INTL J BONOROWO WETLANDS
Volume 15, Number 2, December 2025
Pages: 71-85

P-ISSN: 2775-8052
E-ISSN: 2775-8044
DOI: 10.13057/bonorowo/w150202

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

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[2]Department of Biology, Faculty of Science, Universiti Putra Malaysia. 43400 UPM Serdang, Selangor, Malaysia
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Manuscript received: 11 November 2024. Revision accepted: 24 July 2025.

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

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

INTRODUCTION

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

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

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

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

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

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

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

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

MATERIALS AND METHODS

Study area

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

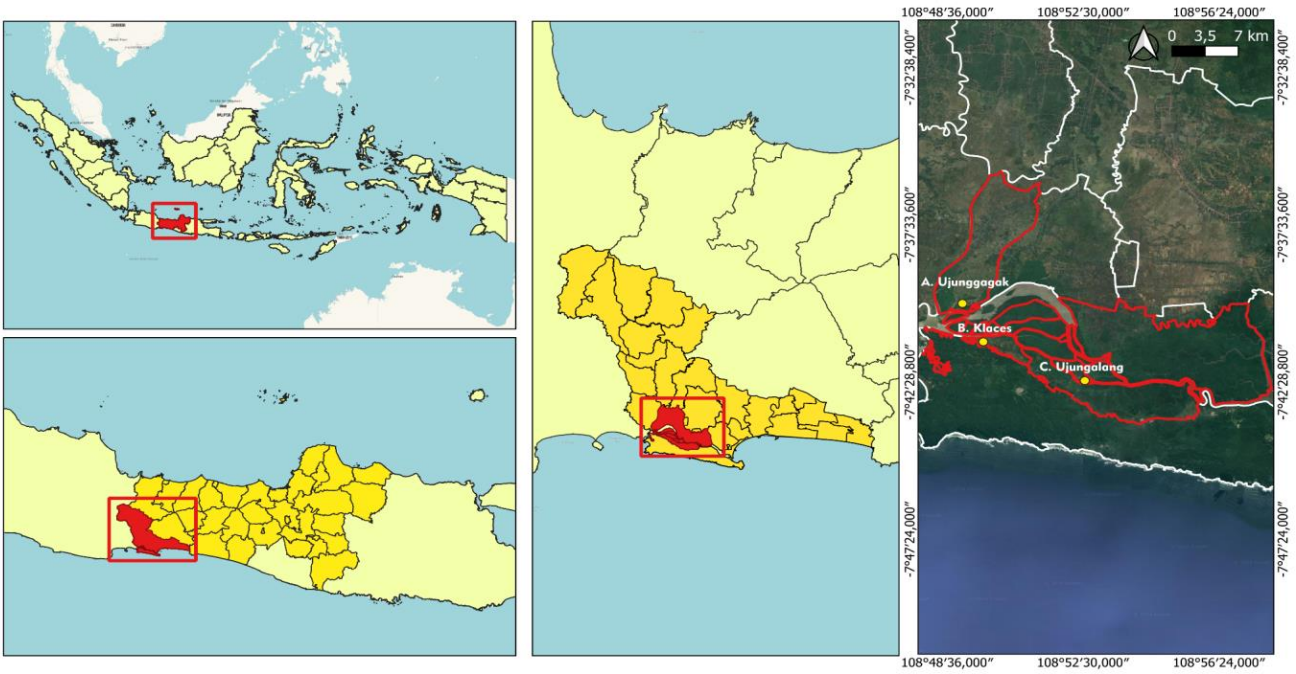

Figure 1. Map of study sites in Segara Anakan Lagoon, i.e. Ujunggagak, Klaces, and Ujungalang Villages, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia

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

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

Data collection

Community survey and questionnaire

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

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

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

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

Field observation and ecological measurements

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

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

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

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

Sustainability indicators and attributes

To evaluate the sustainability of mangrove ecosystems in Segara Anakan Lagoon, Kampung Laut, this study adopted a multidimensional framework comprising four key dimensions: ecological, economic, socio-cultural, and institutional. Each dimension was represented by five attributes, selected based on their contextual relevance, measurability, and alignment with local conditions. The

selection process was guided by national monitoring protocols and prior applications of the Rapfish method in coastal ecosystem assessments (Fadilah et al. 2021; Damastuti et al. 2022).

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

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

Table 1. Sustainability attributes and indicators per dimension

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

Data analysis

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

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

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

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

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

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

Leverage analysis

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

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

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

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

Monte Carlo simulation and model validation

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

In addition to Monte Carlo deviation, two statistical measures were used to assess model validity: the stress value and the coefficient of determination (R^2). A stress value below 0.25 indicates a satisfactory goodness-of-fit between input data and the ordination space (Sofian et al. 2019), while an R^2 above 0.90 demonstrates that the MDS

configuration captures the majority of variance in the dataset. These combined metrics ensured that the results generated were stable and suitable for further interpretation and policy application.

RESULTS AND DISCUSSION

Characteristics of respondents

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

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

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

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

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

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

Table 3. Community perceptions of mangrove benefits and threats

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

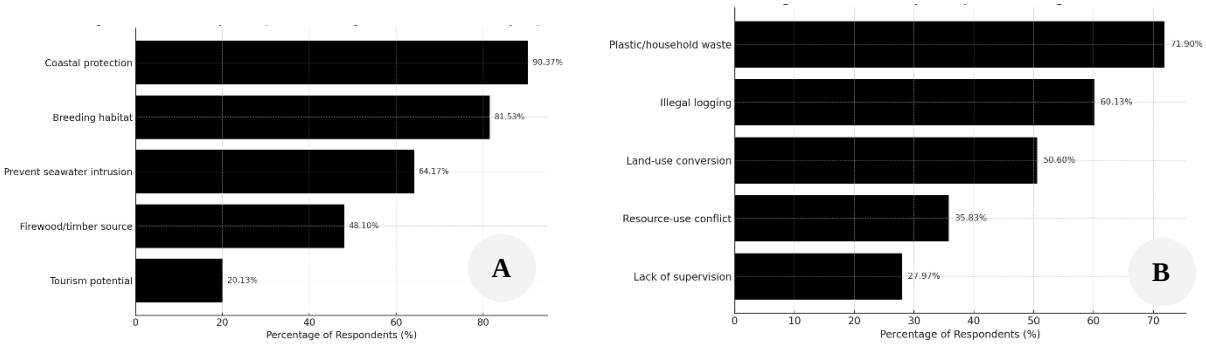

Figure 2. Community perceptions of mangrove ecosystem services and threats: A. Perceived benefits and B. Perceived threats

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

Ecological and environmental conditions

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

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

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

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

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

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

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

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

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

Sustainability index per dimension

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

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

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

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

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

Overall sustainability status

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

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

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

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

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

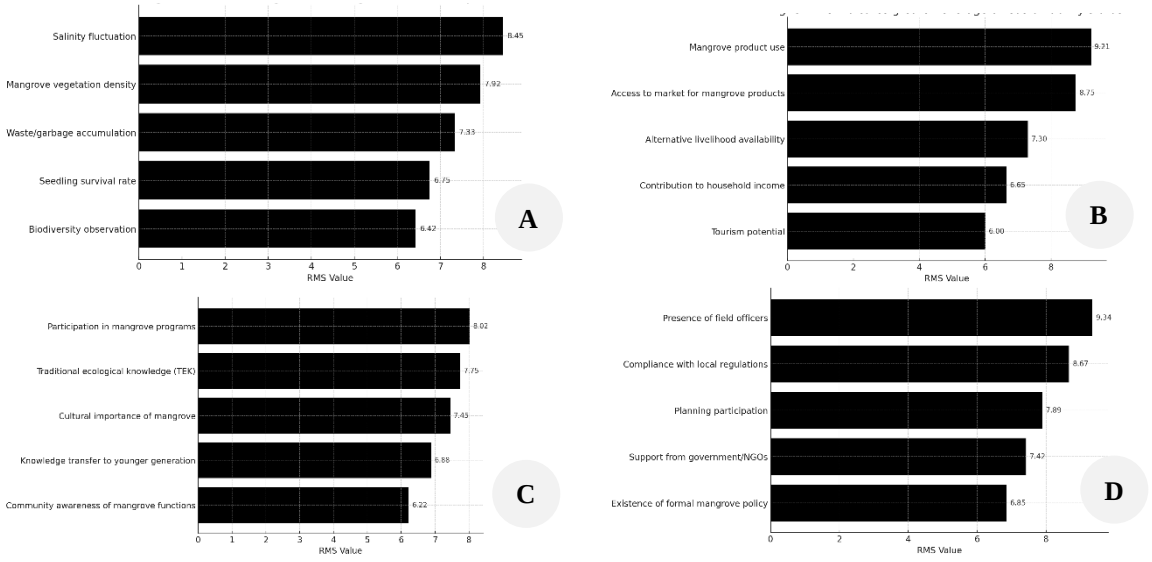

Figure 3. Root Mean Square (RMS) values of key sustainability attributes across four dimensions: A. Ecological, B. Economic, C. Socio-cultural, and D. Institutional

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

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

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

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

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

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

Sensitive attributes in each dimension

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

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

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

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

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

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

Table 7. Strategic leverage attributes per dimension

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

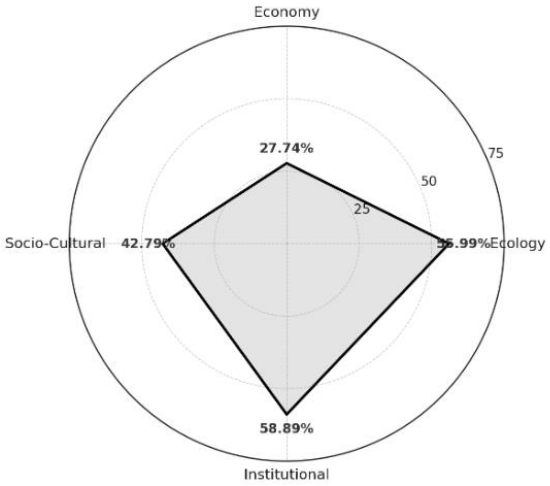

Figure 4. Kite diagram of multidimensional sustainability

Model robustness and validation

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

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

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

Discussion

Ecological dimensions of sustainability

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

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

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

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

Institutional support and governance effectiveness

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

Table 8. Monte Carlo validation results and model stress values

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

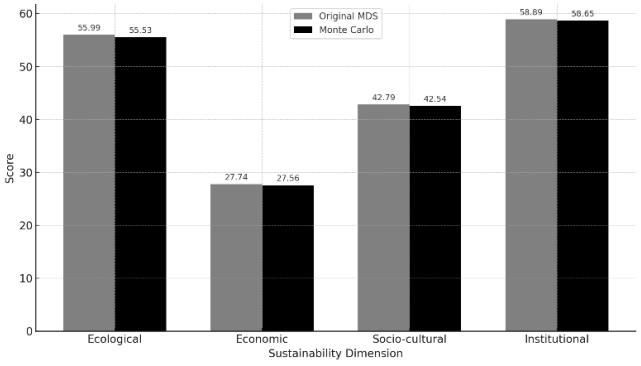

Figure 5. Monte Carlo vs. MDS score comparison

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

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

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

Economic vulnerability and resource dependency

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

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

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

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

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

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

Socio-cultural participation and environmental values

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

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

and social capital (Theresia et al. 2015; Koesdaryanto et al. 2024).

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

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

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

Strategic leverage points for sustainable intervention

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

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

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

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

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

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

Methodological robustness and applicability of Rapfish

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

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

One of Rapfish's key strengths is its flexibility to integrate multiple data types—from perception-based surveys to ecological observations—without requiring a high level of data standardization. This makes it highly suitable for data-limited coastal settings, where complex interdependencies between resource systems and social institutions often preclude purely quantitative modeling (Fadilah et al. 2021). In this study, Rapfish allowed for

rapid yet holistic diagnostics, enabling stakeholders to visualize trade-offs and prioritize interventions using the kite diagram and leverage plots.

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

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

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

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

ACKNOWLEDGMENTS

The authors express their sincere gratitude to the sub-district authorities of Kampung Laut, Indonesia and the heads of Ujunggagak, Klaces, and Ujungalang Villages for granting research permissions and providing valuable local insights. Special thanks are extended to the local community members who participated in the survey and shared their experiences, as well as to the boat operators and field guides who assisted in navigating the mangrove channels during data collection.

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