Original Article

Sustainability status of mangrove rehabilitation in Natuna Regency, Indonesia: A rapid appraisal using RAPFISH

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Abstract

Mangrove rehabilitation success is determined not only by biophysical recovery but also by social engagement, economic viability, and institutional governance. However, sustainability constraints in locally managed rehabilitation sites remain insufficiently characterized. The aim of this study was to evaluate the sustainability status of mangrove rehabilitation in Bandarsyah Village, Natuna Regency, Indonesia, and to identify key leverage attributes across ecological, social, economic, and institutional dimensions. A Rapid Appraisal for Fisheries approach using Multidimensional Scaling (RAPFISH–MDS) was applied across four sustainability dimensions. Data were derived from structured field observations, document review, and semi-structured interviews with key stakeholders, including local government officers, rehabilitation practitioners, and community representatives. Sustainability attributes were scored using a standardized rubric and analyzed using MDS. Leverage analysis identified sensitive attributes influencing sustainability, while Monte Carlo simulation assessed the robustness of ordination results. The findings revealed that the ecological (MDS score 72.02) and social (72.52) dimensions were classified as sustainable, suggesting favorable environmental conditions and relatively strong community engagement. In contrast, the economic (MDS score 49.79) and institutional (34.75) dimensions were less sustainable, indicating limited livelihood benefits, weak financing continuity, and constrained governance capacity. Leverage analysis identified mangrove density, community access, rehabilitation funding, and policies and planning as the most influential attributes. Monte Carlo analysis confirmed the stability of the ordination, with small deviations from MDS scores (2.52–4.24), low stress values (0.10–0.11), and high model fit (R^2=0.99). While mangrove rehabilitation in Bandarsyah Village is supported by ecological resilience and social participation, long-term sustainability is constrained by economic and institutional weaknesses. Strengthening financing mechanisms, operationalizing site-level planning, and improving governance enforcement are critical to sustaining rehabilitation outcomes in Natuna Regency.

Keywords: Mangrove, multidimensional scaling, rapid appraisal for mangroves, sustainability status, Natuna Regency

Introduction

Mangrove ecosystems rank among the most biologically productive environments, offering abundant natural resources and significant economic value [1,2]. Mangrove ecosystems deliver a wide array of essential services, including their critical role in stabilizing coastlines and mitigating

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erosion [3,4]. They are also recognized as significant carbon sinks, playing a key part in carbon storage and sequestration processes [5,6]. Additionally, mangroves serve as vital habitats, supporting diverse wildlife populations and sustaining commercially valuable species [7-10]. Beyond ecological functions, mangroves contribute to human well-being by supporting livelihoods through activities such as ecotourism, aqua silviculture, and the harvesting of forest products [11-13]. Based on Ramsar mangrove conservation strategies, their alignment with Sustainable Development Goal (SDG) 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) is highlighted through the development of socio-ecological indicators to address ecosystem threats and monitor SDG progress [14]. Thus, efforts to protect and rehabilitate mangrove habitats are crucial for preserving biodiversity and promoting its growth.

Like many other coastal areas in Indonesia, the mangrove ecosystem in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia has experienced significant stress and degradation. In general, the decline of mangrove ecosystems is primarily caused by human-related pressures, such as oil spills, industrial effluents, transformation of land for aquaculture and farming, and poorly managed dredging associated with coastal development [15-18]. Moreover, climate change exacerbates this loss through impacts like rising sea levels, shoreline erosion, increased frequency of severe storms and drought intensity [19-23]. If the quality of the mangrove ecosystem declines, it will negatively affect the productivity of marine and fisheries resources that rely on its existence.

A rehabilitation program has been implemented in Bandarsyah Village to address this issue. Mangrove ecosystem rehabilitation is a critical process for restoring the functions of degraded ecosystems, although it may not fully return them to their original condition [24-25]. These rehabilitation activities aim to restore the ecological functions of mangroves, repair damaged habitats, and recover lost environmental services due to ecosystem degradation [19,26,27]. In reality, efforts to rehabilitate the mangrove ecosystem face significant challenges [28]. One of the main obstacles is the low survival rate of planted mangroves [29]. The primary technical cause of planting failure is the mismatch between the chosen species and the site's conditions, such as salinity levels, soil characteristics, climate factors, and selective predation by herbivores [30-31]. Even though the institutional entities have initiated repeated rehabilitation efforts, they have yet to yield satisfactory results [32]. Despite the numerous activities undertaken to restore the damaged mangrove ecosystem, the persistently low success rate remains challenging for all stakeholders. This failure indicates that the methods and approaches used may be inappropriate or fail to fully account for the local conditions and dynamics of the ecosystem.

To assess the sustainability of mangrove rehabilitation, the present study employed the Multidimensional Scaling (MDS) in Rapid Appraisal of Fisheries (RAPFISH) approach, which utilizes a specific computational technique known as the MDS algorithm [33]. This method has been reported in various studies for assessing the sustainability of mangrove ecosystems. The MDS approach has also been applied in previous mangrove studies, such as in assessing the sustainability of ecosystem-based disaster risk reduction (Eco-DRR) in urbanized areas [34]. This approach has been applied in studies focusing on the sustainable renewable energy production of mangrove ecosystems [35] such as to assess the sustainability of business models based on ecological products [36], to analyze the sustainability of beach and mangrove tourism [37-38] and to evaluate the sustainability level of mangrove forest management [39-41].

Despite the wide application of RAPFISH in mangrove sustainability studies [35-41], previous work has not sufficiently clarified how sustainability constraints manifest in rehabilitation sites. In particular, the literature provides limited site-specific evidence on which leverage attributes should be prioritized to improve rehabilitation performance beyond replanting, especially for governance and financing conditions in locally managed settings. To address this gap, this Natuna (Bandarsyah Village) study delivers a baseline four-dimension sustainability diagnosis (ecological–social–economic–institutional) for a rehabilitation area situated in the other use area (APL) context with surrounding critical assets, and identifies the most sensitive leverage attributes to guide targeted interventions. This study aims to evaluate the sustainability level of mangrove rehabilitation efforts and identify the key contributing factors in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia. To operationalize the SDG framing, we link SDG 13–15 to measurable proxies already embedded in our indicator rubric, including stand structure and shoreline resilience as climate/coastal protection signals, sustainable access and use indicators as community–ecosystem interaction signals, and zoning, compliance, and planning indicators as governance signals. Its importance lies in the potential to contribute to environmental conservation while providing valuable insights into practical strategies for managing sustainability [42-43].

Methods

Study design, setting, and period

This study used a rapid appraisal design to assess the sustainability of mangrove rehabilitation using the RAPFISH-MDS framework (ecological, social, economic, and institutional dimensions). Primary data and secondary data were collected on August 2024. Bandarsyah Village, located in Bunguran Timur Subdistrict of Natuna Regency is one of six urban villages in the area (**Figure 1**). Covering an area of 1,411.43 ha, the village is home to a diverse range of professions among its residents, including government employees, traders, farmers, and fishermen. One of the village's natural assets is its mangrove ecosystem, which spans approximately 11 ha. These mangroves play a vital role for both the environment and the local community, as they not only provide habitat for various marine species but also serve as a natural barrier against coastal erosion and function as a natural filter for pollutants.

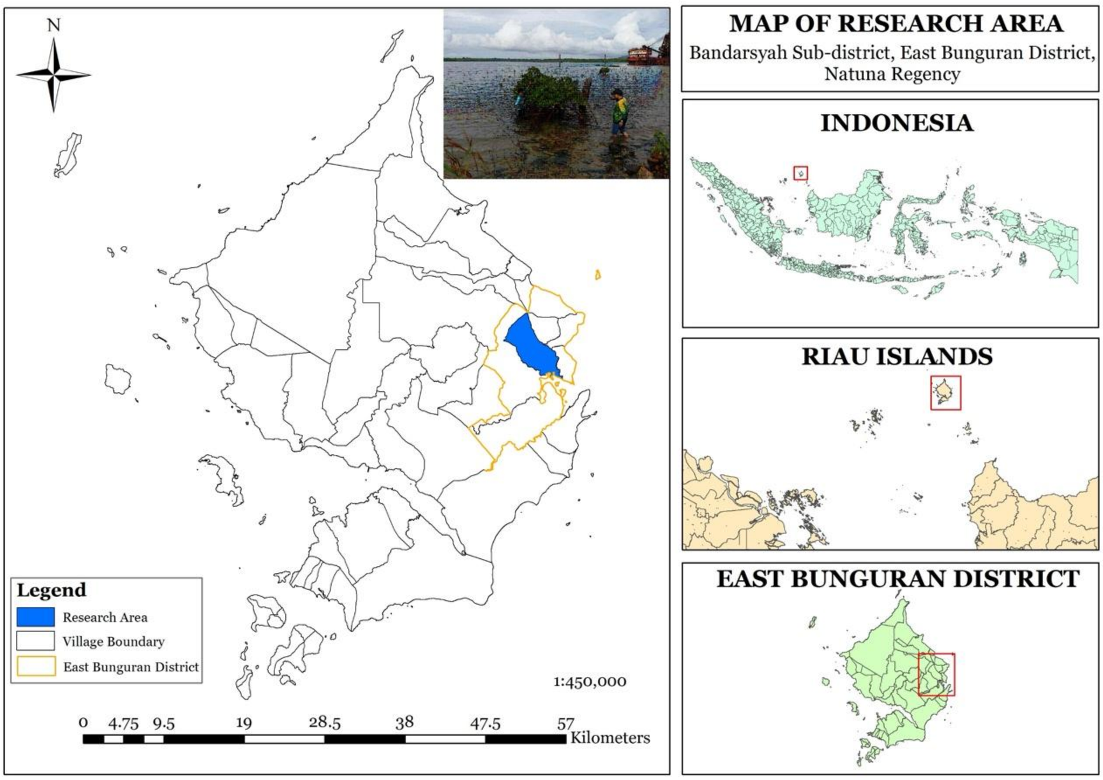

Figure 1. Location of the mangrove rehabilitation study site in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia.

The mangrove area in Pering of Bandarsyah Village is located within APL. APL is a land category that does not fall under the designation of protected forest, conservation forest, or production forest. This means the land does not have the same level of protection as other forest areas and can be used for various purposes such as agriculture, settlements, industry, and other commercial activities. Although this area falls under APL, which legally allows land utilization for purposes other than forest conservation, the ecological importance of the mangroves in Bandarsyah Village emphasizes the need for special protection. There are regulations and policies governing the utilization and protection of mangrove ecosystems within APL to prevent environmental degradation and maintain their ecological functions. Both central and local governments have established regulations that mandate mangrove conservation and rehabilitation efforts. These include prohibitions on illegal logging, environmental quality monitoring, and replanting programs aimed at preserving and restoring damaged ecosystems. Beyond ecological benefits, the mangroves in Pering also serve to protect vital surrounding areas, such as the historic Penagi Old Town and Raden Sadjad Airport. Mangroves help maintain coastal stability, which is essential for protecting heritage sites like Penagi Old Town, and they reduce the risk of damage that could affect the operations of the nearby airport.

Data collection

Respondents were selected using a purposive sampling strategy to identify information directly involved in mangrove rehabilitation and management, followed by snowball sampling to include additional stakeholders recommended by the initial informants. In total, 14 respondents (n=14) participated in the study. Respondents consisted of personnel from the Environmental Agency, the sub-district head, nursery/seedling staff, and members of the local tourism awareness group (*Pokdarwis*). Key informants were defined as individuals who (a) hold formal roles or operational responsibilities relevant to mangrove rehabilitation/management, or (b) possess direct knowledge and experience related to rehabilitation implementation, community use/access, program coordination, or local governance and planning. A summary of respondent characteristics is provided in **Table 1**.

Table 1. Respondent characteristics and stakeholder composition included in the study

Stakeholder group	Number	Role/relevance to study
Environmental Agency of Natuna Regency	10	Government staff relevant to mangrove/environment management and program implementation
Sub-district head of Bunguran Timur	1	Local governance/coordination and administrative oversight
Nursery/seedling staff	1	Operational knowledge on seedling supply/propagation and rehabilitation inputs
Pokdarwis (tourism awareness group)	2	Community perspective on mangrove use/access and local engagement/activities

The sustainability assessment of mangrove rehabilitation was conducted using a structured scoring system encompassing four main dimensions: ecology, social, economic, and institutional, as presented in **Table 2**. Each dimension consisted of multiple indicators with clearly defined criteria, scored on a scale from 0 to 3, where a score of 0 represents the worst condition and a score of 3 represents the best condition [3]. Ecological indicators included mangrove diversity, density, and cover; pressures from land-use change; temperature, pH, and salinity; tidal influence; rehabilitation area size; dominant vegetation; substrate type; seed availability for rehabilitation; land pressure; and resilience to abrasion. Data for these indicators were obtained through field surveys, direct measurements using instruments such as thermometers, pH meters, and refractometers, as well as satellite imagery, document reviews, and remote sensing.

Social indicators assessed community knowledge, education and training, access to mangrove areas, community-induced damage, awareness levels, roles in mangrove management, and resource utilization conflicts, with data gathered through structured interviews, community consultations, and field observations. Economic indicators covered community utilization of mangroves, availability of funding for rehabilitation, alternative livelihoods, recreational use, forest product utilization inventory, stakeholder involvement, and land-use zoning, drawing information from government records, community interviews, and tourism data. Institutional indicators examined the presence and implementation of policies and planning frameworks, the availability of regulations and roles of non-formal institutions, involvement of community-based organizations, coordination among stakeholders, availability of trained field personnel, and compliance with management regulations, assessed through document reviews, stakeholder interviews, and institutional data.

Table 2. Parameters for assessing the sustainability of mangrove rehabilitation used in the study

Indicator	Notes (score 0–3)	Data source	References
Ecology			
Mangrove diversity	No diversity (0); low diversity (1); moderate diversity (2); high diversity (3)	Field survey + document review	[34,44]
Mangrove density	Sparse (<1,000 trees/ha) (0); moderate (1,000–1,500 trees/ha) (1); dense (>1,500 trees/ha) (2); optimal (>2.000 trees/ha) (3)	Field survey + document review	[34,44-46]
Mangrove cover	Sparse (coverage <50%) (0); moderate (coverage 50–75%) (1); dense (coverage 75–90%) (2); very dense and ecologically stable (coverage >90%) (3)	Satellite imagery	[34,45-46]
Mangrove pressure (land use change)	Severe land conversion (0); natural area reduction (1); slight human-induced decrease (2); no decrease in area (3)	Time-series analysis (Google Earth Pro)	[34, 45]
Temperature	Poor (>35°C) (0); fair (33–35°C or 20–22°C) (1); good (30–32°C or 22–25°C) (2); optimal (26–29°C) (3)	Field instrument (thermometer)	[47]
pH	Poor (<5.5 or >8.5) (0); fair (5.5–6.0 or 8.0–8.5) (1); good (6.0–6.5 or 7.5–8.0) (2); optimal (6.5–7.5) (3)	Field instrument (pH meter)	[48]
Salinity	Poor (<5 or >40 ppt) (0); fair (5–15 ppt or 35–40 ppt) (1); good (15–25 ppt or 30–35 ppt) (2); optimal (25–30 ppt) (3)	Field instrument (refractometer)	[49]
Tidal influence	Poor (no tidal influence) (0); fair (rarely or constantly flooded) (1); good (semi-diurnal but unstable) (2); optimal (semi-diurnal, balanced cycles) (3)	Tidal app + field observation	[44]
Rehabilitation area size	Poor (<0.5 ha) (0); fair (0.5–1.0 ha) (1); good (1.0–2.0 ha) (2); optimal (>2.0 ha) (3)	Community interview	[34,45-46]
Dominant vegetation	Poor (no mangroves) (0); fair (non-native or poorly adapted species) (1); good (native but low regeneration) (2); optimal (Rhizophora spp. or fast-regenerating native species) (3)	Field vegetation inventory	[44]
Substrate Type	Poor (coarse sand or pure peat) (0); fair (sand-dominated) (1); good (mud-dominated or sandy mud) (2); optimal (silty-sand) (3)	Field sampling + manual texture test	[50]
Seeds availability for rehabilitation	No seed availability (0); limited seed availability (1); sufficient seeds (2); abundant natural seed stock (3)	Field observation + community interview	[34]
Land pressure (encroachment/conflict)	Severe land-use conflict (0); high encroachment (1); moderate pressure (2); no land-use conflict (3)	Community interview + document review	[34, 45]
Resilience to abrasion (erosion/accretion rate)	Critical erosion (0); severe erosion (1); moderate erosion (2); stable/accreting shoreline (3)	Field observation + remote sensing	[34,45-46]
Social			
Community knowledge	No knowledge (0); low awareness (1); moderate understanding (2); high literacy (3)	Interview	[34,46]
Education and training	No education/training (0); rare/unstructured training (1); occasional programs (2); frequent and structured capacity building (3)	Interview + institutional records	[34,46]
Community access to mangrove	Open and unregulated access (0); semi-regulated with conflicts (1); fully regulated and equitable access (2); transparent, inclusive, and enforceable access system (3)	Field observation + community interview	[34]
Community-induced mangrove damage	Severe anthropogenic damage (0); frequent but minor damage (1); occasional damage with mitigation (2); no community-induced damage (3)	Field observation + interview	[34,46]
Community awareness level	Completely unaware (0); low awareness (1); moderately informed (2); highly aware and proactive (3)	Community interview	[34,46]

Indicator	Notes (score 0–3)	Data source	References
Community roles in mangrove management	No involvement (0); nominal participation (1); partial participation (2); active co-management (3)	Interview + document review	[34]
Resource utilization conflicts	Severe and unresolved conflicts (0); occasional conflicts with resolution efforts (1); rare conflicts with effective resolution mechanisms (2); no conflicts (3)	Stakeholder interview	[34,46]
Economic			
Community utilization of mangrove	Over-exploited (0); partially regulated but unsustainable (1); mostly regulated with some sustainable practices (2); fully regulated and sustainable utilization (3)	Community + stakeholder interview	[34,46]
Funding for rehabilitation	No funding (0); very limited and irregular funding (1); consistent and sufficient funding ensuring ongoing rehabilitation (2); long-term, multi-source, and well-managed funding (3)	Government records + interview	[34]
Alternative livelihoods	No alternative livelihoods (0); limited alternative income sources (1); some viable alternative sources of income (2); diverse and sustainable alternative livelihoods established (3)	Community interview	[34,46]
Recreational use	Unregulated tourism causing severe damage (0); partially regulated recreational activities (1); well-managed ecotourism with minimal ecological impact (2); sustainable ecotourism integrated with conservation efforts (3)	Field observation + tourism data	[34]
Forest product utilization inventory	No inventory and uncontrolled extraction (0); partial or outdated inventory (1); inventory exists but lacks enforcement (2); comprehensive and enforced inventory regulating sustainable use (3)	Document review + interview	[34,46]
Stakeholder involvement	No stakeholder involvement (0); minimal and sporadic coordination (1); regular stakeholder meetings with moderate coordination (2); active and collaborative multi-stakeholder involvement (3)	Interview + meeting documentation	[34,46]
Land use zoning	No zoning and severe land-use conflicts (0); zoning in place with occasional conflicts (1); clear zoning with effective enforcement and compliance (2), integrated zoning with participatory planning and conflict resolution mechanisms (3)	Government spatial plan + interview	[34]
Institutional			
Policies and planning	No policies/planning framework (0); policies exist but weak and not implemented (1); policies exist with partial implementation (2); strong policies with effective implementation and enforcement (3)	Government document review	[34,46]
Availability of regulations and roles of non-formal institutions	No regulations and non-formal institutions not involved (0); regulations exist but weak, non-formal institutions rarely involved (1); regulations exist with moderate enforcement, some involvement of non-formal institutions (2); comprehensive regulations with active roles of non-formal institutions (3)	Interview + document review	[34,46]
Involvement of community-based organization	No involvement (0); minimal involvement (1); moderate involvement (2); active participation in planning, implementation, and monitoring (3)	Interview	[34,46]
Coordination among stakeholders	No coordination among stakeholders (0); minimal and informal coordination (1); strong, structured coordination among most stakeholders (2); strong, structured, and active coordination among all stakeholders (3)	Stakeholder interview	[34,46]
Availability of field personnel	No field personnel available (0); very limited and untrained personnel (1); adequate personnel but insufficient capacity (2); sufficient, trained, and dedicated field personnel (3)	Interview + institutional data	[34]
Compliance with management regulations	Rampant violations, no enforcement (0); low compliance; violations are frequent; monitoring/enforcement is weak or irregular; sanctions rarely applied (1), Moderate compliance; most actors comply but violations still occur occasionally; monitoring/enforcement is periodic; sanctions may be applied inconsistently (2); high compliance with effective enforcement mechanisms (3)	Field observation + institutional data	[34,46]

The scoring system applied in this process ranges from 0 to 3, with 0 indicating the bad condition and 3 indicating the good condition. Scoring was conducted through a structured consensus meeting among the research team, using triangulated evidence from interviews, field observations, and documents. When initial opinions differed, the score was reconciled through evidence-based discussion and validated via focus group discussion (FGD) with key informants. The final score for each attribute was documented along with the justification to maintain transparency and reproducibility.

Data analysis

The sustainability of mangrove rehabilitation was assessed using the MDS method in a modification of the RAPFISH analysis framework developed by the Fisheries Centre at the University of British Columbia [51]. RAPFISH–MDS analysis is commonly conducted using either an Excel add-in or an R script. The Excel-based RAPFISH add-in is popular because it produces rich, transparent outputs: the entire index-building process is documented within the Excel worksheets. However, its main drawback is instability, it is highly dependent on the host Excel environment and can be disrupted by other add-ins/macros. This is critical because it often lacks proper debugging, so errors may go unnoticed and partially processed results can still be used. Another limitation is compatibility, the add-in typically runs only on 32-bit Excel, while most modern computers use 64-bit systems. An alternative is the R-script implementation of RAPFISH, which is generally faster and works on both 32-bit and 64-bit systems. However, it may provide less complete outputs (such as stress and R^2 are sometimes not reported).

In contrast to the two tools above, we used a Python-based application, Rapython, which produces outputs comparable to the Excel add-in while providing a simpler, GUI-driven workflow than R, allowing users to run analyses through structured data input without scripting. Rapython was performed using Python coding to conduct multidimensional analysis. This application was developed by Agung Budi Santoso. The MDS is commonly used to create indices from various dimensions, thereby enabling researchers to measure and classify multiple objects more easily [42]. The steps of the RAPFISH analysis using Python are shown in **Figure 2**. MDS standardization was performed using a fixed GOOD–BAD scoring direction, where higher scores indicate better conditions. Monte Carlo analysis was conducted using 100 iterations with 1% noise to assess the stability of the ordination.

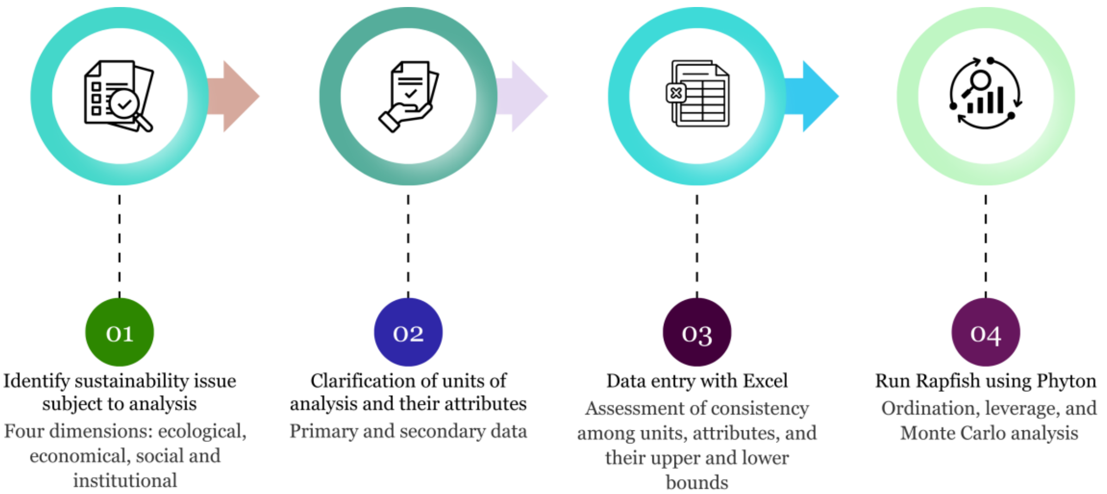

Figure 2. Workflow of the Rapid Appraisal of Fisheries (RAPFISH) analysis implemented in Python for evaluating the sustainability of mangrove rehabilitation used in this study.

The MDS is a multivariate technique designed to handle non-metric data. It is categorized as an ordination method applied within a reduced-dimensional space. Ordination, in this context, refers to a technique that represents objects as points distributed along axes, which are organized based on a defined order or relational structure, typically within a two-dimensional or multi-axis diagram. The process of ordination or distance measurement in MDS is formulated through the following equations [52-53]:

Euclidean distances:

$$d_{\{ij\}} = \sqrt{\{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2 + \ldots\}} \quad (1)$$

where $d_{(i,j)}$ is the distance between object i and object j.
Calculating the regression:

$$d_{ij} = \alpha + \beta\sigma_{ij} + \varepsilon \quad (2)$$

where a is the regression constant, β is the regression coefficient, and ε is the error term (the difference between observed and predicted distances).

In RAPFISH, regression is carried out using the alternating least square scaling (ALSCAL) algorithm, which works through repeated iterations to minimize error. This algorithm matches the squared distances (d_{ijk}) with the squared original data (O_{ijk}) across three dimensions (i, j, k). The difference between them is expressed in an equation known as S-stress.

$$\text{Strees} = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i \sum_j \left(d_{ijk}^2 - O_{ijk}^2\right)^2}{\sum_i \sum_j O_{ijk}^4}\right]} \quad (3)$$

After obtaining the ordination value, the next step is the leverage analysis and Monte Carlo analysis [33]. Leverage analysis is used to identify which attributes in each dimension most influence the sustainability index, shown by the root mean square (RMS) values. The higher the RMS, the more sensitive the attribute is to sustainability. The calculation follows a general equation.

$$\text{RMS} = \sqrt{\left[\frac{\sum_{i=1}^{n}\{Vf(i,1) - Vf(,1)\}^2}{n}\right]} \quad (4)$$

Monte Carlo analysis, using a scatter plot method, tests the reliability of each dimension's index value at a 95% confidence level. It helps evaluate how scoring errors, such as mistakes in procedure, misinterpretation of attributes, differences in judgment, data entry errors, missing data, or high stress values, affect sustainability results. The sustainability assessment results are shown in a radar diagram.

After defining the sustainability dimensions, 5–12 attributes are set for each, with scores ranging from 0 (bad) to 3 (good). The sustainability index ranges from 0 to 100 and is grouped into categories shown in **Figure 3**. Scoring the attributes gives an overview of each dimension's sustainability status.

Ethical consideration

This study involved human participants to obtain perceptions and institutional information related to mangrove rehabilitation. Participation was entirely voluntary, and verbal informed consent was obtained from all participants after providing an explanation of the study objectives, procedures, expected duration, and participants' rights, including the right to decline participation or withdraw at any time without consequences. No clinical procedures, biological sampling, or interventions were performed. The study collected non-sensitive information and did not record personal identifiers. All responses were anonymized, securely stored, and reported only in aggregated form. Because the research posed no more than minimal risk and involved anonymized, non-interventional data collection, the requirement for formal Institutional Review Board (IRB) or ethics committee review was waived through an administrative determination, in accordance with institutional policies governing low-risk social research.

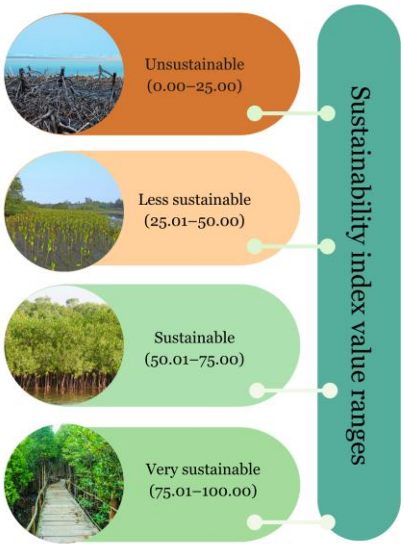

Figure 3. Interpretation categories for the Rapid Appraisal of Fisheries (RAPFISH) sustainability index (0–100) used in this study.

Results

Ordination analysis

The RAPFISH analysis results highlighted the sustainability of mangrove rehabilitation across four dimensions—ecological, economic, social, and institutional—based on the sustainability index ranges presented in **Figure 3**. According to these classifications, index values above 50 indicate "Good" or sustainable conditions, whereas values below 50 reflect "Down" or less sustainable status. In line with this scheme, the MDS scores show that the ecological (72.02) and social (72.52) dimensions fall within the "Good" quadrant (**Figure 4** and **Table 3**), indicating favorable biophysical conditions and strong community participation that jointly support the sustainability of rehabilitation efforts. By contrast, the economic dimension records an index of 49.79, placing it at the boundary between the "Bad/Down" and "Good" categories (**Figure 4** and **Table 3**), which suggests that the economic contributions generated by mangrove rehabilitation remain limited and have not yet translated into substantial improvements in local livelihoods. The institutional dimension has the lowest index value (34.75), clearly occupying the "Down" or less sustainable category (**Figure 4** and **Table 3**). The social and ecological dimensions are classified as sustainable, while the economic and institutional dimensions are categorized as less sustainable (**Figure 5**).

Sensitivity analysis

The factors that influenced the sustainability of mangrove rehabilitation across the four dimensions are presented in **Figure 6**. In the ecological dimension, the highest value was recorded for mangrove density (5.71), followed by mangrove diversity, mangrove cover, and mangrove pressure (each at 4.69), while other factors such as salinity (2.31), tidal influence (2.09), and land pressure (2.09) showed a moderate influence. In the economic dimension, funding for rehabilitation occupied the most dominant position with a value of 8.34, followed by recreational use, stakeholder involvement, and land use zoning (each at 2.47).

In the social dimension, community access to mangroves had the highest impact (7.19), followed by community knowledge (6.64), community awareness level (4.32), and community-induced mangrove damage (4.32). Meanwhile, in the institutional dimension, all factors were relatively low, with the highest value reaching only 0.14 for policies and planning and availability of regulations, while coordination among stakeholders and regulatory compliance were valued at only 0.07, indicating significant weaknesses in governance and institutional aspects in supporting mangrove rehabilitation (**Figure 6**).

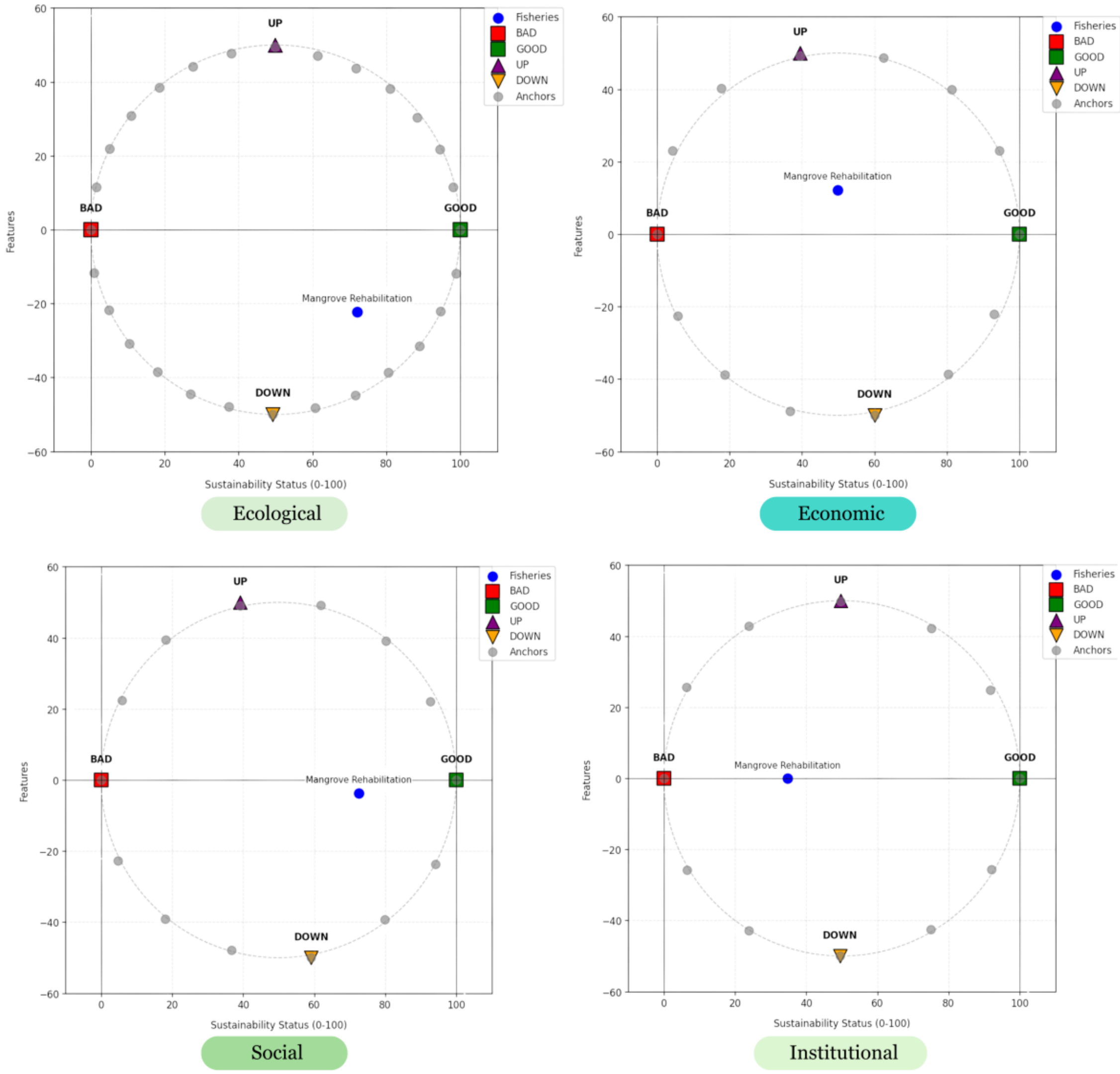

Figure 4. Ordination analysis on mangrove rehabilitation in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia.

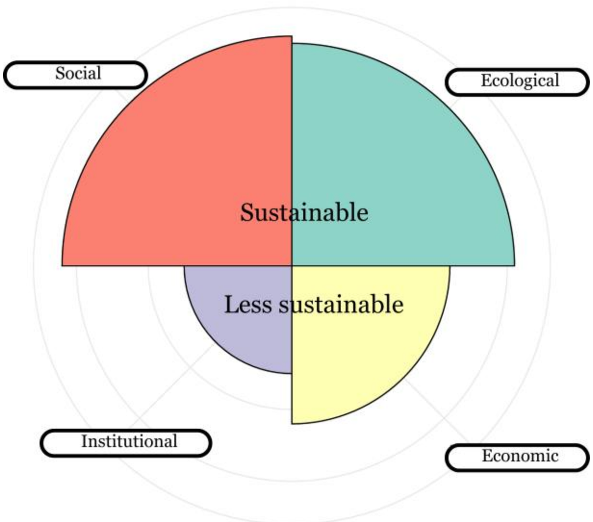

Figure 5. Radar graph of mangrove rehabilitation sustainability status in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia.

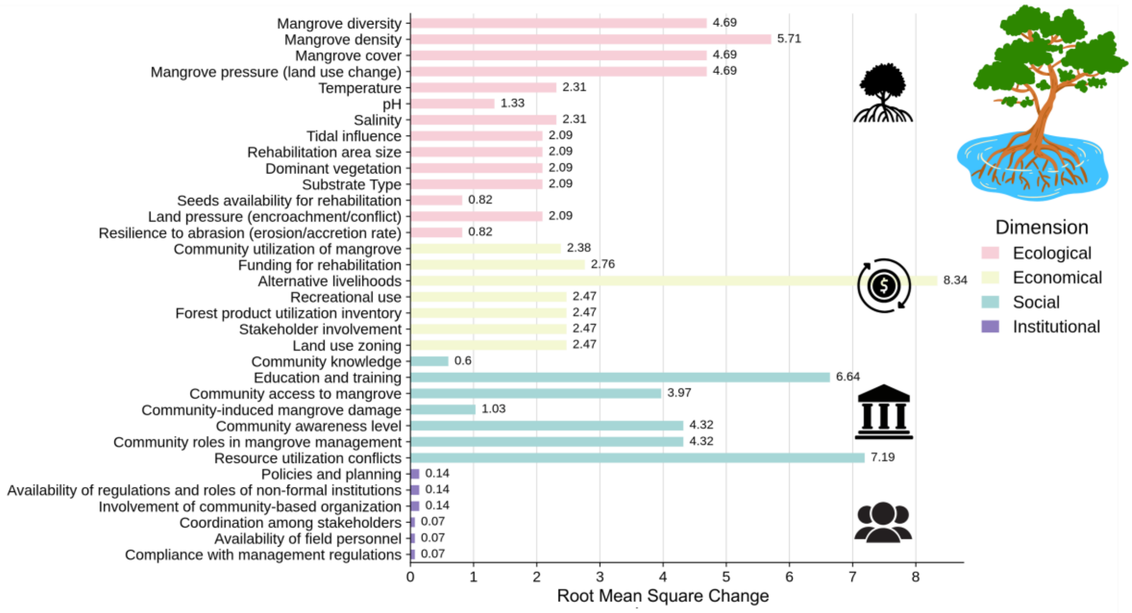

Figure 6. Leverage analysis on mangrove rehabilitation in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia.

Monte Carlo analysis

Based on the analysis results, no substantial differences were observed between the ordination (**Figure 4**) and the Monte Carlo analysis (**Figure 7**) across the four dimensions of mangrove rehabilitation sustainability. The ordination consistently indicated varying sustainability levels, with the ecological (72.02) and social (72.52) dimensions performing relatively well, the economic dimension (49.79) remaining at a marginal level, and the institutional dimension (34.75) recording the lowest sustainability status (**Table 3**). The Monte Carlo analysis showed a stable distribution of points around the main ordination positions, confirming that the overall pattern of sustainability scores was robust across all dimensions. Although some dimensions exhibited a slightly wider spread of points than others, this variation did not alter the ranking of sustainability levels among the ecological, economic, social, and institutional dimensions.

The Monte Carlo test showed only small differences compared with the MDS values, with deviations ranging from 2.52 to 4.24 (**Table 3**). These relatively low differences, together with low stress values (0.10–0.11) and a high coefficient of determination (R^2=0.99), indicate an excellent model fit and high reliability of the ordination results. Taken together, the ordination and Monte Carlo analyses confirm that the sustainability indices obtained for each dimension are statistically robust, stable under resampling, and thus suitable for informing management and policy decisions related to mangrove rehabilitation in Natuna Regency.

Table 3. Outcomes of Multidimensional Scaling (MDS) analysis and Monte Carlo test at the 95% confidence level

No	Dimension	Sustainability index				
		MDS	Monte Carlo	Difference	Stress	R^2
1	Ecological	72.02	67.77	4.24	0.11	0.99
2	Economic	49.79	46.77	3.01	0.11	0.99
3	Social	72.52	68.34	4.17	0.11	0.99
4	Institutional	34.75	32.22	2.52	0.10	0.99

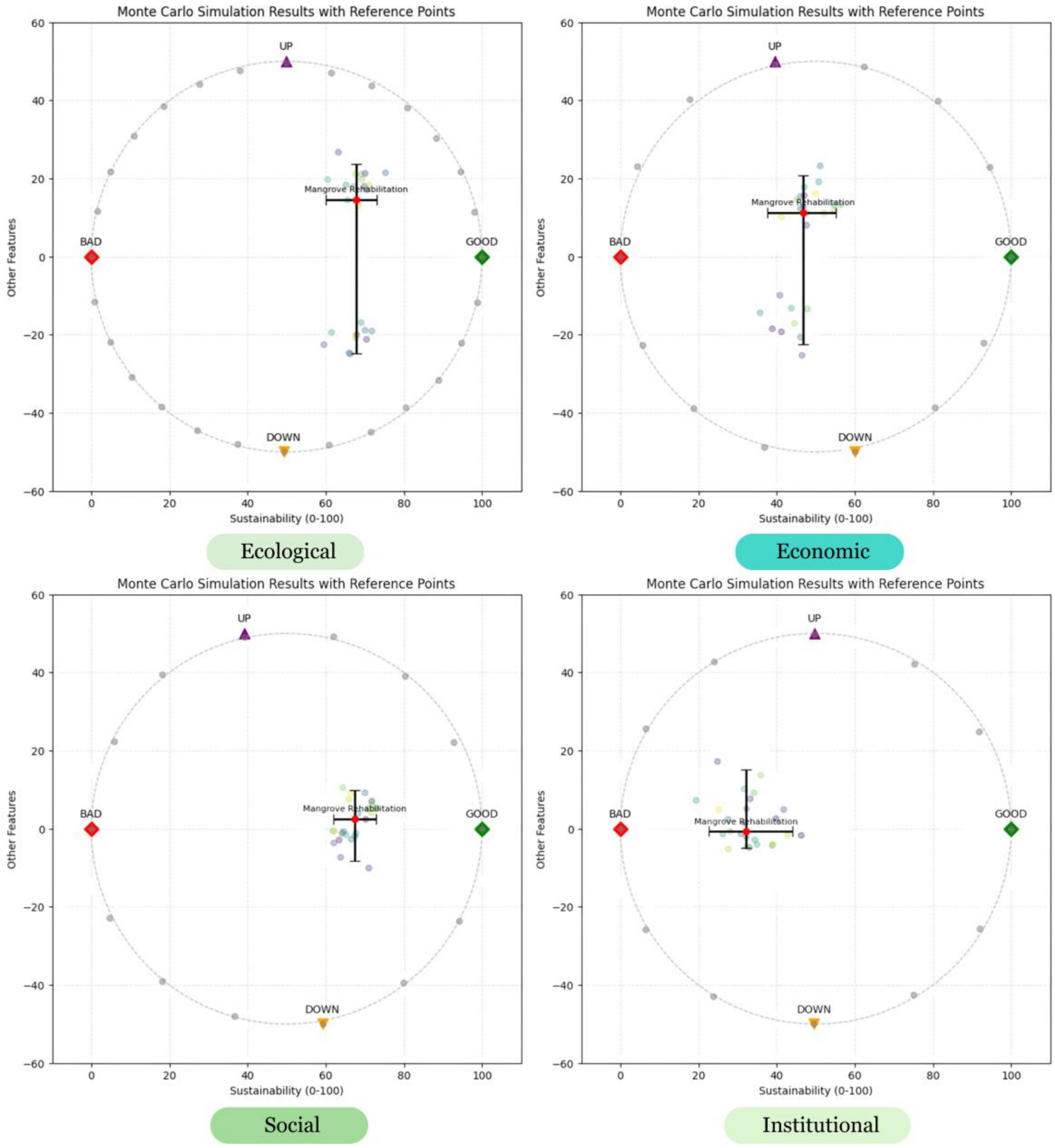

Figure 7. Monte Carlo analysis on mangrove rehabilitation in Bandarsyah Village, Natuna Regency, Riau Islands Province, Indonesia.

Discussion

Ecological dimension

Based on data from the mangrove rehabilitation management, the species diversity in the area was classified as low. Dominant vegetation refers to plant species that significantly prevail in a given area and strongly influence the surrounding ecosystem. It is typically characterized by the primary species with the highest population density, accompanied by supporting species that coexist within the habitat. These dominant species play a key role in shaping the ecosystem's physical, chemical, and biological characteristics, including growth patterns, nutrient cycling, and interspecific interactions. In this rehabilitation site, *Rhizophora spp*. constituted the dominant vegetation, widely distributed across the mangrove forest. The dominance of *Rhizophora spp*. in rehabilitation efforts is attributed to their high survival rates, adaptability to varying tidal regimes and substrate conditions, and effectiveness in stabilizing coastal zones [54]. These species are commonly utilized in mangrove rehabilitation and restoration programs, typically planted at 1 × 1 meter spacing, with costs varying depending on the site characteristics and planting methods employed [55]. Optimal growth and development of *Rhizophora spp*. seedlings in nursery conditions have been observed in a substrate mixture of 75% mud and 25% sand, with propagules inserted to one-quarter of their length [56]. Moreover, their establishment has been shown to temporarily modify the soil's physical and chemical properties, thereby creating more favorable conditions for the subsequent establishment and growth of *Rhizophora spp* [57].

The typology of mangrove cover refers to the structural and compositional variations in vegetation that characterize mangrove ecosystems within a given area. In the rehabilitation sites, two primary cover types had been identified: sparse mangroves and open land. Sparse mangroves are characterized by low canopy density, with significant gaps between individual trees that permit substantial light penetration to the forest floor. These stands are commonly found in sheltered coastal zones, lagoons, and estuarine environments subject to tidal influence, where salt-tolerant mangrove species can establish. The reduced canopy cover and tree density, however, may indicate ecosystem stress or degradation resulting from both natural and anthropogenic factors. In contrast, open land comprises areas devoid of vegetative cover, whether of natural origin or due to human activities. Such areas are typically located along coastlines or estuarine zones and often arise from land conversion for infrastructure development, aquaculture, or are the product of natural erosion processes. From an ecological restoration perspective, open land represents a high-priority target for mangrove reforestation efforts aimed at re-establishing critical ecosystem services, such as shoreline stabilization, habitat provision, and carbon sequestration. However, mangrove density in the area was very low, classified as sparse (<1,000 trees/ha). Maintaining a balance of tree density, ecological complexity, and species diversity is essential for boosting carbon sequestration and promoting healthier mangrove ecosystems in rehabilitation action [58].

In this mangrove rehabilitation area, there were two main types of substrates: sandy mud and muddy sand. Sandy mud is a substrate dominated by fine silt particles with a small proportion of sand, whereas muddy sand consists primarily of sand particles with a minor mixture of silt. Ecologically, sandy mud substrates are more favorable for sustaining mangrove ecosystems due to their higher capacity to retain nutrients and moisture. In contrast, areas with muddy sand require special attention in rehabilitation efforts, such as adding a layer of silt to improve soil moisture and enhance substrate stability. Mangroves can thrive in pure mud substrates and can tolerate sandy-mud substrates [59].

Salinity levels can influence seawater density, ocean current patterns, marine ecosystems, and various biophysical processes occurring in coastal areas. Salinity is affected by factors such as freshwater input, rainfall, seasonal variation, topography, tidal cycles, evaporation, and river mouth discharge. In the rehabilitation area, the mean salinity was recorded at 32.43 ppt. This indicates that the water conditions in the mangrove rehabilitation zone are relatively normal and conducive to supporting a natural environment for most mangrove species. Salinity strongly influences nitrogen cycling in mangrove sediments, reducing denitrification and altering nitrifier and denitrifies microbial communities [60]. Rising salinity reduces mangrove growth, diversity, and nutrient availability, favoring salt-tolerant species while diminishing overall forest productivity and carbon storage [61]. In high-salinity areas, large trees grow less, so smaller trees contribute more to the forest's growth [62]. Salinity suppresses mangrove seedling growth and survival, while low salinity supports early growth and moderate salinity favors better performance after 15–20 weeks [63].

In the Pering mangrove rehabilitation area, no significant coastal abrasion or accretion has been observed. This stability can be attributed to several factors. The coastline remains relatively stable, with minimal erosion from wave action, likely due to the presence of mangroves in certain areas which, although sparse, still function as natural wave barriers. The complex root systems of mangroves help anchor the soil and prevent erosion, providing protection where mangroves have been rehabilitated or occur naturally [64]. The absence of accretion indicates that there is no substantial sediment deposition along the shoreline, which may result from limited sediment supply from rivers or surrounding land, or from ocean current patterns that do not favor sediment accumulation. While accretion is absent, the lack of excessive sedimentation also suggests that the area is not subject to disturbances that could disrupt the mangrove ecosystem. Mangrove plantations enhance coastal protection by promoting sediment deposition through aboveground structures and stabilizing it with belowground roots, reducing erosion and supporting elevation gain [65]. Such stable conditions benefit mangrove rehabilitation programs, as the coastal ecosystem is not threatened by rapid shoreline changes.

The degree of acidity or pH is used to indicate the level of acidity or alkalinity in a body of water, and it has a significant impact on ecosystems, including mangrove ecosystems. In the mangrove rehabilitation area, the recorded average pH value was 6.68, which falls within an optimal range that supports healthy mangrove growth. According to Ruzanna *et al.* [66], stated that a pH with such a value is classified as very suitable for mangrove rehabilitation. A balanced pH is essential for supporting aquatic biota activities and the decomposition of organic matter, which in turn influences the availability of nutrients required by vegetation, including mangroves [67].

In mangrove rehabilitation areas, tidal influence plays a crucial role in shaping environmental conditions that support the growth and recovery of mangrove ecosystems. Tidal frequency refers to how often high and low tides occur within a day. In this site, the dominant tidal pattern was semi-diurnal, meaning there are two high tides and two low tides each day. Both high tides generally reach similar heights, while both low tides exhibit nearly the same low-water levels. A study reported that the tidal regime in Karimunjawa is mixed with a diurnal tendency, influencing groundwater distribution, sediment characteristics, and mangrove spatial patterns [68] while another study highlighted that higher mean sea level elevations exacerbate mangrove forest degradation [69].

Temperature in the mangrove rehabilitation area is a key environmental factor influencing mangrove growth and ecosystem health. While optimal temperatures vary by geographic location, mangroves generally thrive in tropical and subtropical regions where conditions remain warm year-round. In this rehabilitation site, water temperatures were relatively uniform, averaging 28.5°C and 29.1°C. These values indicate stable thermal conditions within the optimal range for mangrove development. Such warm temperatures support essential physiological processes, including photosynthesis, respiration, and enzyme activity, which are critical for mangrove growth. The stability of these temperatures provides a consistent environmental setting, allowing mangrove seedlings to establish and grow without significant stress from extreme temperature fluctuations. Mangrove wetlands are highly productive, carbon-rich ecosystems, with their canopy height and carbon stocks strongly influenced, including by temperature, with Indonesia holding about 25% of the estimated 5.03 Pg global mangrove carbon stock [70]. Ecologically, rising temperatures can accelerate physiological stress in seedlings, hinder the development of strong root systems [71]. In the long term, reduce the success of mangrove regeneration and expansion, thereby diminishing their coastal protection function [72].

The size of the rehabilitation site is a key parameter in determining the scale and scope of mangrove restoration activities. In this area, the rehabilitation extent was planned based on indicative location data and information obtained from local communities or area stakeholders. The site is divided into four distinct segments: Segment 1 covering 1.04 ha, Segment 2 covering 0.55 ha, Segment 3 covering 0.68 ha, and Segment 4 covering 1.01 ha, resulting in a total rehabilitation area of 3.28 ha. This segmentation facilitates more focused and efficient planning and implementation of rehabilitation efforts, taking into account the specific characteristics and conditions of each segment. Land pressure in the form of encroachment or conflict is absent, indicating that there are no land-use conflicts in the rehabilitation area. However, there are challenges related to mangrove pressure caused by land use change, particularly in the form of natural area reduction.

Economic dimension

A systematic inventory of mangrove forest products is essential to guide sustainable use and inform management decisions. This inventory should document both timber and non-timber products, their seasonal availability, harvesting methods, and market values. In mangrove rehabilitation areas, such data are currently limited, which hampers the ability to set sustainable harvest levels. Establishing a regular inventory system would provide a scientific basis for regulating extraction and preventing overexploitation. Providing alternative livelihoods can reduce community dependence on extractive mangrove resource use [73]. The potential alternatives include ecotourism [12, 74-75], aquaculture integrated with mangrove conservation (silvofishery) [76-78], and value-added processing of marine/mangrove products [13]. The successful introduction of these options requires comprehensive capacity-building, initial capital investment, and the establishment of reliable market linkages to ensure economic viability [79]. When effectively implemented, such initiatives not only diversify income sources but also strengthen community support for conservation objectives. For example, eco-tourism, when accompanied by appropriately regulated recreational activities, offers a dual benefit of generating revenue while promoting environmental education and awareness, thereby aligning livelihood development with mangrove ecosystem protection [80].

Sufficient and continuous funding is a key factor in the success of mangrove rehabilitation programs. According to Camacho *et al.* [81], rehabilitation efforts are more effective when guided by an integrated, ecosystem-based approach that accounts for interactions between restoration activities and local economic practices. In mangrove rehabilitation areas, funding had primarily come from government programs, donor agencies, and limited private sector contributions. While initial planting efforts often receive adequate financial support, long-term maintenance and monitoring are less consistently funded, resulting in lower survival rates of planted seedlings. This supports the view of Pham *et al.* [82] that sustainable mangrove conservation requires steady incentives, good governance, fair community involvement, and clear land-use planning to address conflicts with aquaculture. Given that mangrove rehabilitation is a long-term program, innovative strategies are needed to address funding limitations. For example, on Carey Island, Malaysia, an ecofriendly rehabilitation project used a submerged breakwater to reduce wave energy, trap sediments, and create favorable conditions for mangrove regrowth [83].

In mangrove ecosystems, zoning can designate core conservation zones, sustainable use areas, and buffer zones to protect against external pressures. According to Campbell *et al.* [84], zoning in mangrove ecosystems organizes areas for conservation, sustainable use, and buffering to balance habitat protection with community needs and reduce land-use conflicts. In this study area, formal zoning for mangrove areas was not yet fully established, leading to potential overlaps between conservation and development interests. Implementing zoning supported by legal frameworks and community agreements can reduce land-use conflicts and safeguard critical habitats [43]. A similar finding was also reported by another study [85], for example, zoning distinguishes buffer zones that allow mixed forestry and aquaculture from full protection zones that prioritize strict conservation to balance ecological protection and community livelihoods in Vietnam.

Social dimension

The level of community knowledge regarding mangroves is a critical determinant in the long-term success of rehabilitation initiatives. In the rehabilitation location, although there was general awareness of the existence and benefits of mangroves, the depth of ecological understanding, particularly concerning their roles in shoreline stabilization, carbon sequestration, and biodiversity support, remains moderate and varies among community members. Such disparities in knowledge can affect both the extent of community participation and the overall effectiveness of conservation interventions. However, understanding of the broader ecosystem services provided by mangroves, such as carbon sequestration, climate regulation, and habitat provision for diverse species, remains limited. Insufficient awareness initiatives result in limited information reaching the local community, which directly reduces their participation in mangrove management [86]. In addition, educational initiatives and hands-on training are crucial for equipping communities with both theoretical understanding and practical skills for management [87].

In the studied area, formal training opportunities remain limited, with most learning occurring through informal, experience-based knowledge transfer. Expanding structured programs, covering topics like species selection, planting techniques, monitoring methods, and adaptive management, can enhance local capacity for independent and sustainable [88]. In mangrove management, education serves not only as a driving force but also as a key foundation for preserving ecosystems and addressing the challenges they face [89]. Community involvement in rehabilitation projects is significant but sometimes limited to the initial planting phase, with less participation in long-term monitoring and adaptive management. Expanding roles to include decision-making, surveillance, and benefit-sharing mechanisms can strengthen local ownership and sustainability of conservation outcomes.

Controlled community access to mangrove areas is necessary to balance livelihood needs with conservation goals. The access was generally unrestricted, allowing residents to use mangroves for fishing, harvesting forest products, or recreation. While this access supports socio-economic activities, it also required regulation to prevent overuse and habitat degradation. Zoning systems or seasonal restrictions may help ensure ecological integrity while maintaining community benefits. Human activities, such as wood harvesting, land conversion for aquaculture, and waste disposal, can negatively impact mangrove health. In the mangrove rehabilitation area, community-induced damage appeared relatively low compared to heavily urbanized coasts, but occasional clearing and resource extraction had been noted. Resource use conflicts can arise when different stakeholders compete for mangrove or coastal resources, for instance, between conservation priorities and aquaculture or development interests. In this case, no major land-use conflicts were recorded, which is a positive foundation for collaborative management. Even if conflicts arise, resolving them through a heavy-handed approach is not recommended, as such methods often exacerbate or prolong disputes between management authorities and local communities [29]. According to Feti *et al.* [90], a strategic approach to minimizing conflict is the adoption of co-management, which focuses on fostering alignment and creating harmonious collaboration. Nonetheless, early conflict prevention strategies, such as stakeholder mapping, participatory planning, and transparent benefit-sharing, are advisable to maintain this harmony as development pressures grow.

Institutional dimension

The existence of clear policies and strategic planning is fundamental to the effectiveness of mangrove rehabilitation and management. The rehabilitation initiatives have generally aligned with national and regional coastal management policies; however, the absence of a detailed, locally tailored mangrove management plan limits the precision of interventions [91]. According to Purwanti *et al.* [92], strengthening ties between local governments and community monitoring groups can improve the enforcement of sanctions against those who damage or misuse mangrove land, creating a stronger deterrent effect. Complex social and economic conditions in mangrove areas, combined with unclear authority boundaries, have led to overlapping laws and responsibilities among governing institutions [93]. The suboptimal condition of mangrove rehabilitation is caused by poor communication, conflicting policies among institutional stakeholders [94]. This variation arises from the diverse perspectives and interests held by stakeholders involved in mangrove management [95]. Furthermore, the failure of governance systems in mangrove management may be due to the lack of application of the principles of legitimacy, fairness, and integration [96]. Integrating mangrove policies with actions is key to protecting the ecosystem and supporting the communities that depend on it [97].

Although policies and planning showed the highest leverage in the institutional dimension (0.14), the overall institutional index remains low, indicating that institutional conditions are uniformly weak and therefore do not operate effectively as a lever. This pattern suggests an implementation-capacity constraint, where policies/plans may exist but are not translated into consistent field-level action. In the study site, institutional performance is particularly limited by insufficient dedicated field personnel and weak routine monitoring, which reduces the frequency and quality of patrols, compliance checks, maintenance scheduling, and documentation of violations. As a result, access rules and rehabilitation protocols are applied inconsistently, follow-up actions are delayed, and coordination tends to be ad hoc rather than continuous. Strengthening the institutional dimension therefore requires not only improving planning instruments, but also increasing field staffing and establishing a routine monitoring and reporting system with clear responsibilities and measurable implementation indicators.

Although the Bandarsyah rehabilitation site lies within an APL, this status is not neutral for sustainability. Because APL permits multiple non-forest land uses, it increases conversion pressure and can weaken governance by blurring spatial boundaries, complicating access control, and reducing compliance when roles, sanctions, and monitoring are not operationalized on the ground. This context helps explain the low institutional index. Therefore, rehabilitation in APL requires a zoning-based protection design (core, controlled-use, buffer zones) supported by clear access rules and site-specific enforcement, especially given the mangroves' protective role for strategic assets such as the old town and the airport.

Formal regulations, including local bylaws and national conservation laws, form the legal backbone of mangrove protection in Indonesia, with oversight distributed across local, provincial, and national levels through key agencies such as the Ministry of Environment and Forestry and the Ministry of Maritime Affairs and Fisheries [96]. Despite this legal framework, violations of existing laws and regulations continue to occur, largely due to weak enforcement mechanisms and inconsistencies between overlapping policies. In the rehabilitation mangrove area, while these regulations were formally established, their practical implementation at the community level often relies heavily on non-formal institutions such as customary leadership structures, village forums, and religious councils. These local regulations play a significant role in promoting conservation norms, mediating disputes, and fostering compliance, particularly in contexts where formal enforcement remains limited [98]. The implementation of customary rules encourages communities to not only be recipients of policies, but also become drivers in the management and protection of resources, thus supporting sustainable management at the village level [99]. Strengthening the synergy between formal regulations and these non-formal governance systems is essential for enhancing both the legitimacy and the effectiveness of mangrove management [100]. Furthermore, strong community compliance with management rules, supported by minimal land-use conflicts and generally positive attitudes toward conservation, underscores the importance of integrating participatory governance approaches into future conservation strategies.

Community-based mangrove management (CBMM) groups, such as fisherfolk associations, women's organizations, and youth environmental clubs, play a crucial role in mobilizing local participation and sustaining post-planting activities. In study location, some CBMM groups had actively participated in mangrove planting campaigns; however, their involvement in long-term monitoring, data collection, and community awareness initiatives remains limited. Providing targeted technical training, small-scale funding, and recognition programs can empower these organizations to take a more active and consistent role in conservation management. Effective coordination among government agencies, NGOs, academic institutions, private enterprises, and community groups is also essential to prevent overlapping efforts and ensure efficient use of resources [101]. However, in the study sites, coordination was still largely ad hoc, often occurring only during the initial phases of projects. The lack of dedicated personnel and the occasional absence of specialized training have constrained both the continuity and the technical quality of rehabilitation efforts. These challenges hinder long-term planning, weaken enforcement, reduce stakeholder engagement, and undermine sustainable resource management. Establishing a permanent multi-stakeholder coordination forum, with clearly defined roles, open communication channels, and joint work plans, can help integrate initiatives, prevent conflicts, and align rehabilitation activities with broader development strategies [34].

Implication conservation and recommendation

Mangrove rehabilitation in Bandarsyah Village should prioritize strengthening ecological conditions by planting species that are most adaptive to local environments, particularly *Rhizophora spp*., which have been shown to tolerate high salinity (32.43 ppt) and sandy mud substrates. To make ecological improvement measurable, the program should adopt density-based targets using the same classes defined in Table 1: moving from the current "sparse" condition (<1,000 trees/ha) toward the "dense–optimal" classes (>1,500–2,000 trees/ha) through phased enrichment planting and survival-based replanting (i.e., replanting only after assessing survival and causes of mortality). In areas dominated by muddy sand substrates, land improvement measures are needed prior to planting, such as adding mud to increase soil moisture retention and nutrient availability, so that seedlings are not placed in conditions that structurally limit growth. Moreover, because semi-diurnal tides with water levels reaching up to two meters may trigger erosion in open areas, site-level planting design should explicitly reduce washout risk. Ridge planting methods and spaced clump techniques can be implemented as standard operating practices in exposed zones, supported by simple erosion control actions and

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routine post-tide checks during early establishment. Ecological performance should be tracked through permanent plots (trees/ha), survival rates at 3–6–12 months, and evidence of erosion or sediment instability in planted segments.

From a social perspective, strong local community support is essential for rehabilitation success, but participation should be organized into defined roles and responsibilities that directly support measurable ecological outcomes. Community empowerment can be strengthened through technical training (species selection, planting design, and maintenance), nursery management, and structured involvement in monitoring and maintenance activities. Establishing or formalizing community-based mangrove management groups is recommended not only as a participation mechanism, but also as an implementation unit responsible for routine maintenance, reporting, and visitor/access management. To reduce pressure in rehabilitation plots and align with sustainability goals, community access should be managed through clear zoning and enforceable use rules consistent. Implementation can be monitored by tracking the number of violations, conflict reports, and compliance trends, alongside community benefit indicators such as ecotourism visitation records and local income opportunities from non-timber mangrove products.

The success of rehabilitation programs also depends on strong institutional support and cross-sector collaboration. Local governments, academics, NGOs, the private sector, and community members should establish a coordination mechanism that is not merely ad hoc, but tied to a planning cycle with scheduled meetings, a documented annual workplan, and clear task allocation across stakeholders for planning, implementation, and evaluation. Given that funding for rehabilitation is a sensitive leverage factor, diversification of funding sources should be framed as a concrete financing design rather than a general suggestion. A multi-source financing model can combine baseline public funding with corporate social responsibility partnerships and site-based revenue mechanisms. Importantly, the financing plan should explicitly allocate resources not only for planting, but also for maintenance, protection, and monitoring. Financing progress can be monitored through operational indicators such as annual committed versus disbursed funds, the proportion of the budget dedicated to maintenance, the number of active funding sources and the duration of their commitments, and the timeliness of disbursement relative to planned field activities.

Science-based monitoring is required to ensure program efficiency and accountability and should be designed as a routine system rather than a one-time evaluation. Satellite imagery and drone surveys can be used periodically to document shoreline changes, canopy development, and potential conversion signals, while regular field surveys confirm survival, density class changes, and local drivers of mortality. Monitoring outputs should directly feed back into management decisions. This feedback loop also supports transparent reporting to funders and stakeholders, reinforcing institutional legitimacy and enabling adaptive management.

Finally, although the Bandarsyah mangrove area is classified as an APL, special zoning protection is essential to prevent land conversion and safeguard mangroves' protective function for critical assets, including Raden Sadjad Airport and Penagi Old Town, from abrasion and tidal flooding risks. Policy recommendations will be stronger if written as implementable actions with measurable implementation indicators. In parallel, rehabilitation strategies should incorporate climate change adaptation measures. Establishing a strong policy framework with clear implementation metrics will provide legal certainty and support the long-term sustainability of rehabilitation programs.

Limitation study

RAPFISH proves most effective when applied as a comparative or multi-criteria approach across multiple units, enabling the identification of differences in sustainability levels. Since this study focused on a single location, the analysis was limited to calculating the sustainability index for each dimension and categorizing its status. These results function as a baseline or internal evaluation rather than a comparative assessment. Future studies are encouraged to extend the analysis to multiple mangrove rehabilitation sites or adopt a time-series perspective.

RAPFISH could be strengthened by integrating interpretive structural modeling (ISM) and matrix of crossed impact matrix multiplication applied to classification (MICMAC), which allow for the examination of structural interrelationships among factors and the prioritization of critical leverage attributes. Additionally, the relatively low institutional and economic scores warrant further investigation through Social Network Analysis (SNA), as this method can reveal actor dynamics, stakeholder interactions, and collaboration patterns that significantly affect the sustainability of mangrove rehabilitation initiatives.

Conclusions

RAPFISH–MDS assessment indicates that mangrove rehabilitation in Bandarsyah Village has achieved relatively strong ecological conditions and community support, but remains constrained by economic benefits and institutional capacity. The leverage analysis suggests that future improvements should prioritize: (1) strengthening stand structure through survival-based enrichment planting to increase mangrove density, (2) managing community access through zoning and enforceable use rules, (3) securing predictable multi-source financing that covers not only planting but also maintenance and monitoring, and (4) operationalizing policies and planning through clear roles, routine supervision, and compliance mechanisms. Because the site is located in an APL where conversion pressure can occur, zoning-based protection and site-specific enforcement are essential to sustain rehabilitation outcomes and safeguard strategic coastal assets. Methodologically, this study demonstrates the usefulness of RAPFISH–MDS as a rapid diagnostic approach to identify priority leverage points for adaptive mangrove management. These priorities support progress toward SDG 13, SDG 14, and SDG 15 by strengthening climate resilience, coastal protection, and ecosystem sustainability.

Ethics approval

Participation was voluntary, and verbal informed consent was obtained after explaining the study purpose, procedures, expected duration, and participants' right to skip any question or withdraw at any time without consequence. No clinical procedures or interventions were performed. Personal identifiers were not collected; all data were anonymized, securely stored, and reported only in aggregate form. As the study involved minimal risk, was non-interventional, and used non-sensitive, anonymized data, the requirement for formal ethical clearance was waived through an administrative determination in accordance with common institutional policies for low-risk social research.

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Competing interests

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Underlying data

Available upon reasonable request.

Declaration of artificial intelligence use

The authors used ChatGPT during the writing process for translation, paraphrasing, and discussion purposes throughout the development of this manuscript. We confirm that all AI-assisted processes were critically reviewed by the authors to ensure the integrity and reliability of the results. The final decisions and interpretations presented in this article were solely made by the authors.

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