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Multidimensional Sustainability Assessment of Mangrove Ecosystems in Luwuk Timur, Banggai Regency, Indonesia Using RAP-MFRAST and Monte Carlo Validation

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ABSTRACT

Mangrove ecosystems are ecologically, socially, and economically vital for maintaining coastal stability. However, severe mangrove destruction has occurred in the Luwuk Timur coastal area, Banggai Regency, due to land-use changes for aquaculture ponds, settlements, and illegal logging. This study assessed the sustainability status and ecological condition of mangroves using the Rapid Appraisal for Mangrove Forest Sustainability (RAP-MFRAST) method combined with Multidimensional Scaling (MDS) analysis. Primary data were collected through direct observation and purposive-sampling interviews, while secondary data were obtained from government agencies and literature reviews. Four sustainability dimensions—ecological, economic, social, and institutional—were evaluated using 29 attributes. Results show that the ecological dimension falls into the moderately sustainable category (index 71.29), and the economic (50.46) and institutional (51.86) dimensions are also moderate, but the social dimension is less sustainable (47.37). The relatively high ecological index reflects strong biophysical support, including mangrove cover and biodiversity, indicating that the East Luwuk mangrove ecosystem retains good ecological capacity. In contrast, lower scores for social and economic dimensions reveal major challenges such as limited community participation, low environmental awareness, financial constraints, and weak institutional support. Model reliability was confirmed by Monte Carlo validation, yielding stress levels below 0.15 and R^2 values above 0.94 for each dimension. Overall, degradation of social and institutional quality is the main barrier to effective mangrove management. Adaptive solutions require multiparty involvement, stronger institutional capacity, and greater community engagement in ecosystem-based conservation. These findings provide important evidence for developing policies to support sustainable coastal resource management.

INTRODUCTION

Mangrove forests are a vital component of tropical coastal ecosystems, providing ecological, economic, and social benefits. They serve as natural seawalls that protect

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shorelines against storm erosion and seawater intrusion, act as spawning and nursery grounds for marine life, play a key role in blue carbon sequestration, and supply coastal communities with resources such as fuelwood, building materials, and fisheries support **(Alongi, 2018)**. Their multifunctionality makes mangroves a strategic asset for sustainable coastal development, particularly in Indonesia, which hosts the largest extent of mangrove forests worldwide **(Sasmito *et al.*, 2023)**.

Despite their importance, Indonesian mangroves face growing threats from land conversion, aquaculture expansion, coastal development, and uncontrolled resource harvesting **(Lewis & Brown, 2014; KLHK, 2022)**. In Banggai Regency, Central Sulawesi Province, more than 5,652 hectares of mangroves have been severely degraded **(Utina *et al.*, 2019)**. Within this region, the East Luwuk Subdistrict—part of the Banggai Dalaka Local Conservation Area—is under intense ecological pressure despite its high biodiversity, including rare species such as *Scyphiphora hydrophyllacea* **(Kalsum, 2022)**.

The socio-economic context has further exacerbated these vulnerabilities. In East Luwuk, local communities use mangrove products for fuelwood, traditional medicine, construction, and small-scale aquaculture and fisheries **(Muhsimin *et al.*, 2018)**. However, limited education, weak local institutions, and persistent land-use disputes among communities, private companies, and government agencies have hindered effective management **(Kalsum & Sumardi, 2022)**. Spatial analysis from 2008–2019 showed that the subdistrict lost approximately 1,146 hectares of mangroves to ponds, settlements, and agricultural land **(Kalsum, 2022)**.

Previous studies emphasize that mangrove restoration cannot rely solely on technical planting, but must be embedded within broader socio-ecological, legal, and participatory frameworks **(Lewis, 2005; Brown *et al.*, 2014)**. Community-Based Ecological Mangrove Rehabilitation **(Brown *et al.*, 2014)**, Context-specific and adaptive approaches such as Ecological Mangrove Rehabilitation (EMR) **(Lewis & Brown, 2014)**, and Building with Nature **(Bosma *et al.*, 2020)** have shown promise, particularly when combined with local participation and resolution of land tenure issues. Supporting this, a recent study in Indragiri Hilir highlighted that restoration success depends not only on degraded land availability but also on biophysical suitability, socio-economic pressures, and institutional capacity **(Massa *et al.*, 2023)**.

In East Luwuk, mangrove forest degradation has largely resulted from land conversion and unsustainable practices. A qualitative study by **Kalsum *et al.* (2022)** identified conversion to fish ponds, rice fields, and settlements as key drivers, but did not assess the sustainability status of mangroves or the policy interventions required. To address this gap, the present study assessed the sustainability of the East Luwuk mangrove ecosystem using a multi-dimensional framework encompassing ecological, economic, social, and institutional dimensions.

Given the complexity of mangrove management, sustainable solutions must involve stakeholders and be guided by data-driven assessment tools. One such tool, the Rapid

Appraisal for Mangrove Forest Sustainability (RAP-MFRAST), integrates Multidimensional Scaling (MDS) to evaluate sustainability across four dimensions **(Pitcher & Preikshot, 2001; Sabrina *et al.*, 2022)**. This framework also identifies leverage factors that strongly influence sustainability, while robustness of results can be validated through Monte Carlo analysis, which estimates data uncertainty **(Fauzi, 2019)**.

Against this background, the objectives of the current research were twofold: (1) to evaluate the sustainability of East Luwuk Subdistrict's mangrove ecosystems across four dimensions (ecological, economic, social, and institutional); and (2) identify the most sensitive indicators that can serve as leverage points for adaptive and participatory mangrove management. The findings are expected to provide both scientific insights and practical guidance for evidence-based mangrove restoration and management strategies in Central Sulawesi and other tropical coastal regions of Southeast Asia.

MATERIALS AND METHODS

1. Location, and research methods

This research was conducted in East Luwuk, Banggai Regency, Central Sulawesi Province, across four villages: Kayutayo (Station 1), Hunduhon (Station 2), Uwedikan (Stations 3 and 4), and Bantayan (Station 5). Site selection was based on several criteria, including mangrove vegetation condition, level of human disturbance, and representation of ecosystem characteristics under both socio-economic and ecological pressures. The research location map is presented in Fig. (1).

Data collection

The study employed survey and field observation methodologies, supported by both primary and secondary data sources.

Primary data consisted of direct field measurements of biophysical characteristics, including mangrove species identification, damage assessment, and biodiversity records. In addition, Focus Group Discussions (FGDs) were conducted to gather social, economic, and institutional information. Participants included representatives from the Environmental Agency, Fisheries Department, Regional Development Planning Board (BAPPEDA), Forestry Agency of Central Sulawesi Province, the Balantak Forest Management Unit (KPH Balantak), subdistrict and village officials, academics, and coastal community groups (fisheries and aquaculture).

Secondary data were obtained through literature reviews and institutional records from relevant agencies, such as the Banggai Fisheries Office, the Central Sulawesi Provincial Marine and Fisheries Agency, fisheries extension services, and other supporting institutions. These included previous research reports, scientific publications, institutional documents, and local government regulations related to mangrove biodiversity, conservation, and socio-ecological conditions.

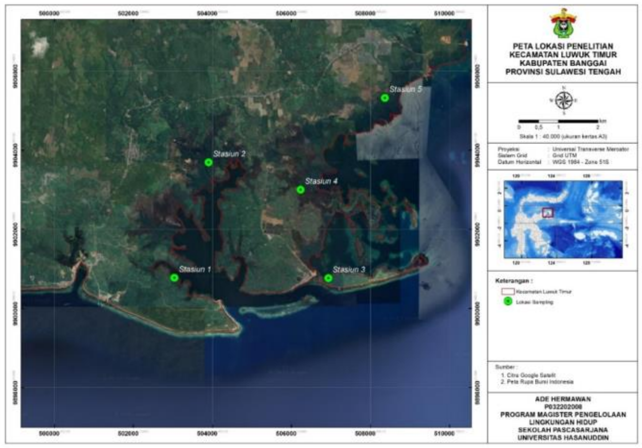

Fig. 1. Research location

2. Sustainability analysis

2.1. *Analysis of RAP* MFRAST

The sustainability status of the mangrove ecosystem was evaluated using the Rapid Appraisal for Mangrove Forest Sustainability (RAP-MFRAST), a methodological adaptation of the Rapid Appraisal for Fisheries (RAPFISH) framework **(Pitcher & Preikshot, 2001)**. This approach employs Multidimensional Scaling (MDS) to assess sustainability across four dimensions: ecological, economic, social, and institutional. Each dimension is composed of multiple attributes measured on an ordinal scale, allowing for the quantification of relative sustainability status within and across dimensions.

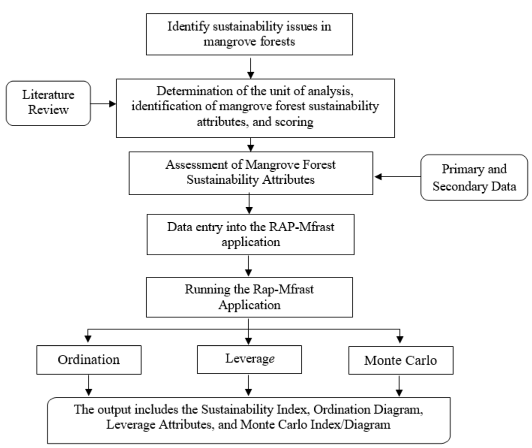

Fig. 2. Analytical framework for mangrove forest sustainability assessment using the RAP-MFRAST method

The RAP-MFRAST approach employs Multidimensional Scaling (MDS) to evaluate mangrove forest sustainability through six major steps:

1. **Identification of sustainability attributes** (ecological, economic, social, institutional) from literature, field observations, and secondary data.
2. **Scoring attributes** on a 0–4 ordinal scale.
3. **MDS ordination** to determine configuration, stress, and R^2 values.
4. **Computation of sustainability indices** for each dimension and overall status.
5. **Sensitivity analysis** through Root Mean Square (RMS) values to identify key attributes.
6. **Validation of results** using Monte Carlo simulations.

The resulting index values were categorized into four sustainability levels:

- **0.00–25.00** = Not sustainable
- **25.01–50.00** = Less sustainable
- **50.01–75.00** = Moderately sustainable
- **75.01–100.00** = Sustainable

These indices were presented visually using kite diagrams for each sustainability dimension **(Fauzi, 2019; Hidayah *et al.*, 2024)**.

2.2. Leverage analysis

Leverage analysis was applied to identify sensitive attributes that significantly influence the sustainability index. The RAP-MFRAST software calculates RMS values for each attribute, and variables with the highest RMS—or values greater than half of the maximum RMS—are categorized as leverage attributes. These represent the primary drivers for targeted intervention strategies **(Sabrina *et al.*, 2022)**.

As highlighted by **Yunus *et al.* (2023)**, leverage analysis strengthens the validity of the model, especially when combined with Monte Carlo testing. Identifying leverage attributes has been widely recognized as a pivotal step in guiding mangrove ecosystem restoration and adaptive management **(Damastuti *et al.*, 2022; Sabrina *et al.*, 2022)**.

2.3. Monte Carlo simulation

To account for uncertainty and test model reliability, the RAP-MFRAST framework integrates Monte Carlo analysis. This simulation considers potential variability due to scoring subjectivity, expert bias, missing data, and inconsistencies in inputs. The method compares MDS results with Monte Carlo outputs to establish confidence intervals.

A model is considered robust when the difference between MDS and Monte Carlo results is less than 5 points, which indicates >95% precision **(Fauzi & Anna, 2013; Fauzi, 2019)**. The reliability of this combined approach has been validated in previous studies. For instance, **Adiga *et al.* (2015)** demonstrated that RAPFISH-based frameworks are reliable for multidimensional sustainability assessments of coastal and fisheries systems, particularly when leverage and Monte Carlo techniques are applied simultaneously. This ensures statistically sound conclusions supported by strong R^2 values and low MDS stress scores.

RESULTS AND DISCUSSION

The sustainability attributes of the mangrove ecosystem in Luwuk Timur, Banggai Regency, were identified through an integration of literature review, Focus Group Discussions (FGDs), and stakeholder consultations. From this process, 29 key attributes were selected and categorized into four dimensions: ecological, economic, social, and institutional (Table 1).

Table 1. Sustainability attributes of each dimension

	Sustainability Dimension	**Sustainability Attributes**
1	Ecology	1. Land Use Zoning 2. Mangrove Seedling Availability 3. Coastal Abrasion 4. Fauna Diversity Mangrove 5. Mangrove Canopy Cover 6. Mangrove Density 7. Mangrove Rehabilitation 8. Land Pressure on Mangrove
2	Economy	1. Accessibility of Mangrove Areas 2. Welfare Level of Coastal Communities 3. Community Income Compared to Regional Minimum Wage 4. Alternative Sources of Income 5. CSR Financial Support 6. Government Budget for Mangrove Management 7. Community Use of Mangrove Resources
3	Social	1. Researchers Attention to Mangrove Issues 2. Mangrove Degradation by Local Cummunities 3. Local Wisdom 4. Conflicts Over Mangrove Resources 5. Community Participan in Mangrove 6. Community Education Level 7. Knowledge and Awareness of Mangroves
4	Institutional	1. Sanction Enforcement 2. Integration of Management Programsan 3. Legal Recognition of Mangrove Area 4. Involvement of Local Institutional 5. Participation of Field Officers 6. Community Compliance with Regulations 7. Availability of Formal Regulatory Framework

Modified from **Pitcher and Preikshot (2001)** and **Yunus *et al.* (2023)**.

The ecological dimension relates to biophysical conditions and includes indicators such as vegetation cover, environmental stress, and ecosystem functioning. The economic dimension reflects the role of mangroves in supporting community livelihoods, including income generation for local communities and financial support from government and private sectors. The social dimension emphasizes public awareness, participation, and conflict over resource use. Finally, the institutional dimension refers to the enforcement of policies, inter-agency coordination, and the presence of local governance structures.

These attributes form the analytical basis of the RAP-MFRAST assessment. Data were quantitatively analyzed using Multidimensional Scaling (MDS) and statistically validated with Monte Carlo simulation. This framework enables a comprehensive and multidimensional evaluation of mangrove sustainability while also identifying leverage points for targeted policy interventions to strengthen resilient, community-based management in eastern Indonesia.

1. Sustainability status of mangrove ecosystems: Ecological dimension

The RAP-MFRAST ordination analysis produced a Sustainability Index of 71.29 for the ecological dimension, placing it in the *moderately sustainable* category (range: 50.01–75.00). This suggests that the mangrove ecosystems in Luwuk Timur Subdistrict still maintain substantial ecological resilience, supported by existing vegetation cover and biodiversity, but remain vulnerable to anthropogenic pressures (Fig. 3).

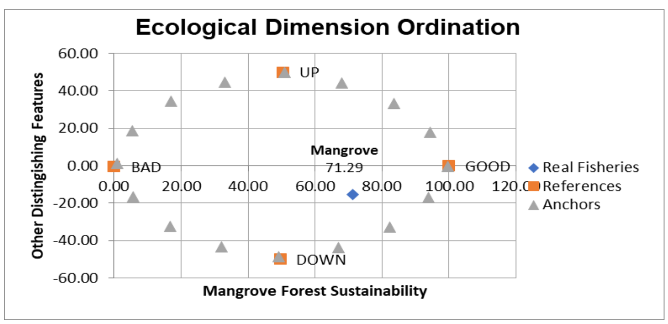

Fig. 3. MDS ordination chart of the ecology dimension of mangrove ecosystems

The ecological dimension forms the primary foundation of mangrove ecosystem sustainability, as it reflects the system's ability to maintain its structure, functions, and ecological services. In Uwedikan and Hunduhon villages, abandoned traditional shrimp ponds have exhibited natural succession, with spontaneous mangrove regrowth occurring without human intervention. This recovery process demonstrates that ecological resilience remains active when anthropogenic pressures are reduced. As highlighted by **Alongi (2018)**, natural regeneration is a critical indicator of ecological robustness.

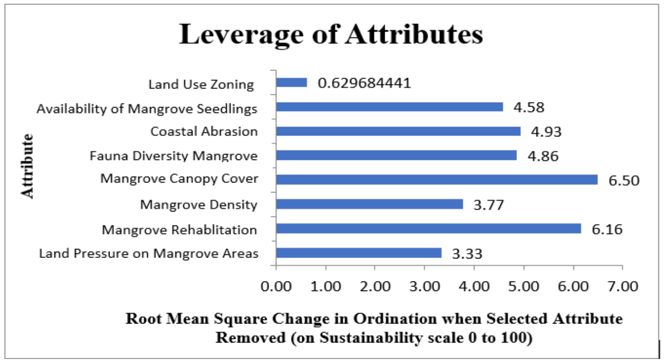

Fig. 4. Analysis results of sustainability leverage attributes for ecology dimension

Leverage analysis of the eight ecological attributes identified seven with the highest Root Mean Square (RMS) values, indicating their significant influence on sustainability status (Fig. 3). These sensitive attributes were: mangrove cover (6.50), mangrove rehabilitation (6.15), coastal abrasion (4.93), faunal diversity (4.86), availability of mangrove seedlings (4.58), vegetation density (3.77), and land pressure (3.33).

Among these, mangrove cover and rehabilitation efforts were the most sensitive, highlighting both the spatial integrity of mangrove vegetation and the importance of active restoration interventions. In Luwuk Timur, back-mangrove zones near settlements are generally degraded, while middle and front zones dominated by *Rhizophora* and *Avicennia* species remain relatively intact. Rehabilitation should therefore prioritize the degraded back zones. **Bengen (2013)** emphasized that changes in mangrove cover are strongly associated with uncoordinated land-use policies, which are evident in Luwuk Timur due to aquaculture expansion and industrial coastal development. Recommended interventions include:

- Regular monitoring of mangrove cover through satellite imagery and field surveys,
- Participatory rehabilitation using local species, and
- Regulatory protection of critical mangrove areas.

Coastal abrasion also emerged as a sensitive attribute, underscoring the importance of strengthening green belts. **Dahuri *et al.* (2001)** noted that abrasion intensifies in coastal areas lacking natural buffer zones. Establishing and maintaining coastal buffers is thus essential for long-term sustainability.

Faunal diversity and seedling availability represent indicators of biodiversity quality and rehabilitation success. According to **Setyawan *et al.* (2002)**, biodiversity depends on habitat zoning and suitable vegetation composition. Suggested interventions include:

- Identifying and protecting key faunal and floral species,
- Training local community groups in seedling propagation, and
- Establishing low-cost hydroponic nurseries, as recommended by **Syakir *et al.* (2021)**.

Vegetation density and land pressure reflect the urgent need to manage land conversion and maintain vegetation quality. **Kalsum *et al.* (2022)** reported that pond construction and settlement expansion have significantly reduced natural mangrove cover in Luwuk Timur. Effective responses include:

- Regulating planting distances during rehabilitation, and
- Enforcing legal sanctions against illegal land conversion.

These findings are consistent with **Giri *et al.* (2011)**, who stressed that sustaining mangrove cover and supporting natural regeneration are critical for long-term ecosystem resilience. Furthermore, **Friess *et al.* (2020)** emphasized that effective restoration requires the use of local species, integration of eco-hydrological principles, and community involvement. Addressing the current limitation of seedling availability in Luwuk Timur requires active involvement from the KPH Balantak and the establishment of village-based nurseries.

The only attribute found to be non-sensitive was land-use zoning, with an RMS value below the significance threshold. This suggests that zoning regulations in the study area have been either ineffective or poorly implemented.

2. Sustainability status of mangrove ecosystems: Economic dimension

The RAP-MFRAST analysis of the economic dimension yielded a Sustainability Index of 50.46, placing it at the *moderately sustainable* level (range: 50.01–75.00). However, this value lies at the lower threshold of the category, indicating that the economic function of mangroves in the East Luwuk coastal area is still fragile and unstable. Without appropriate and sustainable policy interventions, the economic dimension is vulnerable to decline, which could push the system into a less sustainable category (Fig. 5).

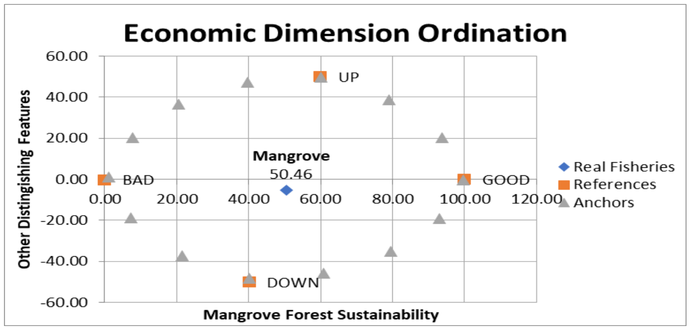

Fig. 5. MDS ordination chart of the economic dimension of mangrove ecosystems

Leverage analysis identified two attributes as the most sensitive in influencing the economic sustainability index: government budget for mangrove management (4.31) and accessibility of mangrove areas (2.21).

The limited allocation of government budget has structurally constrained the implementation of mangrove protection, rehabilitation, and sustainable utilization activities. This budget gap restricts patrol operations, ecotourism development, and community training programs related to conservation. **Yunus *et al.* (2023)** highlighted that inadequate funding often results in dependency on external assistance, such as NGOs or the private sector, while also reducing local community incentives for conservation participation.

Accessibility of mangrove areas also plays a critical role in economic sustainability. In locations such as Hunduhon Village (Station 2) and Uwedikan Village (Stations 3 and 4), improved coastal infrastructure has created relatively open access. While this facilitates utilization for fisheries and ecotourism, it simultaneously increases the risk of ecological degradation if not supported by zoning regulations and effective monitoring. **Fauzi and Anna (2013)** explained that accessibility exerts a double-edged effect: it can stimulate economic productivity, but it also opens pathways for uncontrolled exploitation when poorly regulated.

The economic potential of mangroves in Banggai Regency remains underutilized. **Putranto *et al.* (2018)** estimated the economic value of mangrove ecosystems at approximately IDR 62 million/ha/year, yet this potential has not been realized due to the absence of a clear zoning framework and conservation regulations, leading to resource conflicts and degradation. Similarly, **Kusmana (2014)** reported that villages in Java with high access to mangrove forests showed a stronger tendency toward land conversion and timber exploitation.

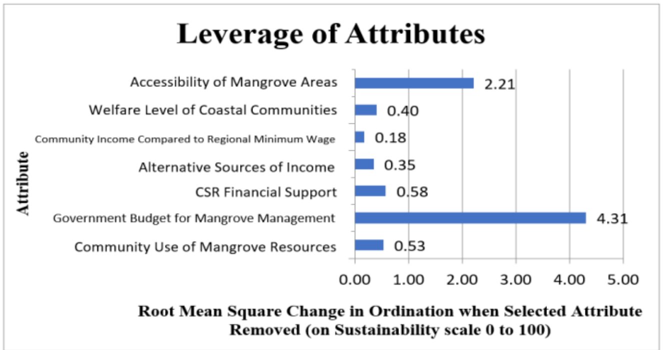

Fig. 6. Analysis results leveraging the economic dimension of sustainability attribute

To enhance the sustainability status of the economic dimension, several strategic interventions are recommended:

1. **Integration of mangrove management programs into regional development policies** through the *Anggaran Pendapatan dan Belanja Daerah* (APBD).

2. **Promotion of funding collaboration** with the private sector (CSR initiatives) and NGOs to support conservation and community-based activities.

3. **Provision of supporting infrastructure**, such as environmentally friendly footpaths, boardwalks, and observation towers, to facilitate ecotourism and education.

4. **Development of mangrove-based alternative livelihoods**, including ecotourism, mangrove crab (*Scylla* spp.) cultivation, and payment for ecosystem services (PES) schemes.

Primavera *et al.* (2012) emphasized that the long-term success of mangrove conservation depends largely on providing real economic incentives for coastal communities. In the East Luwuk study area, no such schemes currently exist, leaving mangrove forests vulnerable to pressures from land conversion and resource exploitation. Strengthening the economic aspect of sustainability therefore requires a collaborative approach, increased budget allocation, and carefully designed access regulations based on conservation zoning and sustainable utilization.

4. Sustainability status of mangrove ecosystems: Social dimension

The RAP-MFRAST analysis of the social dimension produced a Sustainability Index of 47.37, which falls within the *less sustainable* category (range: 25.01–50.00). This result indicates that the social dimension is the weakest among the four assessed (ecological, economic, social, and institutional). The finding reflects limited community engagement and weak social support for mangrove ecosystem sustainability efforts in the East Luwuk coastal area.

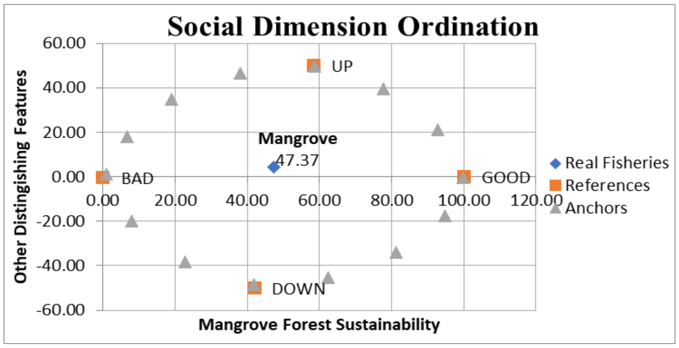

Fig. 7. MDS ordination chart of the social dimension of mangrove ecosystems

Leverage analysis identified two highly sensitive attributes influencing the social sustainability index: (1) community education level (RMS 5.60) and (2) conflicts over mangrove resources (RMS 4.29).

The education level of coastal communities in East Luwuk is predominantly at the elementary school level. This condition contributes to limited public understanding of the ecological functions of mangroves, weak awareness of conservation regulations, and reduced capacity to access training or information on sustainable management. **Rosyada *et al.* (2018)** noted that low levels of ecological knowledge often drive unsustainable mangrove exploitation. Similarly, **Mondal *et al.* (2021)** emphasized that ecological education plays a pivotal role in shaping pro-conservation behaviors. Recommended interventions include: (i) environmental education programs, (ii) locally based training, and (iii) integration of mangrove conservation into school curricula. Evidence from **Aghniyah *et al.* (2020)** in Central Sulawesi shows that communities participating in ecological training gained better understanding and were more actively involved in mangrove protection. Likewise, **Saru *et al.* (2019)** reported that mangrove education programs linked to ecotourism improved both awareness and participation in sustainable management.

Conflicts over mangrove resources also represent a major challenge. These disputes typically involve traditional fishers, farmers, companies, and government institutions, and often stem from the unauthorized conversion of mangroves into shrimp or milkfish ponds, as well as tree felling for fuelwood and construction by economically disadvantaged households. Such cases have been documented in several East Luwuk coastal villages, including land tenure disputes between local communities and private companies **(Kalsum & Sumardi, 2022)**. Overlapping institutional authorities and regulatory inconsistencies between government agencies further exacerbate the problem.

Rahmawaty (2006) argued that community-based management approaches can reduce conflict intensity among land users. Recommended interventions include: (i) establishing participatory mediation forums, (ii) strengthening local institutions, and (iii) drafting resource-use agreements grounded in customary law. **Walters *et al.* (2008)** also emphasized that long-term solutions to coastal conflicts require multi-stakeholder agreements and recognition of community governance rights.

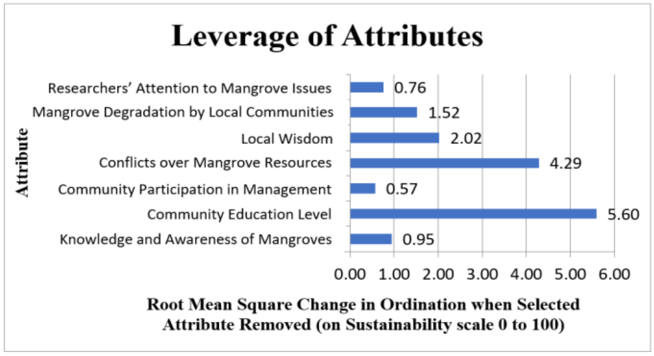

Fig. 8. Analysis results of the sustainability leverage attribute for the social dimension

Overall, the social dimension is a critical determinant in achieving mangrove ecosystem sustainability along the East Luwuk coast. Without strategic interventions aimed at enhancing community capacity and strengthening governance mechanisms for resource conflict resolution, the broader goal of sustainable mangrove management will remain difficult to realize.

5. Sustainability status of mangrove ecosystems: Institutional dimension

The **institutional dimension** plays a strategic role in supporting mangrove ecosystem sustainability, encompassing formal institutions, policy frameworks, regulatory instruments, and cross-sectoral implementation mechanisms. Analysis using the RAP-MFRAST approach across seven institutional attributes produced a Sustainability Index of 51.86, which falls into the *moderately sustainable* category (range: 50.01–75.00).

These results indicate that while institutional structures and policies for mangrove management are in place, their effectiveness, cross-institutional coordination, and integration with community participation remain limited. Strengthening these aspects is essential to ensure that institutional arrangements provide a robust foundation for long-term sustainability.

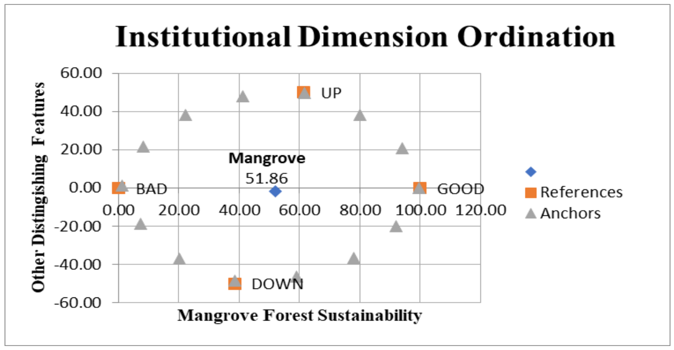

Fig. 9. MDS ordination chart of the institutional dimension of mangrove ecosystems

As noted by **Kalsum (2022)**, mangrove management in East Luwuk involves multiple actors across different administrative levels. At the central level, key institutions include BPDASHL Palu-Poso and BPKH Region XVI Palu. At the provincial level, the Forestry Service, Environmental Service (DLH), and the Marine and Fisheries Service of Central Sulawesi Province play important roles. At the district level, management responsibilities fall under the DLH Banggai, KPH Balantak, and the East Luwuk Subdistrict government. Finally, at the local level, actors include village governments, NGOs such as Japesda, the private sector, and universities. This multi-level governance structure highlights the complexity of mangrove management and underscores the need for strong cross-institutional coordination and policy synchronization to achieve holistic and effective ecosystem management.

An illustrative example comes from Uwedikan Village, where the local community, with support from the NGO Japesda, has proposed a Social Forestry scheme for mangrove management. This initiative demonstrates the potential to strengthen participatory, community-based institutions. However, sustained success requires stronger formal support from government institutions to ensure long-term program continuity and integration into broader conservation policies.

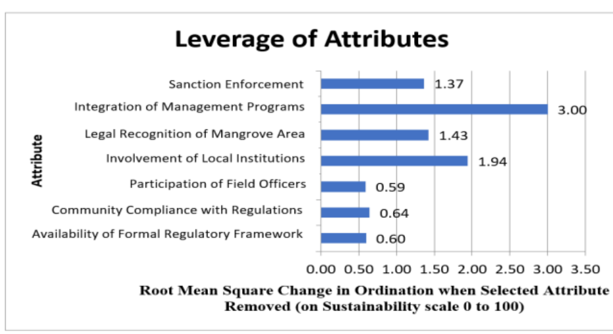

Fig. 10. Analysis results of leveraging the sustainability attributes of institutional dimension

Leverage analysis of the institutional dimension identified two of the most sensitive attributes: (1) integration of management programs (RMS = 3.00) and (2) involvement of local institutions (RMS = 1.94). These attributes are critical for building more coordinated and responsive governance systems.

The integration of management programs reflects the extent to which cross-sectoral institutions—such as the DLH, Fisheries Service, Village and District Governments—coordinate under a unified management framework. Field observations show that overlapping authorities and policy discontinuities between sectors remain a challenge. **Abdullah and Papea (2021)** noted that the Balantak KPH faces persistent coordination barriers between village, district, and provincial governments, leading to fragmented and ineffective conservation programs. Similarly, **Sabrina *et al.* (2021)** reported that weak communication between central and regional agencies, coupled with overlapping regulations, constitutes a major obstacle for mangrove management nationwide.

The involvement of local institutions also remains limited, undermining the effectiveness of monitoring and conservation initiatives. Local organizations such as the Forest Farmers Group, the Sustainable Mangrove Institute, and *Pokmaswas* in Uwedikan Village have begun contributing to conservation efforts, but they are not yet fully integrated into decision-making or policy evaluation processes. **Nainggolan *et al.* (2024)** observed that Indonesia's coastal management structures remain predominantly bureaucratic and disconnected from grassroots social networks. In contrast, **Hidayah *et al.* (2024)** highlighted that adaptive participation by local institutions has been pivotal for the success of mangrove rehabilitation programs. Similarly, **Luturkey *et al.* (2025)** found that community-based ecotourism groups in North Sulawesi strengthened both monitoring and education functions, thereby enhancing collective conservation awareness. Supporting this, **Clifton *et al.* (2010)** demonstrated in Maluku and Papua that customary-based monitoring and management systems significantly increased compliance with conservation rules.

To strengthen the institutional dimension in East Luwuk, strategies should prioritize:

- Improving cross-agency coordination,
- Strengthening local institutional capacity,
- Integrating management programs across government levels, and
- Establishing regulations that support community-based co-management.

Improvements in the institutional index will largely depend on clarifying authority structures, ensuring policy consistency, and empowering community initiatives in sustainable mangrove governance.

6. Multidimensional sustainability status of mangrove ecosystems

The multidimensional sustainability index of the mangrove ecosystem in Luwuk Timur was 55.49, placing it within the *moderately sustainable* category (range: 50.01–75.00). This indicates that overall mangrove management and ecosystem conditions are satisfactory but require further improvement—particularly in the social and institutional dimensions—to achieve optimal sustainability.

Among the four assessed dimensions, the ecological dimension scored the highest (71.29), reflecting relatively strong biophysical support. This was followed by the institutional dimension (52.86) and the economic dimension (50.46), both moderately sustainable. The social dimension, however, scored lowest at 47.37, placing it in the less sustainable category and underscoring the urgency of interventions targeting education, conflict resolution, and community participation.

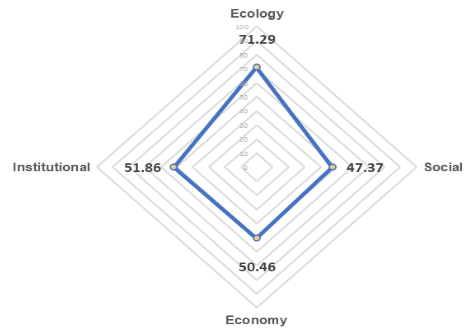

Fig. 11. Kite diagram illustrating the sustainability patterns across each dimension

The relatively high score in the ecological dimension reflects the presence of strong biophysical support, such as mangrove cover and biodiversity. However, the lower indices in the social and economic dimensions reveal limited community participation, low environmental awareness, financial constraints, and institutional challenges. Table (2) summarizes the sensitive leverage attributes that most influence the Sustainability Index for each dimension:

Table 2. Key leverage attributes for sustainability in each dimension

	Sustainability Dimension	Sustainability Attributes
1	Ecology	1. Mangrove Canopy Cover 2. Mangrove Rehabilitation 3. Coastal Abrasion 4. Fauna Diversity Mangrove 5. Mangrove Seedling Availability 6. Mangrove Density 7. Land Pressure on Mangrove
2	Economy	1. Government Budget for Mangrove Management 2. Accessibility of Mangrove Areas
3	Social	1. Community Education Level 2. Conflicts Over Mangrove Resources
4	Institutional	1. Integration of Management Programs 2. Involvement of Local Institutional

These leverage attributes represent critical intervention points that must be prioritized in strategic programs and policy planning. Strengthening social attributes, such as environmental education and resource-use conflict resolution, is essential to improving the sustainability of the mangrove ecosystem in Luwuk Timur. Likewise, enhancing program integration and institutional participation is consistent with the findings of **Friess *et al.* (2020)**, who emphasized that mangrove conservation efforts in Southeast Asia are frequently hindered by structural barriers, including poor inter-agency coordination, land-use conflicts, and inadequate incentive mechanisms. Taken together, these insights confirm that factors such as land pressure, program coherence, and community engagement are decisive in shaping local sustainability outcomes.

7. Validation of the RAP-MFRAST model with Monte Carlo simulation

Monte Carlo analysis was conducted to assess the reliability of the RAP-MFRAST model by testing the influence of data uncertainty and random errors on the results. According to **Fauzi (2019)**, the model can be considered statistically valid at the 95% confidence level if the difference between RAP-MFRAST and Monte Carlo outputs is less than 5%.

Table 3. Validation of RAP-MFRAST and Monte Carlo for each dimension

Dimension	**MDS**	**Monte Carlo**	**Difference**	**Stress**	**R2**	**Sustainability Status**
Ecologyi	71.29	68.977	2.313	0.14	0.95	Moderately Sustainable
Economy	50.46	49.995	0.465	0.14	0.94	Moderately Sustainable
Social	47.37	46.617	0.753	0.14	0.94	Less Sustainable
Institutional	52.86	51.649	1.210	0.15	0.94	Moderately Sustainable
Average	**55.495**					**Moderately Sustainable**

The average difference between MDS and Monte Carlo was 2.3%, which is below the 5% threshold, thereby validating the RAP-MFRAST model. Stress values for all dimensions were <0.15, while R^2 values exceeded 0.94, demonstrating high accuracy and a strong fit between the model and the data. **Kavanagh (2001)** suggested that stress values ≤0.20 are acceptable, and R^2 values approaching 1 indicate reliable data representation. This is consistent with **Kusmana in Khairuddin *et al.* (2016)** and **Melo *et al.* (2020)**, who noted that MDS results with stress <0.20 and R^2 near 1 are statistically valid and representative of original field data. These results confirm that the attributes selected in this study reliably reflect the real sustainability conditions of mangrove ecosystems in Luwuk Timur.

The multidimensional assessment further revealed that the social dimension is the weakest aspect of mangrove ecosystem sustainability in Luwuk Timur. This finding aligns with **Supriatna *et al.* (2021)**, who observed that inadequate integration of social and institutional factors often accelerates long-term resource degradation. Similarly, **Handayani *et al.* (2020)**, studying Sayung-Central Java, reported that social aspects frequently emerge as barriers to achieving mangrove resource sustainability.

Strengthening the social dimension through environmental education, active community involvement, and participatory conflict resolution is therefore an essential step toward sustainable coastal ecosystem management. Evidence from community-based management models demonstrates this potential: for example, **Christian (2021)** in Riau and **Damastuti *et al.* (2022)** in Central Java showed that empowering local institutional capacity fosters participatory governance and enhances long-term mangrove conservation outcomes.

CONCLUSION

This study found that the sustainability status of the mangrove ecosystem in the coastal area of Luwuk Timur is above fair, supported by a multidimensional sustainability index of 55.49. Of the four dimensions assessed using the RAP-MFRAST approach, the ecological dimension ranked the highest (71.29), reflecting a moderately high degree of ecological resilience. The institutional (52.86) and economic (50.46) dimensions also fell within the *moderately sustainable* category, although both were close to the minimum threshold. In contrast, the social dimension scored lowest (47.37), placing it in the *less sustainable* category and identifying it as the most critical area requiring immediate intervention.

Leverage analysis highlighted several sensitive attributes that exert strong influence on sustainability outcomes, including mangrove cover, land pressure, government funding, community education level, program integration, and community involvement. Validation through Monte Carlo simulation confirmed the robustness of the RAP-MFRAST model, with stress values <0.15 and $R^2 >0.94$, demonstrating high accuracy and consistency with field conditions.

Overall, the findings emphasize that while ecological resilience remains relatively strong, improvements in the social and institutional dimensions—through education, conflict resolution, cross-agency coordination, and participatory governance—are urgently needed to ensure the long-term sustainability of the East Luwuk mangrove ecosystem.

RECOMENDATIONS

Based on the leverage attributes identified, several strategic recommendations are proposed for the sustainable management of the East Luwuk mangrove ecosystem:

1. **Enhance ecological literacy and community education** by integrating mangrove conservation into local school curricula, engaging coastal youth in awareness programs, and providing participatory training for communities.
2. **Resolve conflicts over mangrove resource use** through participatory mapping, the establishment of multi-party mediation forums, and the recognition of local wisdom and community-based management rights.
3. **Strengthen inter-institutional coordination** by developing integrated management programs across government levels and identifying mangrove utilization zones using scientific data and evidence-based planning.
4. **Empower local organizations**, such as Forest Farmer Groups (KTH) and *Pokmaswas*, by improving access to funding, incentives, technical assistance, and institutional coaching.
5. **Optimize financial resources** by allocating budgets effectively and providing financial incentives for ecotourism development, payment for environmental services, and ecosystem restoration programs.
6. **Implement sustainable monitoring systems** supported by scientific research and community participation to ensure adaptive management and long-term ecological resilience.

A holistic and evidence-based implementation of these strategies would enable East Luwuk to become a model of community-driven mangrove management for Central Sulawesi and beyond. Given Indonesia's position as the country with the world's largest mangrove ecosystem, but also one of the most threatened due to land conversion, pollution, and unsustainable coastal development, such an approach is urgently needed. Effective mangrove management in Indonesia must therefore be sustainable, participatory, and science-based, balancing ecological conservation with community livelihood needs.

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