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Towards Sustainable Mangrove-Based Coastal Development through Integrated Assessment in Southwest Papua

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ABSTRACT

This study assessed the sustainability status of a mangrove-based eko-mina-wisata system in Aimas District, Southwest Papua, Indonesia, using a multidimensional approach based on Multi-Dimensional Scaling (MDS). Five sustainability dimensions were evaluated: ecological, tourism, economic, social, and institutional. Data were collected through field observations, structured questionnaires, and stakeholder interviews conducted between October 2023 and March 2025. Attribute scoring was performed using an ordinal scale and analyzed through a Rapfish-based MDS ordination. The results indicated that the ecological, social, and tourism dimensions were classified as moderately sustainable, while the economic and institutional dimensions were categorized as less sustainable. Stress values (<0.25) and high coefficients of determination confirmed the robustness of the ordination model, and Monte Carlo simulations demonstrated minimal sensitivity to scoring uncertainty. Leverage analysis identified mangrove density, income stability, market access, governance clarity, and stakeholder coordination as critical factors influencing sustainability performance. Although ecological conditions remain relatively stable, weaknesses in economic resilience and institutional coordination may pose long-term risks if not addressed. Strengthening governance integration and improving value-chain development are therefore essential to enhance system resilience. The multidimensional assessment framework applied in this study provides a practical decision-support tool for sustainable mangrove management in coastal socio-ecological systems.

INTRODUCTION

Mangrove ecosystems represent coupled socio-ecological systems in which ecological processes and human livelihoods are closely intertwined. Coastal communities depend on mangrove ecosystem services for fisheries production, shoreline protection, and income generation, while management interventions directly influence ecological resilience (Wardhani, 2011; Sumarmi and Purwanto, 2017). The interdependence between ecological integrity and community welfare underscores the need for management approaches that integrate environmental conservation with socio-economic development. In many Indonesian coastal regions, mangrove sustainability is strongly shaped by stakeholder coordination,

community participation, and cross-sectoral governance arrangements (Tobing *et al.,* 2023; Priyadarshini, 2023).

Integrated coastal management frameworks have increasingly emphasized combining mangrove conservation with livelihood diversification and participatory planning. Several studies highlight integrated models that merge silvofishery practices, ecotourism development, and community-based governance within unified management systems (Arfan *et al.* 2021; Normagiat *et al.,* 2023). Comparative policy analyses further stress the importance of coordinated institutional arrangements and local community involvement to ensure sustainable mangrove tourism and management outcomes (Aryanti and Koestoer, 2024). These integrated approaches reflect a shift from sectoral management toward landscape-based and multi-stakeholder strategies aimed at balancing ecological protection and economic productivity (Tobing *et al.,* 2023).

Within this integrated paradigm, silvofishery systems have played a significant role in Indonesia as adaptive production models that combine aquaculture ponds with mangrove conservation. Foundational silvofishery designs demonstrate that maintaining specific mangrove-to-pond ratios can support both ecological functions and aquaculture yields (Fitzgerald, 2000). Empirical studies in the Mahakam Delta and Blanakan areas further show that silvofishery adoption contributes to farmers' income, ecosystem service provision, and tourism-related benefits (Susilo *et al.* 2018; Sumarga *et al.* 2024). These findings suggest that silvofishery systems can function as productive yet conservation-oriented components within broader coastal development frameworks.

Seasonal variability also repreents an important consideration ini sustaining coastal fisheries and livelihood systems. Recent evidence from the Makassar Strait demonstrates pronounced seasonal and monthly variations in fish catches and species composition, with catch patterns changing across monsoonal periods (Loupatty *et al*., 2026). Such temporal variability highlights the importance of adaptive fisheries management and livelihood strategies that can respond to changing environmental and seasonal conditions

Parallel to silvofishery development, mangrove-based ecotourism has emerged as a strategic alternative to enhance community welfare while strengthening conservation incentives. Analytical hierarchy process (AHP) assessments identify ecotourism as a priority strategy for sustaining mangrove areas, particularly when community participation is emphasized (Priyadarshini, 2023). Integrated eco-fishery-tourism concepts further combine conservation, aquaculture, and visitor infrastructure to generate diversified income sources (Arfan *et al.,* 2021). Educational agro-ecotourism models also integrate production, conservation, and tourism functions within a single spatial design (Normagiat *et al.,* 2023). Although the specific term eko-mina-wisata is not explicitly documented in previous studies, its conceptual components silvofishery integration, ecotourism development, and community-based management are well represented within the existing literature. Although eco-mina tourism has previously been examined from a biophysical and development-potential perspective (Fahrizal *et al.,* 2025b), its sustainability has not yet been comprehensively evaluated across ecological, tourism, social, and institutional dimensions remains limited.

Despite the growing recognition of integrated mangrove management, empirical evaluations often focus on partial aspects such as silvofishery income impacts, tourism prioritization, or governance coordination or ecosystem condition. Recent research has demonstrated the value of quantitative indicator-based approaches for assessing mangrove ecosystem health by integrating ecological, environmental, and anthropogenic indicators into a composite assessment framework (Setiawan *et al.,* 2026). However, such ecosystem-health assessments primarily emphasize ecological condition and do not necessarily capture the broader socio-economic, tourism, and institutional dimension that shape the sustainability of integrated coastal utilization systems. Comprehensive multidimensional assessments that simultaneously examine ecological, economic, social, tourism, and institutional dimensions remain limited. Considering that mangrove systems operate as interconnected socio-ecological

units, fragmented evaluations may overlook leverage attributes that critically influence overall sustainability performance.

Southwest Papua represents a coastal region where mangrove ecosystems are closely linked to small-scale fisheries, aquaculture practices, community livelihoods, and emerging tourism initiatives. Previous research in Sorong District demonstrated the biophysical characteristics and development potential of mangrove ecosystems for sustainable eco-mina tourism (eko-mina wisata), highlighting the importance of mangrove species composition, structural characteristics, and ecological conditions in tourism planning (Fahrizal *et al,* 2025b). In Aimas District, mangrove utilization involves customary stakeholders, local communities, aquaculture actors, tourism managers, and government institutions, creating a complex governance landscape. Understanding how these interacting components shape sustainability outcomes requires an integrated analytical framework capable of capturing multidimensional dynamics.

Therefore, this study aims to conduct a multidimensional sustainability assessment of mangrove-based eko-mina-wisata in Aimas District, Southwest Papua, using a Rapfish-based Multi-Dimensional Scaling (MDS) approach. Specifically, the objectives are to: (1) evaluate sustainability status across ecological, tourism, economic, social, and institutional dimensions; and (2) identify key leverage attributes that significantly influence sustainability performance. By applying an integrated socio-ecological assessment framework, this study contributes empirical evidence to support adaptive coastal governance and sustainable mangrove-based development strategies.

METHOD

Study Area

The study was conducted in the mangrove ecosystem of Aimas District, Sorong Regency, Southwest Papua, Indonesia (Figure 1). The area represents a coastal system where mangrove forests are utilized for silvofishery aquaculture, small-scale fisheries, and mangrove-based tourism (eko-mina-wisata). The ecosystem is influenced by tidal dynamics and community-based resource management under customary tenure arrangements. Data collection was carried out from October 2023 to March 2025.

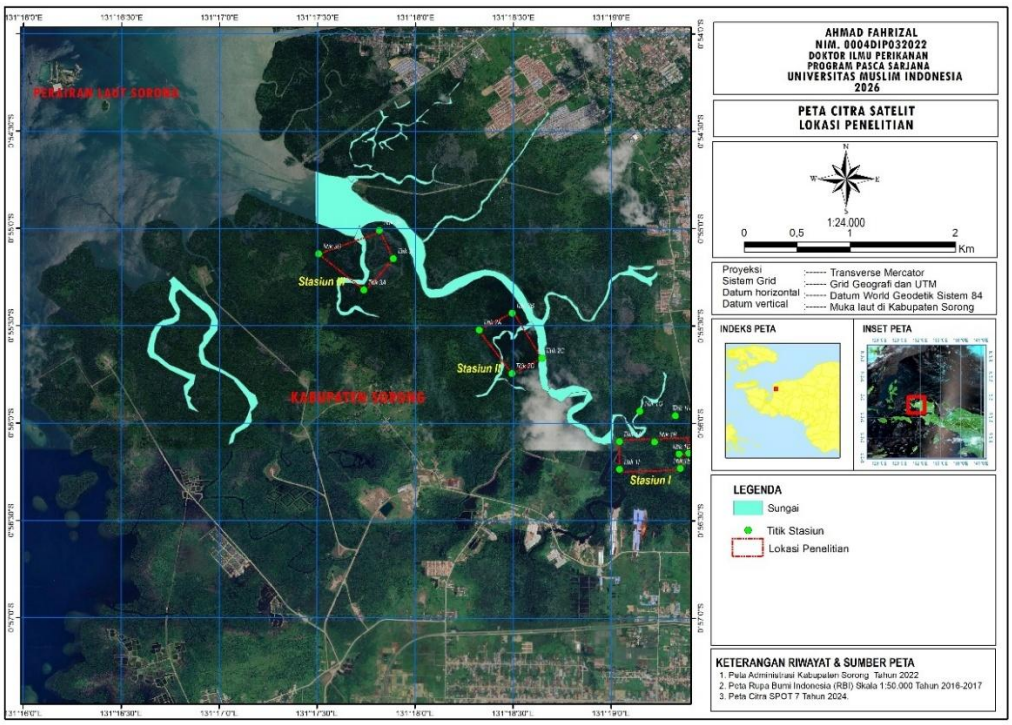


Figure 1. Research Site (Red Box)
Source: Processed Data (2025)

Data Collection and Attribute Scoring

Primary data were obtained through field observations, structured questionnaires, and semi-structured interviews involving key stakeholders, including aquaculture operators, tourism managers, community representatives, and local government officials. Secondary data were collected from institutional reports and relevant publications.

Sustainability was assessed across five dimensions: ecological–conservation, tourism attractiveness, economic, social, and institutional. Attributes within each dimension were adapted from the Rapfish framework (Pitcher *and* Preikshot, 2001) and modified to reflect mangrove-based aquaculture and tourism systems. Each attribute was evaluated using an ordinal scoring scale ranging from 0 (poor/unsustainable condition) to 3 (good/highly sustainable condition). Scoring was based on measurable indicators and validated through cross-checking among field observations and stakeholder responses to ensure consistency.

Multidimensional Scaling (MDS) Analysis

Sustainability status was analyzed using Multi-Dimensional Scaling (MDS) with a Rapfish-based ordination approach. Attribute scores were used to construct Euclidean distance matrices, which were projected into a two-dimensional ordination space. The ordination results were linearly transformed into sustainability index values ranging from 0 to 100. Sustainability categories were defined as follows: 0–24.99 (unsustainable), 25–49.99 (less sustainable), 50–74.99 (moderately sustainable), and 75–100 (sustainable). Separate analyses were conducted for each sustainability dimension.

Model Validation and Leverage Analysis

The goodness-of-fit of the MDS model was evaluated using stress values and coefficients of determination (R^2). A stress value below 0.25 was considered acceptable. To assess model stability and minimize potential scoring bias, Monte Carlo simulations were performed through repeated randomization. Differences between original MDS results and Monte Carlo outputs were used to evaluate robustness. Leverage analysis was conducted by calculating the Root Mean Square (RMS) change in ordination when each attribute was sequentially omitted. Attributes with the highest RMS values were identified as sensitive factors influencing sustainability performance.

RESULT AND DISCUSSION

Multidimensional Sustainability Status

The multidimensional sustainability assessment revealed varying levels of performance across the five evaluated dimensions (Table 1). The ecological dimension obtained the highest sustainability index (64.32), followed by the social (61.47) and tourism (58.26) dimensions, all categorized as moderately sustainable. In contrast, the economic (48.15) and institutional (43.78) dimensions were classified as less sustainable, indicating structural weaknesses in financial resilience and governance arrangements. Overall, the system demonstrates moderate ecological and social stability; however, economic viability and institutional effectiveness remain limiting factors affecting long-term sustainability performance.

Table 1. Sustainability index values of each dimension

Dimension	Index Value	Sustainability Category
Ecological	64.32	Moderately Sustainable
Tourism	58.26	Moderately Sustainable
Economic	48.15	Less Sustainable
Social	61.47	Moderately Sustainable
Institutional	43.78	Less Sustainable

Source: Processed Data (2025)

Model Goodness-of-Fit and Validation

The reliability of the MDS ordination was evaluated using stress values, coefficients of determination (R^2), and Monte Carlo simulations (Table 2). All stress values were below 0.25, indicating acceptable ordination fit. The R^2 values ranged from 0.88 to 0.94, demonstrating strong explanatory power of the model.

Monte Carlo analysis showed minimal differences between original MDS index values and randomized simulations (differences <1.0), confirming model stability and low sensitivity to scoring uncertainty. These results indicate that the sustainability indices generated are statistically robust and reliable for interpretation.

Table 2. Goodness-of-fit statistics of MDS analysis

Dimension	Stress	R^2	Monte Carlo Index	Difference
Ecological	0.14	0.94	63.80	0.52
Tourism	0.16	0.91	57.70	0.56
Economic	0.18	0.89	47.60	0.55
Social	0.15	0.92	60.90	0.57
Institutional	0.19	0.88	43.10	0.68

Source: Processed Data (2025)

Leverage Analysis

Leverage analysis identified several sensitive attributes exerting strong influence on sustainability performance (Table 3). In the ecological dimension, mangrove density and canopy cover were the most influential attributes. Within the economic dimension, income stability and market access showed the highest Root Mean Square (RMS) values, indicating vulnerability in financial sustainability. Institutional sustainability was strongly affected by governance clarity and stakeholder coordination, suggesting that management fragmentation contributes significantly to lower institutional performance. These leverage attributes represent priority intervention points for improving overall sustainability status.

Table 3. Sensitive leverage attributes (highest RMS values)

Dimension	Sensitive Attribute	RMS Value
Ecological	Mangrove density	4.62
Ecological	Canopy cover	4.38
Tourism	Visitor management capacity	4.95
Economic	Income stability	5.21
Economic	Market access	4.87
Social	Community participation	4.44
Institutional	Governance clarity	5.78
Institutional	Stakeholder coordination	5.35

Source: Processed Data (2025)

Ecological Sustainability

The ecological dimension showed the highest sustainability index and was categorized as moderately sustainable, indicating that mangrove ecosystem structure and ecological functioning in the study area remain relatively stable despite ongoing utilization for aquaculture and tourism activities. The leverage analysis identified mangrove density and canopy cover as the most influential attributes, emphasizing their critical role in maintaining ecosystem resilience. Dense mangrove stands contribute to sediment stabilization, carbon sequestration, nutrient cycling, and the provision of nursery habitats for various aquatic organisms, including fish, crustaceans, and molluscs (Eddy *et al.* 2016; Roza *et al.* 2024;

Sumarga *et al.* 2024; Fahrizal *et al*., 2025a). These ecological functions are essential for maintaining productivity in tropical coastal ecosystems.

Previous research in Aimas District has demonstrated that mangrove ecological metrics are closely associated with environmental conditions, highlighting the importance of integrating vegetation structure and environmental parameters in assessing mangrove ecosystem dynamics (Fahrizal *et al*., 2025a). The present study extends this ecological perspective by incorporating mangrove condition tourism, economic, social, and institutionaldimensions.

The relatively stable ecological condition observed in this study may be linked to the continued implementation of silvofishery practices that integrate mangrove conservation with aquaculture activities. Silvofishery systems have been widely recognized as a sustainable alternative to conventional pond aquaculture because they maintain vegetative cover while supporting fish and shrimp production (Wibowo, 2006; Eddy *et al.* 2016; Sumarga *et al.* 2024). However, ecological sustainability in silvofishery systems is highly dependent on maintaining appropriate mangrove-to-pond ratios and minimizing hydrological disturbances (Harefa *et al.* 2021; Suryaperdana *et al.* 2012). Improper pond design or excessive vegetation removal can disrupt tidal water exchange, which may reduce nutrient availability and alter salinity balance, ultimately affecting aquatic biodiversity (Gunawan *et al.* 2007).

Furthermore, the moderate ecological index indicates that the ecosystem remains vulnerable to cumulative anthropogenic pressure. Increasing tourism activities, infrastructure development, and potential aquaculture intensification may gradually alter habitat structure. Several studies in Southeast Asian mangrove ecosystems have shown that early-stage degradation often occurs through reduced seedling recruitment and altered sediment composition before visible vegetation loss becomes apparent (Gunawan *et al.* 2007; Apriyanto *et al.* 2025). Therefore, long-term ecological monitoring programs focusing on vegetation dynamics, water quality parameters, and benthic community structure are essential to detect early warning signals of ecosystem decline (Gunawan *et al.* 2007; Harefa *et al.* 2021; Siswoyo *et al.* 2024).

Tourism Sustainability

The tourism dimension was also categorized as moderately sustainable, suggesting that mangrove-based eko-mina-wisata activities are currently operating within ecological limits. Mangrove tourism provides economic opportunities while simultaneously promoting environmental awareness among visitors and local communities (Silalahi *et al.* 2024; Basyuni *et al.* 2018). The presence of tourism infrastructure, such as boardwalks and observation areas, can enhance public appreciation of mangrove ecosystems and encourage conservation-oriented behavior.

Despite these positive contributions, the leverage analysis identified visitor management capacity as a highly sensitive factor affecting tourism sustainability. Unregulated tourism growth can lead to increased waste accumulation, physical damage to mangrove roots, and disturbance of wildlife habitats (Minata *et al.* 2024; Putra *et al.* 2015). In mangrove ecosystems, trampling of pneumatophores and young seedlings may reduce regeneration capacity, potentially leading to long-term vegetation decline. Additionally, increased boat traffic associated with tourism can generate wave disturbance and sediment resuspension, affecting water clarity and benthic organisms.

Effective tourism management requires the implementation of carrying capacity assessments to determine the maximum number of visitors that the ecosystem can sustain without ecological degradation (Silalahi *et al.* 2024; Minata *et al.* 2024; Muhammad *et al.* 2012; Apdillah *et al.* 2023). The establishment of zoning systems separating conservation areas, tourism zones, and aquaculture areas could reduce spatial conflicts among resource users (Putra *et al.* 2015; Silalahi *et al.* 2024; Apdillah *et al.* 2023). Environmental education programs targeting visitors and local tourism operators can further strengthen sustainability by promoting responsible tourism behavior. Integrating tourism development into broader

coastal management frameworks is also necessary to ensure that tourism expansion does not undermine ecological stability.

Economic Sustainability

The economic dimension recorded a lower sustainability index compared to ecological and social dimensions, reflecting structural vulnerabilities in the financial viability of mangrove-based livelihoods. Income stability and market access were identified as the most influential leverage attributes, indicating that economic sustainability is strongly influenced by external market dynamics and production variability (Silori *et al.* 2009; Pratama *et al.* 2025). Small-scale aquaculture operations often face fluctuating input costs, disease outbreaks, and unpredictable production yields, which can significantly affect household income.

Economic vulnerability may also be associated with temporal variability in fisheries production. Recent evidence from the Makassar Strait indicates substantial seasonal differences in fish catches and species composition, including lower catches during the west monsoon and productive periods during the transition and east monsoon season (Loupatty *et al*., 2026). These seasonal fluctuations suggest that coastal households dependent on fisheries may face changing production and income opportunities throughout the year. In the context of eko-mina-wisata, diversification through aquaculture, ecotourism, and other mangrove-based livelihoods may therefore enhance household resilience to seasonal fluctuations in fisheries production.

Limited market integration further constrains economic performance, as local producers often rely on intermediaries with limited bargaining power. The absence of value-added processing and product diversification reduces profit margins and increases vulnerability to market price fluctuations (Pratama *et al.* 2025; Evans *et al.* 2023). Strengthening economic sustainability requires the development of integrated value chains that connect producers directly with regional or national markets. Establishing community-based cooperatives could enhance collective bargaining capacity, reduce marketing costs, and improve income distribution among stakeholders.

Additionally, the development of alternative mangrove-based products, such as eco-friendly handicrafts, mangrove honey, and processed seafood products, may increase economic diversification (Silori *et al.* 2009; Pratama *et al.* 2025). The growing global interest in blue carbon initiatives and ecosystem service valuation presents additional opportunities for generating conservation-linked revenue (Gevaña *et al.* 2018; Miller *and* Tonoto, 2023; Rasowo *et al.* 2024). Payment for ecosystem services programs could provide financial incentives for maintaining mangrove cover, thereby aligning economic benefits with conservation objectives (Gevaña *et al.* 2018; Flint *et al.* 2018).

Social Sustainability

The social dimension demonstrated moderate sustainability, supported by strong community engagement in mangrove resource management. Community participation plays a fundamental role in sustaining coastal ecosystems, particularly in regions governed by customary tenure systems (Gevaña *et al.* 2018; Eddy *et al.* 2016; Silori *et al.* 2009). Local knowledge regarding tidal cycles, species distribution, and resource utilization practices often contributes to effective ecosystem management (Miller *and* Tonoto, 2023; Evans *et al.* 2023). Community-based monitoring and enforcement mechanisms can enhance compliance with conservation regulations and reduce illegal resource exploitation.

However, social sustainability is influenced by evolving socio-demographic factors, including generational changes, migration patterns, and shifts in livelihood preferences. Younger generations may show reduced interest in traditional aquaculture or mangrove management practices, potentially weakening local stewardship over time (Rasowo *et al.* 2024). Unequal distribution of tourism and aquaculture benefits may also create social tension and reduce collective participation in resource management activities.

Capacity-building programs focusing on sustainable aquaculture techniques, tourism management skills, and environmental education can strengthen social resilience (Gevaña *et al.* 2018; Evans *et al.* 2023). Inclusive decision-making processes that involve women, youth, and marginalized community groups are also essential for ensuring equitable benefit distribution (Rasowo *et al.,* 2024). Strengthening local institutions and promoting community empowerment can enhance long-term social stability and support adaptive ecosystem management.

Institutional Sustainability

The institutional dimension exhibited the lowest sustainability index, indicating governance challenges as a major constraint affecting overall system performance. Governance clarity and stakeholder coordination were identified as the most influential leverage attributes, suggesting fragmentation in management authority and regulatory enforcement (Slobodian *and* Badoz, 2019; Partelow *et al.* 2018). Overlapping responsibilities among conservation agencies, tourism managers, and aquaculture operators may reduce policy effectiveness and create conflicts in resource utilization.

Institutional strengthening requires the establishment of integrated coastal management frameworks that coordinate cross-sectoral planning and decision-making processes (Hoanh *et al.* 2006; Subambang *et al.* 2024; Karlsson-Vinkhuyzen *et al.* 2014). Formal recognition of community-based management systems can enhance regulatory legitimacy and improve compliance (Partelow *et al.* 2018; Putri *et al.* 2019; Ruzol *et al.* 2020). The development of multi-stakeholder management platforms could facilitate information exchange, conflict resolution, and collaborative policy implementation (Duval-Diop *et al.* 2014; Putri *et al.* 2019; Gevaña *et al.* 2021).

Institutional capacity is also closely linked to the availability of technical expertise, monitoring systems, and financial resources. Strengthening institutional networks between local governments, research institutions, and community organizations can enhance adaptive management capacity (Partelow *et al.* 2018; Gevaña *et al.* 2021; Duval-Diop *et al.* 2014). In many coastal ecosystems, strong governance structures have been shown to significantly improve conservation outcomes and economic resilience (Slobodian *and* Badoz, 2019; Hilmi *et al.* 2023).

Inter-Dimensional Interactions and System Resilience

The multidimensional sustainability assessment highlights the interdependence between ecological, economic, social, tourism, and institutional components (Dolorosa *et al.,* 2017; Santoso *et al.* 2019; Hermawan *et al.,* 2025). The relatively stable ecological condition observed in this study may not be sustainable in the long term if economic vulnerability and institutional fragmentation persist. Economic instability can encourage unsustainable resource exploitation, while weak governance structures may limit enforcement of conservation regulations.

Conversely, strengthening institutional coordination and improving economic opportunities can enhance conservation incentives and community participation. The integration of tourism development with mangrove conservation and aquaculture production has the potential to create synergistic benefits, provided that resource utilization is carefully regulated (Azizah *et al.,* 2022; Eunike *et al.,* 2018). Multidimensional management approaches are therefore essential for maintaining long-term system resilience in mangrove-based socio-ecological systems (Dolorosa *et al.,* 2017; Ekasari *et al.,* 2024).

Study Limitations and Future Research Directions

Although this study provides a comprehensive assessment of sustainability performance, several limitations should be acknowledged. The use of ordinal scoring in MDS analysis may introduce subjectivity, despite efforts to minimize bias through stakeholder validation and Monte Carlo simulations (Santoso *et al.,* 2019; Hermawan *et al.,* 2025; Ekasari *et*

al., 2024). Additionally, sustainability assessments represent dynamic system conditions that may change over time due to environmental variability and socio-economic transitions.

Future research should incorporate longitudinal monitoring to evaluate temporal changes in sustainability performance. Integrating ecological field measurements, such as biodiversity indices and water quality parameters, with socio-economic modelling could improve analytical precision (Dolorosa *et al.,* 2017; Azizah *et al.,* 2022). Further studies exploring climate change impacts, blue carbon potential, and ecosystem service valuation would also provide valuable insights for sustainable mangrove management (Gevaña *et al.,* 2018; Miller and Tonoto, 2023; Hilmi *et al.,* 2023).

CONCLUSION

This study demonstrates that the mangrove-based eko-mina-wisata system in Aimas District is generally moderately sustainable, with relatively strong ecological, social, and tourism performance, but constrained by weaker economic viability and institutional capacity. While current utilization practices have not yet exceeded ecological limits, income instability, limited market access, governance fragmentation, and weak stakeholder coordination represent critical leverage factors that may threaten long-term resilience if left unaddressed. Strengthening institutional integration, improving value-chain development, and enhancing economic diversification are essential to support sustainable mangrove management. The multidimensional MDS approach applied in this study provides a practical framework for identifying priority intervention areas and supporting evidence-based coastal management in mangrove-dependent socio-ecological systems.

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