used to evaluate regeneration potential and population dynamics of mangroves at each study site.

In total, 126 quadrats were observed, distributed as follows: 22 in Teluk Waru District, 38 in Tutuk Tolu District, 36 in Parang Island, and 30 in Akat Island. The number of quadrats at each site was adjusted to the local area and mangrove belt width to ensure that the data collected were proportionally representative of the ecological conditions in each location.

Social Data Survey

The social survey was conducted to understand community and stakeholder perceptions, attitudes, and involvement in mangrove ecosystem management. The aspects investigated included: (1) understanding of mangrove functions and urgency, (2) levels and types of continuous mangrove utilization, (3) stakeholder involvement in mangrove management, (4) availability of mangrove management regulations, and (5) potential conflicts of interest occurring in the field.

Social data were collected using two main techniques: structured questionnaires and in-depth interviews. The questionnaires were designed to obtain quantitative data on community perceptions and the intensity of mangrove utilization. Questions were presented in closed-ended formats with a Likert scale, along with several open-ended questions to capture qualitative insights. Meanwhile, in-depth interviews were conducted to explore contextual information that could not be fully captured through questionnaires, particularly regarding management dynamics, regulations, and inter-actor conflicts.

Respondents were determined based on the following criteria: (1) local communities living near mangrove areas, (2) individuals engaged in routine activities in the area (e.g., fishers, aquaculture farmers, wood collectors), (3) village officials or traditional leaders, and (4) environmental management or community assistance institutions. Respondent selection within community groups employed random sampling while ensuring gender and age representation, thereby providing a more representative socio-ecological perspective.

In total, 135 respondents were interviewed, distributed as follows: 25 respondents in Karay Village representing the DTW area, 50 respondents in Kufar, Waras-Waras, and Ga Villages representing the DTT area, 25 respondents in Air Kasar Village representing AI, and 35 respondents in Parang Island (PI). The composition of respondents was adjusted according to the size of the study area and the presence of local communities around mangrove ecosystems to ensure balanced social representation.

Questionnaire data were analyzed using descriptive quantitative methods to obtain frequencies, percentages, and response trends. In contrast, in-depth interview data were analyzed thematically by categorizing information into research themes, such as ecosystem functions, utilization, stakeholder involvement, regulations, and conflicts of interest. This mixed quantitative–qualitative approach provided a comprehensive understanding of community–stakeholder interactions with mangrove ecosystems at the study sites.

Data Analysis

Species Diversity

Analysis of mangrove species diversity was carried out using the Shannon-Wiener diversity index (H′), which accounts for both species richness and the relative abundance of individuals. The index is calculated as:

$$H' = - \sum_{i=1}^{s} pi \ln (pi) \quad (1)$$

where: H' = Shannon-Wiener diversity index, S = number of species, p_i = proportion of individuals belonging to species i relative to the total number of individuals.

To complement this measure, species evenness (*E)* was also calculated to evaluate the distribution balance of individuals among species. Evenness was derived as:

$$E = \frac{H'}{Ln\,(S)} \quad (2)$$

where: E = evenness index, H' = Shannon-Wiener diversity index, and S = number of species observed.

The Shannon-Wiener index (*H′*) reflects the overall species diversity, with higher values indicating greater diversity and lower dominance of particular species. Evenness (*E)*, ranging between 0 and 1, describes how evenly individuals are distributed across species, with values closer to 1 indicating more uniform distribution.

This analytical approach allows the assessment of not only the number of species present but also the ecological balance within the mangrove community. Together, H' and E provide a comprehensive picture of mangrove community structure, which is essential for evaluating the ecological resilience of the studied sites.

Socio-Ecological Resilience

This analysis aimed to assess the extent to which the mangrove socio-ecological system can withstand and adapt to environmental disturbances and pressures. The assessment was carried out using a quantitative weighting and scoring approach applied to a set of relevant ecological and social indicators (Tables 1 and 2).

Table 1. Ecological indicators in the assessment of mangrove ecosystem resilience

Indicator	Criteria	Weight (%)	Score	Description
Mangrove belt thickness (m)	<50; 50–200; 200–500; >500	12	1–4	Influences resistance to abrasion and seawater intrusion
Mangrove density (stands/ha)	<500; 500–1000; 1000–1500; >1500	15	1–4	Strongly related to ecological and carbon functions
Number of mangrove species	1–3; 4–6; 7–9; >10	12	1–4	Higher species diversity increases ecosystem resilience
Seedling recruitment index (RI)	RI≤0; RI= ; RI>0	20	1–3	Indicates the regenerative potential of the ecosystem
Habitat or substrate variation	Rocky; rocky–sandy; sandy–muddy; muddy–sandy	18	1–4	Determines biodiversity and ecosystem functionality
Salinity variation (psu)	>30 psu; 0-10 psu; 10-30 psu.	15	1–3	Affects mangrove species abundance and distribution

The ecological indicators of mangrove density and recruitment index were assessed not only qualitatively but also quantified to obtain a more objective understanding of mangrove regeneration status. Density was analyzed based on the number of individuals per unit area (Rahman et al., 2019), while the recruitment index (RI) was calculated using the equation proposed by Rahman et al. (2024e). The equation can be expressed as follows:

$$D = \frac{N}{A} \quad (3)$$

where: D = density (individuals/ha), N = total number of individuals recorded, and A = area of sample plot (ha).

$$RI = \ln\left(0.7 \times \frac{D\_seedling}{D\_tree} + \frac{D\_sapling}{D\_tree}\right) \quad (4)$$

Table 2. Social Dimension Indicators in the Assessment of Mangrove Ecosystem Resilience

Indicator	Criteria	Weight (%)	Score	Description
Understanding of mangrove functions and urgency	1 = No understanding; 2 = Low understanding; 3 = Moderate understanding; 4 = Very good understanding	20	1–4	Serves as the basis for pro-conservation attitudes
Level and type of continuous mangrove utilization	1 = Highly destructive (e.g., large-scale cutting, conversion); 2 = Moderately destructive (selective cutting,	30	1–4	Destructive or sustainable practices influence ecosystem sustainability

Indicator	Criteria	Weight (%)	Score	Description
	overharvesting); 3 = Low-impact use (traditional, subsistence); 4 = Sustainable use (regulated and conservation-based)			
Stakeholder involvement in mangrove management	1 = No involvement; 2 = Limited involvement of few actors; 3 = Moderate involvement with some collaboration; 4 = High involvement with multi-stakeholder collaboration	20	1–4	Active participation enhances management effectiveness
Availability of mangrove management regulations	1 = No regulations; 2 = Regulations at village level only; 3 = Regulations at district/provincial level; 4 = Regulations available up to national level	15	1–4	Ensures continuity and provides legal protection
Conflict of interest	1 = No conflict; 2 = Conflict between 2 stakeholders; 3 = Conflict involving 3 or more stakeholders	15	1–3	Conflicts reduce conservation effectiveness and collaborative management

Referring to these indicators, the ecological and social resilience indices can be formulated as follows:

$$\mathrm{ERI} = \frac{\sum_{i=1}^{m} S_i \,.\, W_i}{\sum_{i=1}^{m} S_{i-max} \,.\, W_i} \qquad (5)$$

$$\mathrm{SRI} = \frac{\sum_{j=1}^{n} S_j \,.\, W_j}{\sum_{j=1}^{n} S_{j-max} \,.\, W_j} \qquad (6)$$

Where: ERI = ecological resilience index; *SRI* = social resilience index; S_i = score of the *i*-th ecological indicator; S_j = score of the *j*-th social indicator; W_i = weight of the *i*-th ecological indicator; W_j = weight of the *j*-th social indicator; S_i-*max* = maximum score of the *i*-th ecological indicator; S_j-*max* = maximum score of the *j*-th social indicator; *m* and *n* = number of indicators.

The analysis of social-ecological resilience in mangrove ecosystems was conducted using a quantitative approach to assess the system's capacity to withstand environmental pressures and changes. One of the primary instruments in this analysis is the Social-Ecological Resilience Index (SERI), which is calculated based on two main dimensions: ecological resilience and social resilience. These two dimensions are interrelated and together form a complex and dynamic system.

The weighting of each dimension in the index calculation takes into account their relative contribution to the overall system resilience. In this context, the ecological dimension is assigned a weight of 60%, while social resilience is assigned a weight of 40%. This weighting is based on the consideration that:

a) A healthy ecosystem serves as the primary foundation for the sustainability of the social-ecological system. Mangrove ecosystems provide various essential ecosystem services, such as coastal protection, carbon sequestration, habitat provision for biota, and nutrient cycling. Disruption of ecological balance directly affects the loss of these vital functions, which ultimately impacts the social and economic resilience of coastal communities.
b) The social dimension functions as a driver of adaptation and management. Although it is not the primary foundation, social capacity plays a crucial role in determining how communities respond to environmental changes and pressures. Factors such as community participation, institutional capacity, local knowledge, and co-management policies are key to building adaptive and sustainable resilience.
c) The 60:40 weighting reflects a proportional balance between biophysical conditions and adaptive social capacity.

In an interacting social-ecological system, the greater emphasis on the ecological dimension reflects the urgency of maintaining ecosystem integrity as a prerequisite for successful social management. However, the social contribution remains significant in enhancing the system's capacity to withstand and recover from disturbances. The formula for calculating the SERI used in this study is formulated as follows:

$$SERI = (0.6 \times ERI) + (0.4 \times SRI) \quad (7)$$

Where: SERI = Socio-ecological resilience indices; ERI = ecological resilience indices; SRI= Social resilience indices.

The criteria for mangrove social-ecological resilience are established on a scale ranging from very low to very high (Table 3).

Table 3. Categories of Socio-Ecological Resilience Index (SERI) Values

SERI Value	**Resilience Category**	**General Interpretation**
0.00 – 0.20	Very Low	The social-ecological system is highly vulnerable; immediate restoration measures are required.
0.21 – 0.40	Low	The system remains vulnerable; capacity-building interventions are necessary.
0.41 – 0.60	Moderate	The system demonstrates moderate resilience; opportunities for resilience enhancement are open.
0.61 – 0.80	High	The system shows good resilience; adaptive strengthening is still needed.
0.81 – 1.00	Very High	The system has strong resilience; the social-ecological system is highly adaptive.

Result and Discussion

Species Diversity of Mangroves

The distribution of mangrove species across the four study sites showed notable variation between areas. The DTW (Teluk Waru) and PI (Parang Island) sites recorded the highest number of species, with nine species each, whereas DTT (Tutuk Tolu) and AI (Akat Island) had only four species (Table 4). This variation in species richness not only reflects local ecological conditions but is also influenced by environmental factors such as substrate type and salinity range (Bengen et al., 2022).

Table 4. Distribution of true mangrove species across the four study sites

Species	Subdictrict of Teluk Waru	Subdictrict of Tutuk Tolu	Akat Island	Parang Island
Aegialitis annulata	-	-	-	+
Aegiceras corniculatum	+	-	-	+
Avicennia alba	-	-	-	-
Avicennia marina	+	+	-	-
Avicennia officinalis	+	-	-	-
Bruguiera gymnorrhiza	-	-	+	+
Bruguiera sexangula	+	-	-	-
Ceriops tagal	-	-	-	-
Ceriops decandra	-	+	-	+
Kandelia candel	+	-	-	-
Lumnitzera recemosa	+	-	-	-
Rhizophora apiculata	+	+	+	+
Rhizophora mucronata	+	-	-	-
Rhizophora stylosa	-	-	+	+
Sonneratia alba	+	+	+	+
Xylocarpus granatum	-	-	-	+

Notes: Symbol (+) indicates presence, while (–) indicates absence.

Several species are cosmopolitan, such as *Rhizophora apiculata* and *Sonneratia alba*, which were found at all study sites. These species possess broad ecological tolerances to variations in substrate and salinity, enabling them to adapt to diverse habitats (Noor et al., 2006; Rahman et al., 2024c). In contrast, species with restricted distributions, such as *Xylocarpus granatum* and *Aegialitis annulata* on Pulau Parang, as well as *Avicennia officinalis*, *Bruguiera sexangula*, *Kandelia candel*, and *Lumnitzera racemosa* in Teluk Waru, indicate that local environmental factors also play a critical role in determining species presence.

Mangrove community diversity, as depicted by the Shannon-Wiener index (H′) and Evenness (E), reinforces these distribution patterns (Figure 2). Parang Island exhibited the highest mangrove diversity ($H' = 1.75$; $E = 0.84$), thriving on muddy-sand substrates with a salinity range of 20–30 psu. These relatively stable substrates support a variety of mangrove species, while moderate salinity further facilitates the growth of species with medium to high tolerance.

Conversely, mangrove community diversity in DTW was categorized as low, with H′ = 1.28 and Evenness (E = 0.58), dominated by *Sonneratia alba* and *Rhizophora apiculata*. Muddy-sand substrates and salinity levels of 10–30 psu supported these dominant species but limited opportunities for other species to establish. Tutuk Tolu showed the loEast diversity (H′ = 0.98) with similar substrate and salinity conditions as Teluk Waru, yet fewer species were present, likely due to higher anthropogenic pressures.

Mangrove diversity on AI was even lower, with H′ = 1.02 and E = 0.74, occurring on sandy substrates and high salinity (>30 psu). Such conditions restrict the number of species that can survive, allowing only a few high-salinity-tolerant species, such as *Rhizophora stylosa* and *Sonneratia alba*, to dominate. This illustrates how physical environmental factors, particularly extreme salinity, can act as major constraints on mangrove diversity.

Overall, the relationship between species distribution, diversity indices, and environmental conditions demonstrates that more heterogeneous substrates and moderate salinity tend to support higher species diversity, as observed on PI. In contrast, sites with homogeneous substrates or extreme salinity exhibit lower diversity and dominance by specific species, as seen on AI and DTT. These findings confirm that environmental factors play a crucial role in shaping mangrove community structure and, ultimately, influence ecosystem resilience.

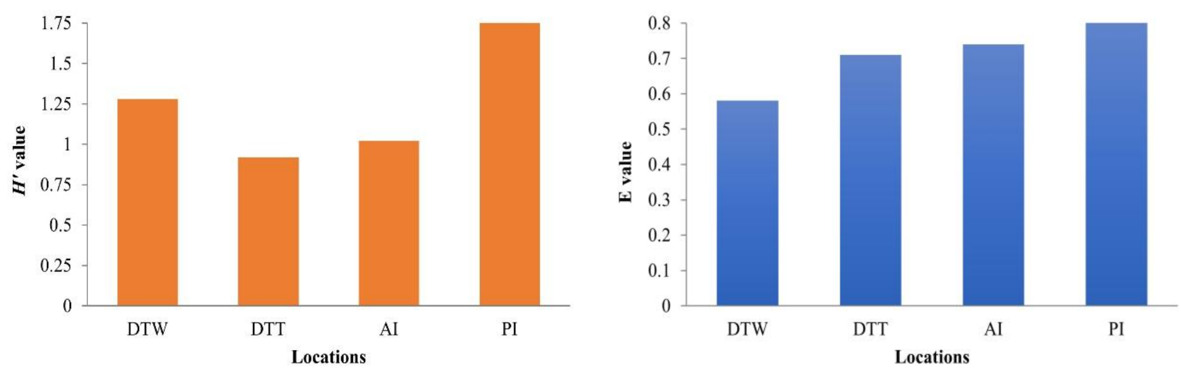

Figure 2. Shannon-Wiener diversity index (H′) and evenness (E) of mangrove communities across four study sites (DTW = Subdistrict of Teluk Waru, DTT = Subdistrict of Tutuk Tolu, AI = Akat Island, PI = Parang Island). Higher H′ values indicate greater species diversity, while E values closer to 1 indicate more balanced distribution of individuals among species.

Mangrove Density and Recruitment Index

The structure of mangrove stands across the four study sites showed significant variation in terms of adult trees, saplings, and seedlings (Table 5). Tutuk Tolu (DTT) had the highest tree density, reaching 1,300 ind./ha, with strong dominance by *Rhizophora apiculata* (491 ind./ha) and *Sonneratia alba* (691 ind./ha). The high tree density at this site indicates a relatively mature mangrove ecosystem, which generally plays a crucial role in carbon storage and coastal protection (Alongi, 2012; Donato et al., 2011).

In contrast, DTW and AI exhibited lower tree densities (867 ind./ha and 1,027 ind./ha, respectively). However, both sites showed a relatively good level of regeneration, reflected by the presence of saplings and seedlings at moderate densities, for example *Rhizophora apiculata* at DTW (63 saplings/ha; 489 seedlings/ha) and at AI (16 saplings/ha; 30 seedlings/ha). This consistent regeneration serves as an indicator of potential ecosystem sustainability, even though adult tree density is lower than at DTT (Ellison, 2008).

Parang Island (PI) presented a different condition, with relatively low adult tree density (791 ind./ha) but the highest number of seedlings (857 seedlings/ha). This indicates strong regenerative potential, supported by muddy-sand substrates and moderate salinity (20–30 psu), which are suitable for early seedling growth. The high number of seedlings of *Rhizophora stylosa* (316 seedlings/ha) and *Sonneratia alba* (419 seedlings/ha) demonstrates the ecosystem's capacity to renew itself following potential disturbances or environmental pressures. This aligns with Tomlinson (2016), who suggested that high seedling density is an important indicator of regenerative resilience in mangrove ecosystems.

Table 5. Density of mangrove trees, saplings, and seedlings (ind./ha) across four study sites (DTW = District of Teluk Waru, DTT = District of Tutuk Tolu, AI = Akat Island, PI = Parang Island).

Species	**Tree (individuals/ha)**				**Saplings (individuals/ha)**				**Seedlings (individuals/ha)**			
	DTW	DTT	AI	PI	DTW	DTT	AI	PI	DTW	DTT	AI	PI
Aegialitis annulata	0	0	0	9	0	0	0	8	0	0	0	4
Aegiceras corniculatum	3	0	0	64	6	0	0	16	4	0	0	8
Avicennia alba	0	0	0	0	0	0	0	0	0	0	0	0
Avicennia marina	42	82	0	0	38	47	0	0	18	42	0	0
Avicennia officinalis	18	0	0	0	18	0	0	0	12	0	0	0
Bruguiera gymnorrhiza	0	0	18	27	0	0	14	12	0	0	7	11
Bruguiera sexangula	6	0	0	0	4	0	0	0	3	0	0	0
Ceriops tagal	0	0	0	0	0	0	0	0	0	0	0	0
Ceriops decandra	0	36	0	173	0	27	0	39	0	11	0	16
Kandelia candel	27	0	0	0	14	0	0	0	3	0	0	0
Lumnitzera recemosa	30	0	0	0	8	0	0	0	2	0	0	0
Rhizophora apiculata	273	491	345	82	63	119	16	55	489	617	30	78
Rhizophora mucronata	15	0	0	0	13	0	0	0	13	0	0	0
Rhizophora stylosa	0	0	545	273	0	0	108	92	0	0	312	316
Sonneratia alba	452	691	118	118	59	82	65	41	116	102	14	419
Xylocarpus granatum	0	0	0	45	0	0	0	8	0	0	0	5
Total	**867**	**1300**	**1027**	**791**	**223**	**275**	**203**	**271**	**660**	**772**	**363**	**857**

Rhizophora apiculata and *Sonneratia alba* were dominant across nearly all sites. *Rhizophora apiculata* contributed substantially to total tree density, particularly at DTT and DTW, while *Sonneratia alba* dominated at DTT and AI. Both species are known for their broad ecological tolerance and high adaptability to variations in substrate and salinity, often allowing them to dominate mangrove ecosystems in Southeast Asia (Noor et al., 2006; FAO, 2007).

From a regeneration perspective, the comparison between the number of trees, saplings, and seedlings provides insight into the natural recruitment status of mangrove ecosystems. Sites with a high proportion of seedlings, such as PI, are predicted to have stronger regenerative potential, whereas sites dominated by adult trees, such as DTT, reflect the stability of an established forest structure. Nevertheless, weak regeneration in some species—for example, *Bruguiera sexangula* and *Avicennia officinalis*, which were only observed in the adult phase at DTW—indicates limitations in natural regeneration, possibly due to substrate conditions or anthropogenic pressures (Kathiresan & Bingham, 2001).

These findings highlight the importance of considering stand structure (trees, saplings, seedlings) when assessing mangrove ecosystem resilience. Ecosystems with a balance between mature trees and juvenile regeneration tend to better adapt to disturbances, whether natural or human-induced (McLeod & Salm, 2006). Therefore, conservation efforts in Seram Bagian Timur Regency should focus not only on protecting mature mangrove stands but also on enhancing natural regeneration success through habitat management and mitigation of external pressures.

In addition to stand density (trees, saplings, seedlings), mangrove regeneration status at the four study sites was analyzed using the Recruitment Index (RI). RI values were calculated based on the ratio of seedlings and saplings to adult trees. Generally, RI > 0 indicates potential or strong regeneration, RI = 0 indicates no regeneration, and RI < 0 reflects weak regeneration in particular species.

The patterns of mangrove vegetation recruitment varied widely by species and location (Table 5). At DTW, several species showed positive regenerative potential, such as *Rhizophora apiculata* (RI = 0.6702), *Avicennia officinalis* (RI = 0.302), and *Rhizophora mucronata* (RI = 0.3775). However, most other species had RI < 0, including *Sonneratia alba* (RI = -1.0545) and *Lumnitzera racemosa* (RI = -1.3831), resulting in an average RI of only -0.0936. This indicates that regeneration occurs for certain species but is uneven across the community.

At Tutuk Tolu (DTT), recruitment patterns tended to be negative, with an average RI of -0.3488. Dominant species such as *Sonneratia alba* (-1.4666) and *Ceriops decandra* (-0.1957) exhibited weak regeneration, although *Rhizophora apiculata* still showed a positive RI (0.3552). This is consistent with the density findings dominated by adult trees, indicating a mature forest structure with limited juvenile regeneration.

Akat Island (AI) exhibited the weakest regeneration, with an average RI of -0.8083. Almost all major species, including *Rhizophora apiculata* (-2.1264), *Sonneratia alba* (-0.6862), and *Bruguiera gymnorrhiza* (-0.0790), had negative RI values. This low regeneration is influenced by sandy substrates and high salinity (>30 psu), which are unsuitable for seedling germination and growth.

In contrast, Parang Island (PI) displayed relatively better regeneration. Although the average RI was still negative (-0.2882), some species had positive RI values, including *Rhizophora apiculata* (0.3534), *Rhizophora stylosa* (0.3328), and especially *Sonneratia alba* (1.3319). The presence of positive RI values indicates substantial regenerative potential, consistent with the high density of seedlings observed at this site.

RI analysis confirms that mangrove regeneration in East Seram is neither uniform across locations nor across species. Sites with more heterogeneous substrates and moderate salinity, such as Parang Island, show relatively better regeneration compared to Akat Island, which has sandy substrates and extreme salinity. This aligns with the findings of Kathiresan and Bingham (2001) that edaphic factors and salinity are primary controls of mangrove germination.

The dominance of adult trees at Tutuk Tolu (DTT) and Teluk Waru (DTW), while providing important ecological functions, warrants caution because weak regeneration in some species could reduce long-term ecosystem sustainability (Duke et al., 2007). Therefore, conservation strategies should prioritize maintaining natural regeneration, for instance through the protection of seedling areas, control of anthropogenic disturbances, and species-specific restoration using locally resilient species with positive RI values.

Table 5. Recruitment Index (RI) of mangrove species across study sites. Positive values (RI > 0) indicate good regeneration, RI = 0 indicates absence of regeneration, and negative values (RI < 0) indicate weak regeneration.

Species	**Subdictrict of Teluk Waru**	**Subdictrict of Tutuk Tolu**	**Akat Island**	**Parang Island**
Aegialitis annulata	–	–	–	0.0545
Aegiceras corniculatum	0.995	–	–	-1.1983
Avicennia marina	0.050	-0.088	–	–
Avicennia officinalis	0.302	–	–	–
Bruguiera gymnorrhiza	–	–	-0.0790	-0.3406
Bruguiera sexangula	-0.044	–	–	–
Ceriops decandra	–	-0.1957	–	-1.3836
Kandelia candel	-0.7564	–	–	–
Lumnitzera racemosa	-1.3831	–	–	–
Rhizophora apiculata	0.6702	0.3552	-2.1264	0.3534
Rhizophora mucronata	0.3775	–	–	–
Rhizophora stylosa	–	–	-0.3416	0.3328
Sonneratia alba	-1.0545	-1.4666	-0.6862	1.3319
Xylocarpus granatum	–	–	–	-1.4559
Average	**-0.0936**	**-0.3488**	**-0.8083**	**-0.2882**

Ecological Resilience (RE)

The variation in mangrove ecological resilience (RE) among the study sites ranged from 0.3944 to 0.7324. The highest RE value was recorded at DTT (0.7324), followed by DTW (0.7183) and PI (0.6620), while AI had the loEast value (0.3944) (Table 6).

The high ecological resilience at DTT and DTW is primarily supported by relatively wide mangrove belts (50–200 m), muddy-sand substrates, and moderate salinity (20–30 psu), which are favorable for growth and regeneration (Kathiresan & Bingham, 2001). Nevertheless, both sites showed limitations in terms of the Recruitment Index (RI), which tended to be low, indicating that natural regeneration is not yet optimal for certain species.

Parang Island (PI) exhibited a medium RE value (0.6620), influenced by muddy-sand substrate conditions and relatively high species diversity (8 species). Additional supporting factors include the presence of species with positive RI values (*Sonneratia alba*, *Rhizophora stylosa*, and *R. apiculata*), indicating better regenerative potential compared to other sites.

In contrast, Akat Island (AI) displayed low RE (0.3944), placing it in the low-resilience category. The main limiting factors were sandy substrates and high salinity (>30 psu), which do not support natural regeneration. This condition is consistent with the average negative RI (-0.8083) and the low number of species exhibiting active regeneration.

Table 6. Ecological Resilience Index (ERI) of mangrove ecosystems across study sites (DTW = Subdistrict of Teluk Waru, TT = Subdistrict of Tutuk Tolu, AI = Akat Island, PI = Parang Island).

Site	Mangrove Belt Width (m)	Density (stands/ha)	Species Richness	Recruitment Index (RI)	Substrate Type	Salinity (psu)	ERI Value
DTW	50–200	867	9	-0.0936	Sandy mud	10–30	0.7183
DTT	50–200	1300	9	-0.3488	Sandy mud	10–30	0.7324
AI	<50	1027	9	-0.8083	Sand	>30	0.3944
PI	50–200	791	8	-0.2882	Muddy sand	10–30	0.6620

Overall, these results reinforce the view that substrate and salinity are primary drivers of mangrove ecosystem resilience (Alongi, 2008; Duke et al., 2007). Sites with muddy-sand substrates and moderate salinity tend to exhibit higher resilience, whereas ecosystems with sandy substrates and extreme salinity are more vulnerable to degradation.

Social Resilience Index (SRI)

Social resilience to mangroves varied in terms of community knowledge, utilization patterns, and stakeholder involvement in mangrove ecosystem management across the study sites (Table 7). In general, Social Resilience Index (SRI) values ranged from 0.6071 to 0.7321, placing all sites in the medium to high category.

At Teluk Waru (DTW) and Tutuk Tolu (DTT), the highest SRI values (0.7321) were observed due to good community understanding of mangrove functions and importance, as well as relatively non-destructive utilization patterns. Respondents at both sites generally used mangroves for firewood on a limited scale, and there was collaborative involvement between the village government and the community in maintaining ecosystem sustainability. These results indicate that ecological knowledge and active community participation play key roles in strengthening social resilience (Rahman et al., 2020; Jentoft & Chuenpagdee, 2009).

Akat Island (AI) showed an SRI value of 0.7143, still within the relatively high category. Although community understanding was only moderate, utilization patterns were more constructive, such as integrating mangroves into marine ecotourism activities. This suggests substantial opportunities for enhancing social resilience through diversified benefits of mangroves, although community involvement remained independent and not institutionally organized. The lack of integration with regency-level regulations also limits the sustainability of management efforts.

In contrast, Parang Island (PI) had the loEast SRI value (0.6071), placing it in the medium category. Community understanding was relatively limited (moderate), and utilization patterns tended to be somewhat destructive, albeit on a small scale, such as for firewood and construction materials. Another weakness was that mangrove management was carried out independently by the community without strong institutional support. This aligns with Nikijuluw (2017), who found that weak regulatory integration and poor coordination among stakeholders reduce the effectiveness of conservation.

Despite variations between sites, conflict of interest was not a major issue, as no serious conflicts in mangrove utilization were observed. This can be explained by the subsistence level of exploitation and the limited involvement of private or industrial actors in mangrove use within the study area. However, potential conflicts should be anticipated if utilization intensifies in the future.

Overall, the results confirm that social resilience is strongly influenced by ecological knowledge, sustainable utilization patterns, and stakeholder involvement in management. The presence of regulations only at the provincial level, without clear integration at the regency and village levels, represents a common weakness that may reduce the sustainability of mangrove management. Therefore, strengthening locally-based policies and empowering community institutions are necessary to enhance social resilience more evenly across all sites (Kathiresan & Bingham, 2001; Rahman et al., 2022).

Table 7. Social Resilience Index (SRI) of mangrove ecosystems across study sites (DTW = Subdistrict of Teluk Waru, TT = Subdistrict of Tutuk Tolu, AI = Akat Island, PI = Parang Island)

Site	Understanding of Functions	Sustainable Utilization	Stakeholder Involvement	Regulatory Availability	Conflict of Interest	SRI Value
DTW	Good understanding	Non-destructive use	Collaborative (gov. & community)	Available at provincial level (not integrated with district)	No conflict	0.7321
DTT	Good understanding	Non-destructive use	Collaborative (gov. & community)	Available at provincial level (not integrated with district)	No conflict	0.7321
AI	Fair understanding	Integrated tourism use	Community-based (less organized)	Available at provincial level (not integrated with district)	No conflict	0.7143
PI	Fair understanding	Small-scale extractive use	Community-based (less organized)	Available at provincial level (not integrated with district)	No conflict	0.6071

Integrated Socio-Ecological Resilience Index (SERI)

The integration of ecological and social resilience reveals the variation in adaptive capacity of mangrove ecosystems across the four study sites (Figure 3). In general, the Integrated Resilience Index (SERI) ranged from 0.5223 to 0.7323, placing most sites in the Resilient category, except for Akat Island, which fell into the Moderate category.

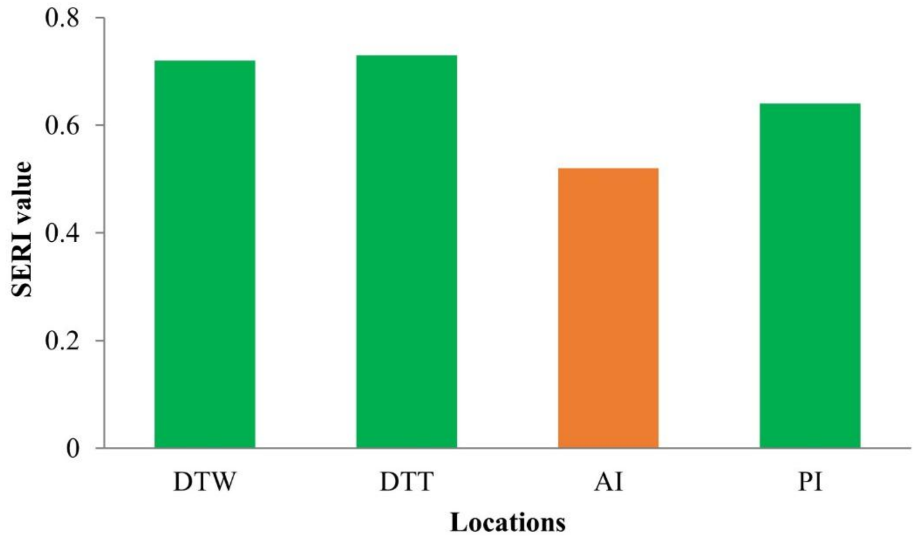

Figure 3. Socio-Ecological Resilience Index (SERI) of mangrove ecosystems across four study sites in East Seram Regency. Values range from 0.00–1.00, where higher values indicate greater resilience. Green bars represent locations categorized as *Resilient* (DTW, DTT, and PI), while the orange bar indicates a *Moderate* category (AI).

Teluk Waru (DTW) and Tutuk Tolu (DTT) ranked highest with SERI values of 0.7238 and 0.7323, respectively. This indicates a relatively good balance between ecological factors (mangrove width of 50–200 m, muddy-sand substrates, moderate salinity) and social factors (high community knowledge, non-destructive utilization, and involvement of village government and local communities). These findings support the view that a combination of biophysical and socio-cultural support can enhance the adaptive capacity of ecosystems (Duke et al., 2007; Rahman et al., 2022).

Parang Island (PI) was also categorized as Resilient with an SERI value of 0.6400. Although the social dimension was weaker (SRI = 0.6071), ecological factors were relatively supportive, particularly the muddy-sand substrate and the presence of several species with positive RI values (*Sonneratia alba* and *Rhizophora stylosa*). This suggests that ecological variables can buffer limitations in social factors, although long-term institutional strengthening remains necessary.

In contrast, Akat Island (AI) fell into the Moderate category with an SERI of 0.5223. The main weakness lay in ecological factors (ERI = 0.3944) due to sandy substrates and high salinity (>30 psu), which are unfavorable for natural regeneration. Although the social factor was relatively strong (SRI = 0.7143) with ecotourism-based utilization, this was insufficient to fully compensate for ecological limitations. This aligns with Alongi (2008), who emphasized that biophysical factors such as substrate and salinity are primary determinants of mangrove ecosystem resilience.

Overall, the study shows that the social-ecological resilience of mangroves in East Seram Regency is dominated by the Resilient category, with the greatest challenges observed at Akat Island. Efforts to strengthen resilience should focus on restoring ecological conditions through adaptive species restoration in sandy, high-salinity habitats, as well as enhancing local institutional capacity to improve cross-stakeholder collaboration (Jentoft & Chuenpagdee, 2009; Kathiresan & Bingham, 2001).

Implications for Sustainable Management

Ecological resilience (ERI), social resilience (SRI), and the Integrated Social-Ecological Resilience Index (SERI) provide crucial insights for sustainable mangrove management in Seram Bagian Timur Regency. The results indicate that most sites (DTW, DTT, and PI) fall into the Resilient category, while Akat Island (AI) is classified as Moderate due to ecological limitations despite relatively strong social factors. This highlights the need for management strategies tailored to the specific ecological and social context of each site.

From an ecological perspective, the low resilience at AI reflects the vulnerability of mangrove ecosystems growing on sandy substrates with high salinity (>30 psu). Restoration efforts at this site should focus on planting species adapted to these conditions, such as *Avicennia marina* and *Sonneratia alba*, which are known for their high ecological tolerance (Alongi, 2008; Tomlinson, 2016). In contrast, at DTW, DTT, and PI, where ecological conditions are more favorable, management should prioritize maintaining existing species diversity and protecting natural recruitment areas (seedlings and saplings) to ensure optimal regeneration.

From a social perspective, the study confirms that community knowledge, sustainable utilization patterns, and stakeholder engagement are key drivers of resilience. Strengthening local institutions and integrating regulations from the provincial to regency and village levels are essential for ensuring management sustainability (Nikijuluw, 2017; Jentoft & Chuenpagdee, 2009). Specifically, at Parang Island (PI), which exhibits lower social resilience, programs for community empowerment and the development of collaborative management platforms are needed to reduce reliance on extractive practices such as firewood collection.

By integrating these ecological and social findings, sustainable mangrove management in East Seram should adopt a social-ecological systems approach that combines habitat-based conservation with community-based governance. Potential strategies include developing ecotourism and livelihood diversification at Akat Island, enhancing environmental education and awareness campaigns at Parang Island, and strengthening collaborative governance at DTW and DTT. These actions will not only increase the adaptive capacity of mangrove ecosystems but also ensure inclusive conservation that delivers economic benefits to coastal communities.

Ultimately, the social-ecological resilience framework employed in this study provides a practical tool for identifying intervention priorities and formulating context-specific management strategies. By addressing ecological limitations while strengthening social capital and governance structures, mangrove ecosystems in Seram Bagian Timur can be managed more effectively to maintain their ecological functions, blue carbon potential, and contributions to the livelihoods of coastal communities.

Conclusion

Mangrove ecosystems in East Seram Regency exhibit variations in species diversity and stand density across different sites. The highest species diversity was observed in areas with muddy-sand substrates and moderate salinity, whereas sites with sandy substrates and high salinity showed limitations in natural regeneration. This underscores that biophysical conditions, particularly substrate type and salinity levels, are critical factors influencing mangrove distribution, growth, and ecosystem resilience.

From a stand structure perspective, sites with high mangrove density tend to have higher productivity and ecological functioning. However, the Recruitment Index indicates that natural regeneration is still limited; thus, even with a considerable number of mature trees, ecosystem sustainability heavily depends on the protection of seedlings and saplings. These findings highlight that species diversity and stand density form the fundamental basis of mangrove ecological resilience.

On the social dimension, coastal communities generally possess good understanding of mangrove functions and utilize resources in a relatively non-destructive manner. Minimal conflicts of interest and community participation alongside government engagement constitute essential social capital for sustainable management. Nonetheless, weak regulations at the regency and village levels reveal institutional gaps that may reduce management effectiveness.

The integration of ecological and social dimensions indicates that most sites exhibit strong social-ecological resilience, while locations with more extreme biophysical conditions show greater vulnerability. This emphasizes that social strengths alone cannot fully compensate for ecological limitations, highlighting the need for site-specific management strategies.

Overall, this study underscores the importance of a social-ecological systems approach in mangrove management. Strategies such as restoring adaptive species, strengthening cross-level governance, empowering community institutions, and diversifying uses through ecotourism and blue economy initiatives are key to enhancing mangrove ecosystem sustainability. Consequently, mangrove ecosystems in East Seram Regency can continue to maintain their ecological functions while providing sustainable socio-economic benefits to coastal communities.

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Declarations

Etchics approval

Ethical approval was not required for this study as it involved only non-invasive interviews and voluntary participation. The study complied with institutional and international ethical standards

Consent to Participate

All human participants involved in this study, including respondents in interviews and surveys, were fully informed about the purpose, procedures, and voluntary nature of their participation. Prior to data collection, each participant provided explicit consent to participate in the research. Participants were assured that their responses would remain confidential and used solely for academic purposes.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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