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Journal of Multidisciplinary Applied Natural Science Vol. 6 No. 3 (2026) https://doi.org/10.47352/jmans.2774-3047.470
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Research Article

# Viability and Sustainability Assessment of the Mangrove Ecosystem: A Case Study of Sausu Tambu, Indonesia

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| Received : March 9, 2026 | Revised : June 28, 2026 | Accepted : July 16, 2026 | Online : July 31, 2026 |
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**Abstract**

The management of mangrove areas is often hindered by the lack of integrated information regarding the ecological conditions and the social aspects of the surrounding communities, as previous studies tend to evaluate both aspects separately. Viability assessment addresses ecological conditions and sources of threats, while sustainability emphasizes multidimensional management strategies. The integration of both is important to bridge ecological diagnosis with long-term management. The research was conducted on the Sausu Tambu mangrove ecosystem by integrating Conservation Action Planning (CAP) and Rapid Appraisal for Fisheries Sustainability (Rapfish). The methodological novelty lies in the two-step matrix that sequentially crosses the viability and threat scores of CAP with the sustainability index of Rapfish, resulting in a final status that reflects the ecological condition and institutional social capacity in an integrated manner. The findings show that this area has nine types of mangroves. The viability is rated as fair, and the threats are rated as medium, which assigns it a vulnerable CAP status. The ecological and social domains of Rapfish are at a moderate level (57.85% and 53.90%), while the institutional domain is slightly lower (49.64%). The intersection of the CAP status with the Rapfish index still results in a final vulnerable status. Actionable conservation strategies include the establishment of management bodies for village mangroves, formulation of village regulations, periodic planting and monitoring, environmental awareness and pride campaigns, inter-party cooperation, and community economic empowerment. These results have consequences for long-term coastal governance and support the Sustainable Development Goals, especially for ocean ecosystems through the protection of coastal habitats and for land ecosystems through the management of mangrove vegetation and biodiversity. The findings can also be used as a model for evaluating other small mangrove areas in Indonesia and tropical coastlines.

**Keywords:** institutional capacity, mangrove ecosystem, sustainability, threats, viability

## 1. INTRODUCTION

The Indonesian mangrove ecosystem covers approximately 4.25 million hectares of coastal areas and represents nearly one-fifth of the world's mangrove area [1][2]. However, since the 1800s, the utilization of mangroves for timber production and the development of aquaculture have led to the loss of more than 200,000 ha of mangrove forests, particularly in Java and Sumatra, by the late 1960s [3]. Degradation happens when trees are cut down in a way that makes small openings and ponds, which makes big, broken-up open areas [4]. Until now, the main pressure comes from land conversion for shrimp farming [5], which not only alters the ecosystem structure but also reduces soil organic carbon reserves and triggers $CO_2$ emissions of up to about 34 kg/m² from mangrove sediments [6].

Pressure on mangrove ecosystems impacts land cover changes and has direct implications for the ecological functions of coastal areas. Mangrove ecosystems play a crucial role in protecting coastlines from abrasion, storms, and extreme waves [7][8] while also providing spawning and nursery habitats for various marine organisms that support fishery productivity [9]. Therefore, the health of mangroves is often used as an indicator of the overall condition of coastal ecosystems [10], [11]. Since the economic benefits of mangroves are often indirect, their presence is frequently deprioritized in decisions regarding coastal space utilization [12][13]. The rise in economic activities and population growth subsequently propels the transformation of mangrove regions for diverse developmental objectives [3][4]. However, mangroves also serve as nature-based solutions in climate change mitigation through their capacity to absorb and store large amounts of carbon [14].

In the context of mangrove management, pressure on the ecosystem is primarily triggered by the intensity of human activities in the surrounding area [15]. The transformation of mangrove areas into tourist destinations presents economic

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**Table 1.** Locations of mangrove sample collection at three observation stations representing different ecological conditions for the collection of biophysical data of the mangrove ecosystem.

| Sampling Station | Coordinate | Site Description |
|---|---|---|
| Station 1 | Latitude 1°2'32.88"<br>Longitude 120°31'54.61" | Located in a coastal tourism area influenced by tourism activities and supporting infrastructure development |
| Station 2 | Latitude 1°1'0.21"<br>Longitude 120°31'2.51" | Adjacent to community shrimp farming areas with anthropogenic activity pressures |
| Station 3 | Latitude 0°59'50.53"<br>Longitude 120°30'19.97" | Adjacent to residential and shrimp farming areas, and still influenced by estuarine environmental characteristics |

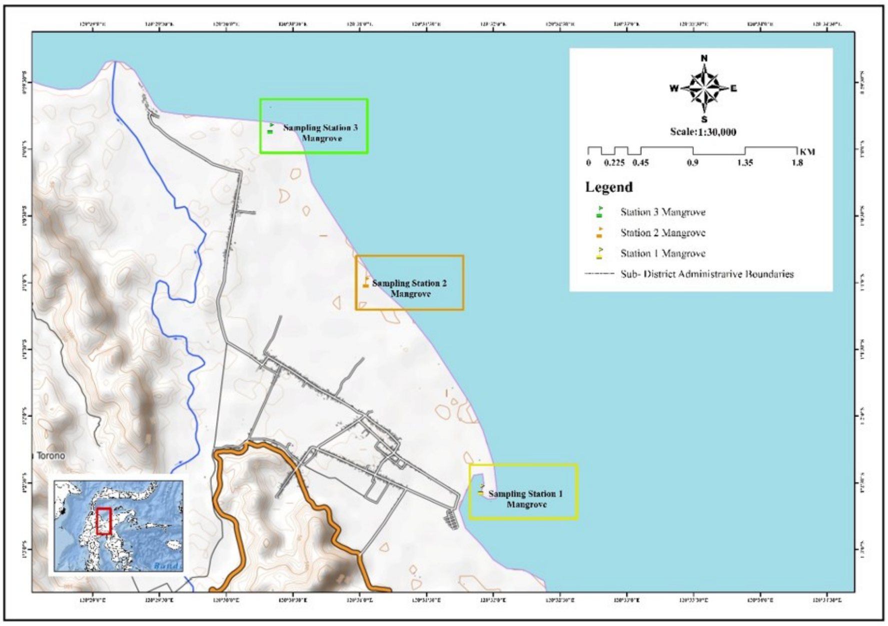


**Figure 1.** Map of the distribution of the mangrove ecosystem and the locations of three observation stations in the Sausu Tambu area.

opportunities while simultaneously increasing the potential for ecological disturbances [16]. Since a mangrove area is developed as a tourist destination, the ecosystem directly and indirectly faces pressures such as disturbances to wildlife, changes in habitat structure, and ecosystem fragmentation. This situation is worsened by large-scale shrimp farming and changing land use for different purposes [17]. On the other hand, traditional fishermen continue to utilize mangroves as fishing areas, resulting in overlapping land use [18]. The increase in human activity can indeed expand the economic value and marketing potential of the area [19], but at the same time, it increases ecological pressure that could potentially reduce ecosystem viability and threaten its long-term sustainability [20].

In mangrove ecosystem studies, the approaches of viability and sustainability have different focuses. Viability studies, generally referring to Conservation Action Planning (CAP) [21][22], focus on the current ecological conditions through ecological indicators to assess whether the ecosystem is still functioning and capable of withstanding pressures [23]. In contrast, sustainability assessments through Rapid Appraisal for Fisheries Sustainability (Rapfish) emphasize multidimensional long-term management aspects [24][25]. The integration of these two approaches becomes important, as viability provides a diagnosis of the current ecological condition and sources of threats, while sustainability translates the results of that diagnosis into long-term management strategies. Thus, the integration of viability and sustainability can bridge the need for conservation and the sustainable use of resources.

Synthesis of the literature from the 2021–2025 period shows that the development of mangrove research in Indonesia is still occurring partially and has not yet been fully integrated into a holistic

**Table 2.** The indicators used to measure viability and sustainability based on the Conservation Action Plan and the Rapid Appraisal for Fisheries Sustainability approach.

| Indicator | Good (3) | Moderate (2) | Bad (1) | Approach |
|---|---|---|---|---|
| **Ecology Domain** | | | | |
| Species composition | > 15 | 5-15 | < 5 | CAP and Rapfish |
| Canopy | ≥ 75% | ≥ 50 – < 75% | < 50% | CAP and Rapfish |
| Density | > 1500 ind/ha | ≥ 1000 – < 1500 ind/ha | 500 – 1000 ind/ha | CAP and Rapfish |
| Diversity | H'> 3 | 1 < H' < 3 | 0 < H' < 1 | CAP and Rapfish |
| Evenness | E > 0.60 | 0.40 < E < 0.60 | E < 0.40 | CAP and Rapfish |
| Dominance index | 0.00 < E < 0.50 | 0.50 < E ≤ 0.75 | 0.75 < E ≤ 1 | CAP and Rapfish |
| Fragmentation | < 30% | 31 - 60% | > 60% | CAP and Rapfish |
| **Social Domain** | | | | |
| Community participation | The community fully participates in every activity related to the management of the mangrove ecosystem. | The community often participates in every activity related to the management of the mangrove ecosystem. | The community never participates in any activities related to the management of the mangrove ecosystem. | RapFish |
| Public awareness | The community is fully aware of the importance of good mangrove ecosystem management. | The community sometimes realizes the importance of good mangrove ecosystem management. | The community has no awareness at all of the importance of good mangrove ecosystem management. | Rapfish |
| Access to resources | The community has full access to natural resources. | The community has limited access to natural resources. | The community does not have access to natural resources. | Rapfish |
| Sense of belonging | The community has a strong emotional bond with natural resources. | The community has a casual emotional bond with natural resources. | The community does not have any emotional attachment to natural resources at all. | Rapfish |
| **Institutional Domain** | | | | |
| Institutional capability | The institutional framework of society fully guarantees the livelihood of the community's professions. | Community institutions sometimes ensure the livelihoods of community professions. | The institutionalization of society does not guaranty the livelihood of the community's professions at all. | Rapfish |
| Community engagement | The institutions present in society always involve the community in resource management activities. | The institutions present in society sometimes involve the community in resource management activities. | The institutions present in society never involve the community in resource management activities. | Rapfish |
| Cooperation | The existing institutions are active and open up extensive cooperation opportunities with other related parties. | The existing institutions rarely open up opportunities for collaboration with other related parties. | The existing institutions do not open up any opportunities for cooperation with other related and unequal parties at all. | Rapfish |

conservation framework. Most studies still focus on the collection of data on diversity, uniformity, and the extent of mangrove cover as the basis for assessing ecosystem conditions [7][26]–[28]. The studies generally stop at the descriptive and inventory stage, without being developed into functional analysis. The development of the approach began to be evident in 2023, when research explicitly using viability to assess the biophysical condition of ecosystems emerged [23]. Subsequently, in the 2024–2025 period, the direction of research evolved toward a multidimensional approach focusing on the evaluation of management and sustainability aspects [24][25]. The research gap lies in the absence of a synthesis that connects the results of viability assessments, which answer whether the ecosystem is still functioning and what threats it faces, with sustainability assessments, which answer how the ecosystem can be managed to continue functioning in the long term. The interconnection of these two aspects also becomes a fundamental question that this study aims to address.

To put it simply, the integration of CAP and Rapfish encompasses three concepts simultaneously. To begin, the concept of socio-ecological resilience encompasses the adaptive capacity of institutions and ecosystems, as mangrove governance is frequently impeded by inadequate institutional resilience and inter-sectoral coordination in numerous countries [29][30]. The second principle of Integrated Coastal Zone Management (ICZM) is a governance system that guarantees the resilience of coastal systems by anticipating change, reducing pressure, and providing recuperation support. Consequently, it necessitates sustainable cross-sector coordination [31][32]. Third, community-based governance is a principle that entails the simultaneous attainment of conservation, empowerment, and economic development through the involvement of local communities. Governance legitimacy is the primary determinant of sustainability [33]. This research not only empirically evaluates the ecological and socio-institutional conditions but also contributes to the theoretical discourse on how these three frameworks reinforce each other in sustaining the sustainability of small-scale mangrove ecosystems.

Sausu Tambu is an area directly facing Tomini Bay [34], and is therefore strongly influenced by oceanographic factors such as tidal dynamics, currents, salinity, and sedimentation, which play an important role in shaping the characteristics of the mangrove ecosystem. However, these ecological conditions began to change since the transmigration program in the 1970s, when agrarian communities started settling in the coastal areas and utilizing

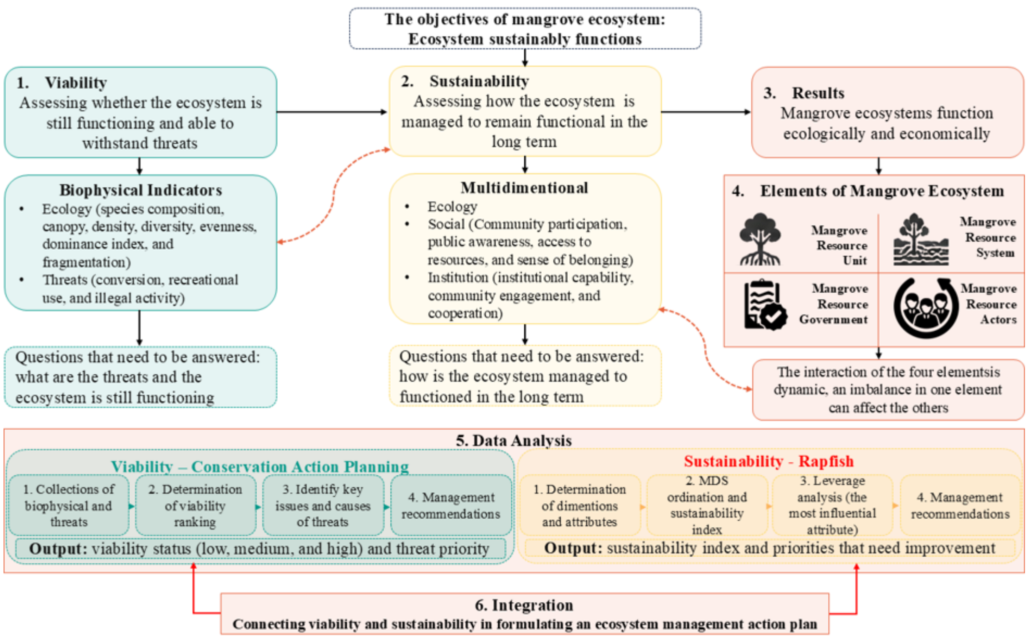


**Figure 2.** Conceptual framework for mangrove management based on the integration of viability and sustainability analysis.

**Table 3.** Taxonomy of threats obtained from the Conservation Action Plan approach developed by The Nature Conservancy.

| Source of threats | Common Taxonomy | Data Collection Method | Data Analysis | Verification into CAP |
|---|---|---|---|---|
| Conversion | Housing | Observation | Documenting | Interview |
| Conversion | Fishpond | Observation | Documenting | Interview |
| Recreational use | Visits and restaurants | Observation | Documenting | Interview |
| The illegal activity | Hunting, logging and poisoning | Observation | Documenting | Interview |

mangrove land for cultivation activities. Over time, the high population growth, driven by strong kinship ties, increasingly heightened the demand for space and triggered massive coastal development. Subsequent economic development accelerated the conversion of mangroves into ponds, particularly shrimp ponds with high economic value. At a more advanced stage, mangrove areas have also developed into tourist destinations initially initiated by forest farmer groups as part of conservation efforts [35], but in practice, they have instead created new pressures on the ecosystem due to uncontrolled tourism infrastructure development.

The research questions guiding this study are outlined as follows: (1) According to the CAP framework, what is the ecological viability and threat category of the Sausu Tambu mangrove ecosystem? (2) Based on the Rapfish analysis, what is the overall sustainability status of the mangrove ecosystem in the ecological, social, and institutional domains? Additionally, which indicators are the most significant leverage factors? (3) How does the threat identification that emerges from the CAP stage inform the priority domains that are assessed in RapFish, thereby enabling both to generate more precise management action plan recommendations? The methodological novelty lies in the two-step matrix that sequentially crosses the viability and threat scores of CAP with the sustainability index of Rapfish, resulting in a final status that reflects the ecological condition and institutional social capacity in an integrated manner.

## 2. MATERIALS AND METHODS

### *2.1. Location and Time of Research*

This research was conducted in the waters of Sausu Tambu, Parigi Moutong Regency, which is part of the Tomini Bay region, in November 2025. In addition, the area is also part of the Coastal Ecosystem Management Zone, as stated in the Regional Regulation of Central Sulawesi Province Number 1 of 2023 concerning the Spatial Planning of Central Sulawesi Province for the Year 2023–2042. The sampling stations consist of three locations determined based on ecological characteristics and the intensity of human activity around the mangrove ecosystem (Table 1 and Figure 1). Sampling was conducted using the purposive sampling method by establishing three observation stations selected based on differences in land use characteristics and levels of anthropogenic pressure around the mangrove ecosystem. This approach was taken so that the data obtained could comprehensively describe the variation in the biophysical conditions of the mangroves due to differences in human activities in the surrounding areas, ranging from areas with tourism pressure and cultivation pressure to areas still influenced by the natural characteristics of the estuary.

### *2.2. Data Collection*

The sampling locations are selected based on the presence and characteristics of mangrove vegetation at the research site. The length of the transects was adjusted to the field conditions, and they were drawn perpendicular to the sea, following the mangrove forest zone. Each transect is constructed with three replications of 10 × 10 m plots spaced 50 to 100 m apart along the transect line. A smartphone's front camera was used to snap a picture of the mangrove canopy cover at the observer's chest or eye level while pointing vertically upward toward the canopy. To avoid taking pictures right next to the tree trunks, five locations within each observation plot were used for photo collection. Multiple images were taken at each location to minimize lighting bias that could affect the estimation of the canopy cover percentage and to ensure an accurate portrayal of canopy conditions. Additionally, photos were not shot in direct sunshine. The Mangrove Guidebook for Southeast Asia [36] is used to identify mangrove species, and the number of tree stands for each species in each tract is then calculated. Parameters such as the number of species, tree abundance, diversity index, canopy cover, and the composition of benthic species associated with the mangrove ecosystem are used to represent its condition.

In addition to collecting ecological data, social and institutional data were also collected by interviewing 60 informants. The selection of informants was carried out using the purposive sampling method, with the main criteria being direct involvement or in-depth knowledge of the social, ecological, and institutional conditions. Informants were interviewed and filled out questionnaires to obtain social and institutional data, as well as information regarding sources of threats to the mangrove ecosystem. The informants consist of various stakeholder elements to ensure the representation of diverse perspectives, including (1) fishermen as direct users of the resources; (2) leaders of the fishermen's community; (3) fisheries extension officers; (4) staff from the Environmental Office; and (5) researchers from universities and research institutions.

The composition of respondents was arranged proportionally, with the largest portion coming from the group of fishermen and local communities who directly interact with the mangrove ecosystem, while government agencies, extension workers, and academics were involved in smaller but still representative numbers to obtain institutional and scientific perspectives. To minimize respondent bias, data source triangulation was conducted, which involved comparing and cross-checking information obtained from various groups of informants. The consistency of answers between fishermen, community leaders, government agencies, and academics was examined to identify the similarities and differences in perceptions regarding social and institutional conditions. In addition, the data from interviews and questionnaires were also validated through field observations, thereby minimizing the potential bias due to individual answer subjectivity or the interests of certain groups.

Next, the integration of mangrove ecological data with social and institutional aspects is used as an indicator to evaluate the viability, sustainability, and threat levels of the mangrove ecosystem. Based on the evaluation results, a Focus Group Discussion (FGD) is conducted to formulate an action plan for mangrove ecosystem management. The action plan

**Table 4.** Matrix of viability and threat cross-referencing of the mangrove ecosystem to determine CAP status.

| Viability\Threats | Low | Medium | High | Very High |
|---|---|---|---|---|
| Very Good | Very Good | Good | Fair | Vulnerable |
| Good | Good | Fair | Vulnerable | Critical |
| Fair | Fair | Vulnerable | Critical | Critical |
| Poor | Vulnerable | Critical | Critical | Critical |

**Table 5.** Cross-tabulation matrix of CAP status and Rapfish sustainability index to determine the final sustainability status of the mangrove ecosystem.

| CAP\Rapfish Sustainability | Very Bad | Bad | Good | Very Good |
|---|---|---|---|---|
| Very Good | Fair | Good | Very Good | Very Good |
| Good | Vulnerable | Fair | Good | Very Good |
| Fair | Critical | Vulnerable | Fair | Good |
| Vulnerable | Critical | Critical | Vulnerable | Fair |
| Critical | Critical | Critical | Critical | Vulnerable |

**Table 6.** Assessment results of ecologic domain for viability and sustainability analysis.

| Indicator | Station 1 | Station 2 | Station 3 | Notes |
|---|---|---|---|---|
| Species composition | 8 | 8 | 9 | Dominated by family Rhizophoraceae |
| Canopy (%) | 74.20 | 65.00 | 70.00 | The canopy cover is moderate based on Minister of Environment's decree No. 201 of 2004. |
| Density (ind/ha) | 2367 | 2867 | 1900 | Density is high based on Minister of Environment's decree No. 201 of 2004. |
| Diversity | 1.60 | 1.79 | 1.96 | Diversity Index is moderate based on Shannon-Wiener category |
| Evenness | 0.77 | 0.79 | 0.89 | Evenness is high |
| Dominance index | 0.26 | 0.23 | 0.16 | Dominace Index is low (stable community structure) |
| Fragmentation (%) | | 48.85 | | Habitat fragmentation is moderate |

is developed based on the threat levels identified from previous interviews, as well as the leverage factors in each evaluated sustainability domain.

### *2.3. Domain-indicators*

In this study, 14 indicators are used, grouped into three domains: ecological, social, and institutional (Table 2). To comprehensively analyze these indicators, the study applies two approaches, the CAP scoring method developed by The Nature Conservancy (TNC) to measure viability and threats [21][22]. Viability is measured using indicators based on existing key ecological attributes, while threats are examined through the taxonomy of threats within the CAP by reviewing the threats and sources of threats summarized in the CAP threat table (Table 2). Meanwhile, to measure ecosystem sustainability, the Rapfish developed by the Fisheries Center, University of British Columbia [37] is used.

The combined use of the CAP and Rapfish frameworks in this study is based on their compatibility in analyzing the mangrove ecosystem as a socio-ecological system in a sequential and complementary manner (Figure 2). CAP is used in the initial stage to assess viability through ecological indicators and sources of threats [21][22], thus being able to answer whether the mangrove ecosystem still functions ecologically and what pressures affect its sustainability. The results of the viability analysis then serve as the basis for applying Rapfish to evaluate sustainability thru a multidimensional approach that encompasses ecological, social, and institutional domains, allowing for the formulation of management strategies [38][39]. Nevertheless, CAP has limitations in the social and governance aspects, while Rapfish tends to rely on expert assessments and respondent perceptions, which can potentially introduce subjectivity. Therefore, the integration of these two methods is expected to mutually cover the limitations of each approach. The integration of these two frameworks in the mangrove ecosystem has never been done, so this approach was chosen to produce a more comprehensive evaluation of the ecological conditions as well as the direction for sustainable mangrove management.

#### *2.3.1. Viability and Threats*

The assessment of viability and threats to the mangrove ecosystem is conducted using the CAP approach, a framework commonly used in evidence -based conservation planning to identify sources of pressure and the level of threat to ecosystems. The viability score of the mangrove ecosystem is determined using rating indicators categorized into the levels of poor, fair, good, and very good. Each viability indicator is assessed based on the actual conditions observed in the field and then categorized into one of these ratings to illustrate the extent to which the mangrove ecosystem's condition supports its ecological functions. Threat scores are based on the standard threat taxonomy in the CAP v6b framework (Table 3). This framework sorts of sources of pressure on the ecosystem into groups of direct threats. Interviews with informants during the previous social and institutional data collection stage provided data on the types and presence of these threats.

The CAP method uses two standard criteria to evaluate each identified direct threat: (1) severity, which measures how much a threat can deteriorate the mangrove ecosystem's condition over a given period if it persists; and (2) scope, which measures how much of the mangrove ecosystem's area is directly impacted by the threat. Without the use of any mathematical aggregation technique, these three factors are evaluated descriptively for every kind of threat before being qualitatively considered to determine an overall threat assessment. Threat scores are categorized into four groups based on the combined evaluation of these two factors: very high, high, medium, and low. These groups adhere to the general criteria for threat classification in the CAP approach.

### *2.3.2. Sustainability*

The determination of indicator scores for each domain in Rapfish uses a Likert scale (1, 2, and 3). Each indicator is assigned a score based on its value, with a maximum score of 3 for good conditions and 1 for bad conditions [38][40]. The use of the Likert scale was chosen because the Rapfish method is fundamentally designed to conduct a rapid appraisal of multidimensional sustainability. The 1–3 Likert scale allows for the transformation of qualitative and semi-quantitative data into consistent ordinal data, which can then be further processed using multidimensional scaling (MDS) analysis, the core of the Rapfish method. To validate the level of subjectivity in the assessment, a Monte Carlo analysis was conducted on the scoring results in each sustainability domain. This analysis aims to address scoring uncertainties due to information limitations, differences in evaluator assessments, data input errors, and high stress values. The reliability of the Rapfish analysis results is considered adequate if the difference between the MDS analysis index value and the average value from the Monte Carlo simulation is relatively small [37][38]. The construction of the sustainability index for each domain refers to the concept used [41], where the sustainability index is grouped into 4 categories: (1) $x < 25$ very bad; (2) $25 < x < 50$ bad; (3) $50 < x < 75$ good; and (4) $x > 75$ very good.

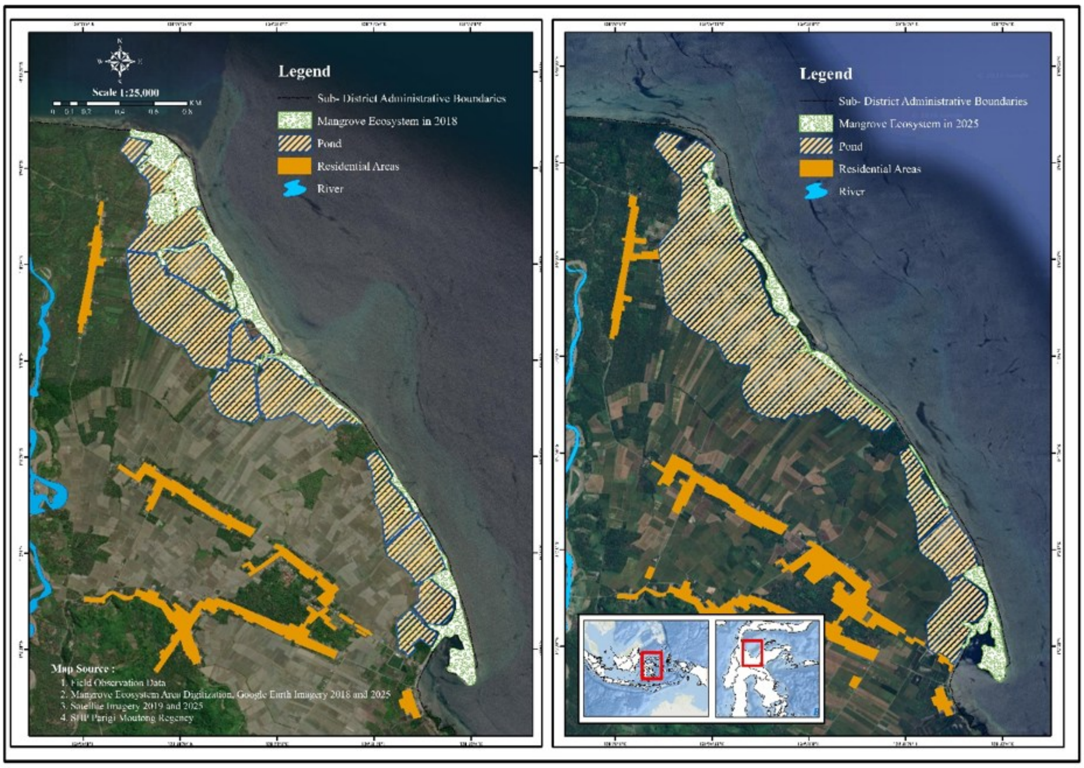


**Figure 3.** Map of mangrove change 2018 (left) and 2025 (right).

**Table 7.** Results of the Assessment of the Social and Institutional Domains Based on the Likert Scale.

| Dimension | Indicator | Results | Notes |
|---|---|---|---|
| Social | Community Participation | Moderate | Community participation is moderate |
| | Public Awareness | Good | The community understands the importance of mangroves as a protector against abrasion and disasters. |
| | Access to Resources | Good | The community has free access to catch fish in the mangrove ecosystem. |
| | Sense of belonging | Poor | A casual emotional bond, ownership of resources is perceived in accordance with capital capability. |
| Institutional | Institutional Capacity | Moderate | A lack of collaboration in resource management, and community institutions are not yet effective. |
| | Community engagement | Moderate | Institutional involvement is sporadic and not yet related to natural resource management. |
| | Cooperation | Moderate | Community institutions have not yet partnered on equal terms; cooperation is still individualistic. |

*2.4. Data Analysis*

Species density is the ratio between the Total Number of Individuals and the Measured Area Unit. Species density is calculated using Equation (1):

$$Di = \frac{\mathrm{ni}}{\mathrm{A}} \quad \textbf{(1)}$$

where, Di is the Density of Mangrove Species, ni is the Total Number of Stands of Mangrove Species (i), and A is the Total Area of the Data Collection Site. Ecological indices such as the Shannon-Weiner diversity index (H'), Pielou's evenness index (E), and Simpson's dominance index [42][43] are calculated using Equations (2) – (4):

$$\mathrm{H}' = -\sum_{i=l}^{s} \mathrm{pi} \ln \mathrm{pi} \quad \textbf{(2)}$$

$$\mathrm{E} = \frac{\mathrm{H}'}{\mathrm{Hmax}} \quad \textbf{(3)}$$

$$\mathrm{D} = \sum_{i=l}^{s} (\mathrm{Pi}^2) \quad \textbf{(4)}$$

where, H' is the Shannon-Weiner diversity index, E is the evenness index, D is the Simpson dominance index, S is the number of mangrove species, Pi is the proportion of individual abundance of the i-th species (ni/N), ni is the number of individuals of each species, N is the total number, and Hmax is ln S.

The extent of mangrove forest fragmentation is calculated using Equation (5) as follows:

$$\mathrm{IFMH} = (1 - \frac{\mathrm{A}}{\mathrm{A_0}}) \times 100 \quad \textbf{(5)}$$

where, A is the current forest area (37 ha), and $A_0$ is the previous mangrove forest area (72.34 ha).

Viability and threat are analyzed using the CAP Excel Tool v6b, which can be found online at the Conservation Action Planning site at the Conservation by Design Gateway: http://conserveonline.org/workspaces/cbdgateway/cap [22]. Meanwhile, for sustainability analysis, the Rapfish Program is used [44]. The Rapfish method essentially uses the Multi-Dimensional Scaling (MDS) approach [45]. The MDS method is one of the ordination methods in a reduced space (dimension) [40] where the stages of MDS consist of standardization tests, multi-dimensional distance measurement, ALSCALL algorithm analysis, two-dimensional distance measurement, and stress value measurement [37][41]. The final interpretation is carried out by cross-referencing the results from both analytical frameworks using a two-step matrix approach. In the first step, the viability scores and threat scores from the CAP framework are cross-referenced to produce the CAP status (Table 4). In the second step, the CAP status is cross-referenced with the sustainability index from the Rapfish analysis (Table 5) to produce the final sustainability status of the mangrove ecosystem, which serves as the basis for determining priorities and directions for the management action plan.

## 3. RESULTS AND DISCUSSIONS

### *3.1. Ecology Domain*

There are nine identified mangrove species in the sampling plot, which belong to four families: Avicenniaceae, Rhizophoraceae, Sonneratiaceae, and Meliaceae. The nine species are *Avicennia alba*, *A. officinalis*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, *C. decandra*, *Rhizophora apiculata*, *R. stylosa*, *Sonneratia alba*, and *Xylocarpus granatum*. In general, the percentage of mangrove vegetation canopy cover falls into the "moderate" category with a value of 65.00–74.20% and a density level of 1900–2367 ind/ha, thus categorized as "good" or "very dense" based on Minister of Environment's decree No. 201 of 2004 (Table 6). The Shannon-Wiener diversity index is 1.60–1.96, which means the diversity is in the "moderate" category, and the evenness index of 0.77–0.89 indicates high evenness or that the mangrove community is in a stable condition. Meanwhile, the mangrove vegetation dominance index is 0.16–0.26, indicating low dominance of mangrove species; in other words, no species dominates. This attribute also means that the ecosystem shows stability. The index also indicates that the ecosystem possesses biodiversity, with a composition that supports mutual interactions among species. However, like other mangrove areas in Indonesia, the mangrove ecosystem at the research site also experiences habitat fragmentation reaching 48.85% (Figure 3), which has the potential to affect habitat connectivity and ecosystem stability in the long term.

In general, the mangrove community at the research site is dominated by species from the Rhizophoraceae family, particularly *R. apiculata*. The dominance of this species is suspected to be related to its high adaptability to various coastal environmental conditions, allowing it to grow optimally and spread widely compared to other mangrove species [46]. However, the composition of mangrove species found in Sausu Tambu is relatively lower compared to the mangrove areas in East Lampung, which are recorded to have 12 species [7], and in East Java, with 17 species [26]. If viewed from the diversity index, the condition of mangroves in Sausu Tambu is also lower compared to the Savu Sea Marine National Park area [28] but still higher than the mangrove ecosystem in Mimika, Papua [27]. Meanwhile, the evenness index value in Sausu Tambu is recorded as lower compared to East Java [26], but higher than the mangrove area in Mimika, Papua [27].

Even though the Sausu Tambu mangrove ecosystem represents a relatively small mangrove ecosystem, its formation, which creates a green belt along the coast, is very important for the area. This is also because it is inhabited by species whose root types are known to slow down water currents, absorb waves, and physically prevent abrasion [2] [47]. It should be noted that the location of the mangrove presence faces the open sea of Tomini Bay, which is known for its strong current

**Table 8.** Assessment of viability and Biodiversity Health Rank of the mangrove ecosystem Processed using Conservation Action Plan.

| Category | Key Attribute | Indicator Rating | Viability Rank |
|---|---|---|---|
| Landscape context | Fragmentation | Fair | Fair |
| | Canopy | Fair | |
| Composition | Species composition | Fair | Fair |
| | Diversity | Fair | |
| | Evenness | Good | |
| | Dominance index | Good | |
| Size | Density | Good | Good |
| **Biodiversity Health Rank** | | | **Fair** |

**Table 9.** Level of threats and pressures on the mangrove ecosystem based on Common Taxonomy dan Threat to Target Rank.

| Source of Threat | Common Taxonomy | Severity | Scope | Threat to Target Rank |
|---|---|---|---|---|
| Conversion | Housing | Low | High | Medium |
| Conversion | Fishpond | High | High | High |
| Recreational use | Visits and restaurants | High | Low | Medium |
| The illegal activity | Hunting, logging and poisoning | Low | Low | Low |
| **Total Score** | | | | **Medium** |

movements [48][49]. Therefore, the presence of mangroves, no matter how small, is essential to protecting the physical beach from oceanographic factors that can damage its existence and stability. In addition, the loss of mangrove ecosystems also has the potential to result in the loss of carbon stock reserves and carbon absorption potential [50]. According to [51], each hectare of mangrove on average contains 1.023 mg of carbon per hectare.

According to [3], various pressures on the mangrove ecosystem, especially agricultural activities, contribute to the loss of approximately 800,000 ha, and it is estimated that around 700,000 ha of mangroves may potentially disappear in the next two decades [52]. The fragmentation occurring in a mangrove forest can reflect its viability as it represents the current condition of connectivity within the ecosystem. However, it can also be viewed as a threat because continuous fragmentation can lead to the disappearance of the ecosystem [21][53]. The fragmentation occurring in the Sausu Tambu area is caused by conversion that increasingly pressures the extent of the mangrove forest. The problem is that the mangroves in this area are relatively small, making them very vulnerable to total destruction due to human activities. Thus, solid coastal spatial planning that is adhered to by all stakeholders is necessary to maintain the integrity of this mangrove ecosystem [54].

In terms of fisheries, habitat fragmentation reduces fishery productivity due to the loss of spawning habitats for fish and other marine biota [55]. This condition also impacts the loss of biodiversity [56] and alters the dynamics of fishery resources [57], which ultimately directly affects fishing communities that rely on the ecosystem services of mangroves for their livelihoods [58]. From the perspective of carbon storage, fragmentation also reduces the ability of mangroves to store carbon [59]. Findings that the carbon stock in rehabilitated ecosystems is still lower compared to natural ecosystems [60] reinforce this conclusion. This means that mangroves that have experienced fragmentation and are then rehabilitated have not yet fully restored their carbon storage capacity to that of undisturbed natural mangrove conditions.

Overall, mangroves with moderate tree species diversity, moderate canopy cover, and moderate fragmentation levels still show fairly good ecosystem resilience, although they are not yet in optimal condition. This condition is important because mangroves play a natural role in helping to mitigate and adapt to climate change [61]. Mangroves are capable of absorbing and storing large amounts of carbon, thereby helping to reduce greenhouse gasses that cause climate change [62][63]. Mangroves also help communities become more prepared to face rising sea levels and storms while simultaneously serving as a source of livelihood for local residents [64]. However, due to the relatively small area of mangroves in Sausu Tambu and the ongoing pressure from land conversion, the resilience of this ecosystem is actually vulnerable and can decline rapidly if fragmentation and canopy loss continue without any management efforts.

### *3.2. Social and Institutional Domain*

The social domain shows that community participation in ecosystem management is still relatively low (Table 7), because most people consider daily economic activities, such as planting rice fields and fishponds and not cutting down mangroves, to be a form of contribution to maintaining the ecosystem. Nevertheless, awareness of the importance of mangroves is relatively high, especially regarding their function in protecting coastal areas from abrasion and disaster threats. From the access perspective, the community feels they have the freedom to utilize resources, especially for fishing in mangrove areas and coastal waters. However, the sense of ownership over the resources is still low because the control patterns are more individualistic and based on capital ability rather than social responsibility or collective management, which can lead to overexploitation and degradation of the mangrove ecosystems, ultimately threatening the ecological balance and the community's long-term access to these vital resources.

From an institutional aspect, the capacity of local organizations such as youth organizations and forest farmer groups has not yet functioned optimally in supporting the sustainability of livelihoods and the improvement of community welfare (Table 7). The community's sporadic involvement in various activities has yet to integrate with systematic natural resource management. The absence of formal partnerships with external parties reinforces this condition, positioning the community as equal actors in the decision-making process. The cooperation that has been ongoing tends to be individual in nature, such as capital loans, and thus has not yet been able to encourage the strengthening of collective institutions or build long-term collaborations that support sustainable mangrove management.

Findings in the social domain indicate that the sustainability of mangrove management is not only determined by the level of community knowledge but also by how ecological values are translated into collective actions [65]. This condition indicates that the understanding of the function of mangroves as coastal protectors does not automatically translate into participatory behavior, especially when daily economic needs remain the top priority [8]. This situation is common among coastal communities that rely on the direct utilization of natural resources for their livelihoods. On the other hand, open access to resources without clear regulations has the potential to encourage patterns of use based on individual interests [66]. If this condition persists in the long term, management tends to operate sectorally, and it becomes difficult to build shared responsibility. The weakness of collective ownership weakens the community's incentive to maintain shared resources, a classic dilemma of the tragedy of the commons where individual interests drive excessive exploitation [67][68]. However, previous work [69] demonstrated that cooperative governance with clear boundaries and joint monitoring can prevent overexploitation, emphasizing the importance of strengthening collective ownership for the sustainability of mangroves.

The existence of local institutions essentially plays a strategic role as mediators, facilitators, and motivators in the management of natural resources at the village level [70]. Through this function, institutions are expected to bridge the interests of the community with conservation goals while also encouraging active participation in ecosystem management. However, the weak institutional capacity, coupled with low public attention and involvement, has resulted in the processes of mentoring, organizing, and capacity building not being optimal [71], which hinders effective collaboration and resource management efforts in the community.

The limited inter-agency cooperation exacerbates the weakness of collective ownership, leading to fragmented and overlapping management due to minimal horizontal-vertical coordination between

**Table 10.** Differences in sustainability indices between Rapfish and Monte Carlo, as well as statistical measurements of Stress and R-squared values.

| Domain | Sustainability Index (%) | Montecarlo (%) | Difference (gap) | Stress Value | Squared Correlation |
|---|---|---|---|---|---|
| Ecology | 57.85 | 57.25 | 0.60 | 0.14 | 0.94 |
| Social | 53.90 | 53.16 | 0.74 | 0.16 | 0.91 |
| Institution | 49.64 | 49.05 | 0.59 | 0.20 | 0.91 |

**Table 11.** Patterns of interaction between ecological, social, and institutional domains in the context of fragmentation.

| Pattern | Direction | Fragmentation context |
|---|---|---|
| Ecological → social and inntitutional | Mangrove fragmentation reduces the ecological benefits perceived by the community, thereby affecting their sense of ownership and institutional participation. | The shrinking mangrove cover is followed by a decline in catch yields and a reduction in ecosystem services, leading the community to perceive mangroves as less valuable. This condition reduces concern, collective participation, and involvement in the activities of the management group. |
| Social and institutinal → ecological | The weakening sense of ownership and low institutional cooperation affect spatial utilization decisions and the level of ecosystem protection. | When mangroves are viewed more as economic commodities rather than shared assets, social oversight weakens, collaboration among actors decreases, and land conversion for shrimp farms, agriculture, and infrastructure increases, leading to greater fragmentation. |
| Feedback | Ecological, social, and institutional changes dynamically influence each other. | Increased fragmentation reduces ecological benefits and social cohesion, which in turn weakens institutional capacity. Weakened institutions further accelerate degradation, trigger spatial use conflicts, and increase socio-ecological vulnerability. |

agencies [72]. Without solid cooperation, it is difficult to establish binding joint regulations. This combination risks creating a reactive management cycle, rather than a proactive one, due to institutional inertia and conflicting mandates [73]. However, various institutions that have been established, such as youth organizations, women's groups, village tourism groups, farmer groups, and forest farmer groups, have enormous potential to support the collective management of mangroves [74]. Solid institutions are not only capable of building cooperation among actors but also creating a sense of ownership over natural resources [75].

### *3.3. Viability*

The overall health condition of biodiversity is generally classified as fair, as indicated by the assessment results of the viability of the mangrove ecosystem (Table 8). The fragmentation level in the landscape context category is fair, suggesting that the continuity of the mangrove landscape is under pressure. Despite this, the canopy cover is still in the fair category, indicating that the ecosystem's protective function is relatively intact. The species composition and diversity levels in the composition category are sufficient, suggesting that the structure of the mangrove community is still well-formed, albeit not optimal. The distribution of individuals among species is comparatively balanced, and there is no excessive dominance of certain species, as indicated by the uniformity value and dominance index, which are classified as favorable. Consequently, the community's stability is preserved.

Meanwhile, in the size category, the vegetation density is in good condition, reflecting the ecosystem's ability to maintain its ecological functions, such as coastal protection and providing habitat for biota. Overall, the combination of these indicators shows that the viability of the mangrove ecosystem is still quite stable, but it requires management efforts to reduce habitat fragmentation so that the ecosystem's condition can improve toward a better category.

### 3.4. Threats

The level of threat to the mangrove ecosystem is generally classified as moderate (Table 9). However, some forms of pressure need special attention based on severity and scope. Severity describes the extent of damage caused by an activity to the ecosystem, while scope indicates the area affected by that activity. The analysis results show that shrimp and fish farming activities have

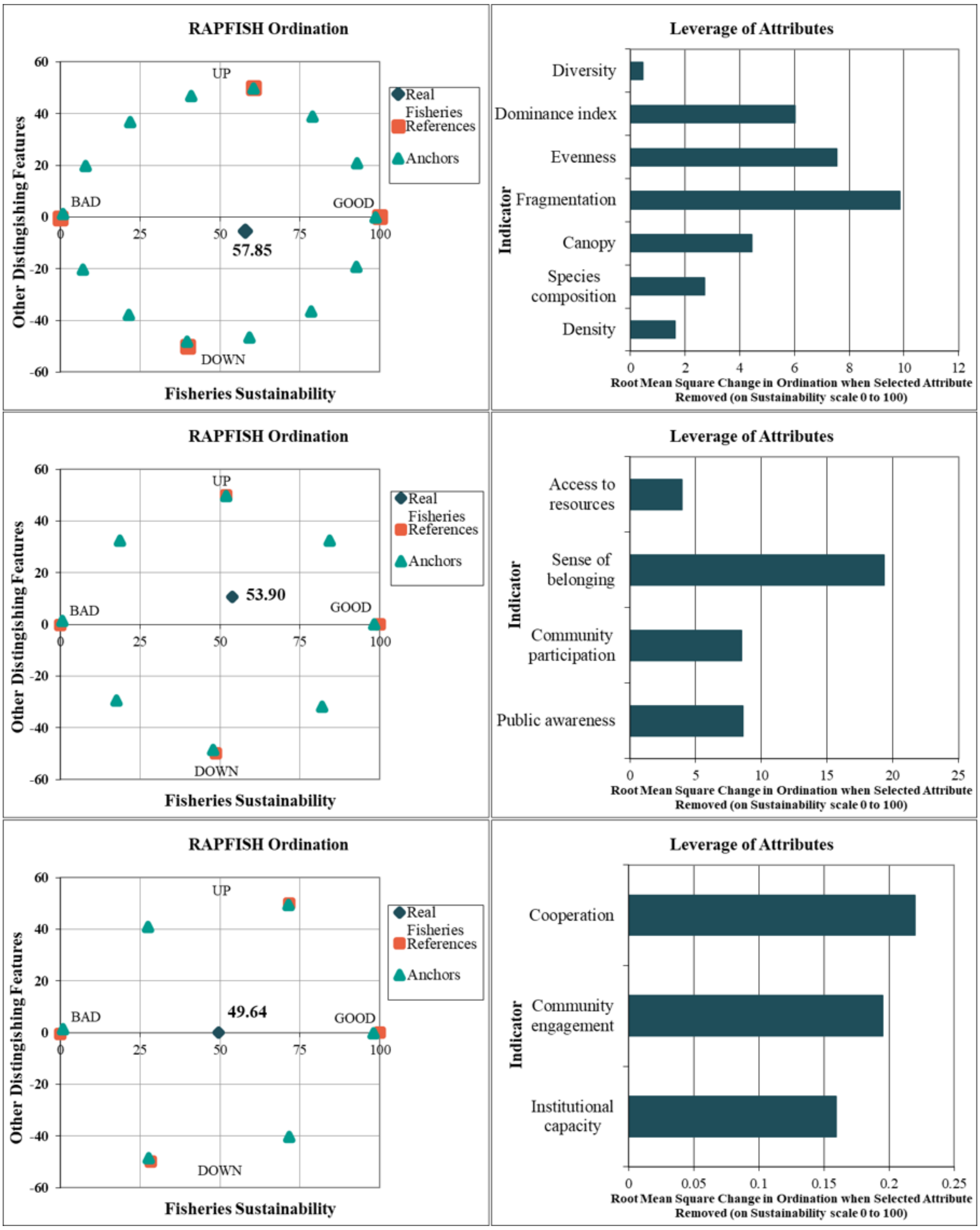


**Figure 4.** Results of the Rapfish analysis and Leverage Factors in the ecological domain (top), social domain (middle), and institutional domain (bottom).

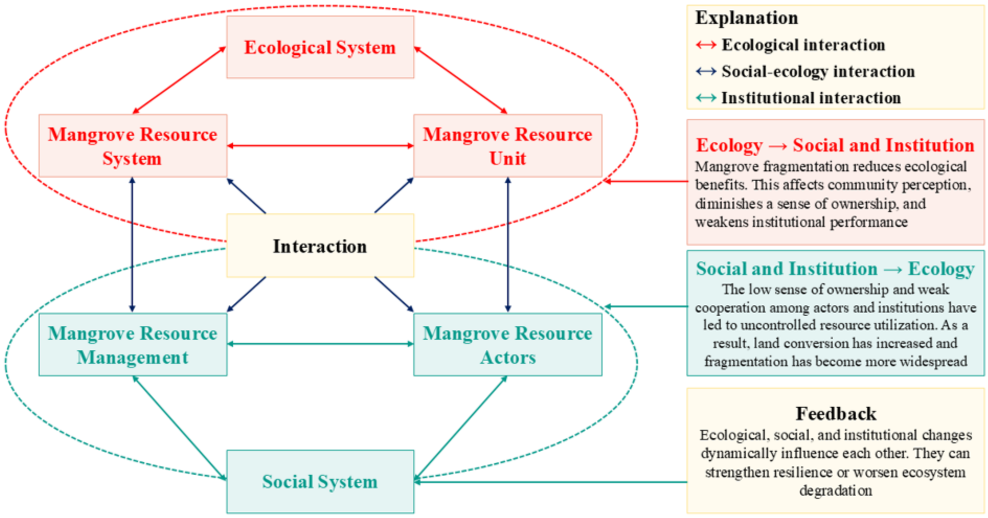


**Figure 5.** The socio-ecological interaction framework showing the dynamic relationships between social actors, governance institutions, and mangrove ecosystems in shaping the sustainability of the area.

equally high levels of severity and scope, making them a major threat to the mangrove ecosystem. This condition is in line with the land use changes occurring in the research area, where the area of shrimp and fishponds increased from 253.08 ha in 2018 to 271.26 ha in 2025 (Figure 3), or an increase of approximately 18.18 ha over a seven-year period.

Tourist activities have also been identified as having high severity but low scope. This condition is related to the development of the mangrove tourism area since 2018 through the Tanjung Karosondaya Mangrove Tourism Area, which is managed by local forest farmer groups. Although the development of tourist facilities has caused changes in habitat structure, the area used is still relatively limited and occupies only a small portion of the mangrove area. In addition, the low number of tourist visits, around 30–40 people per week, means that the pressure from tourism activities has not yet spread widely throughout the area. Meanwhile, the development of settlements shows low severity but high scope. The continuous population growth in this area, which became a transmigration location at the beginning of the New Order era, contributes to this condition. The increasing population has driven the demand for living space and food, marked by the expansion of settlements and the opening of agricultural land by the community. Although the damage caused occurs gradually, its impact is relatively widespread on the coastal landscape. As for illegal utilization activities, they have been identified as having both low severity and scope. During the research, activities still found included the collection of mangrove crabs for subsistence needs, while the logging of mangroves and the poisoning of wildlife have been reported to have almost ceased in the past five years. This condition indicates that the pressure from illegal utilization is relatively controlled, although it still requires monitoring to prevent it from developing into a greater threat in the future.

Shrimp and fish farming activities identified as having high severity and scope indicate that these activities not only cause significant ecological damage but also impact a wide area. These conditions are consistent with various studies indicating that the construction of shrimp and fish ponds in mangrove areas has substantial effects on both the mangrove ecosystem and the adjacent environment, including residential zones [76]. The large-scale conversion of mangroves into shrimp ponds has the potential to disrupt natural hydrological processes, such as water flow patterns, sedimentation, and salinity balance. These changes ultimately reduce habitat quality and affect the productivity of capture fisheries, especially for small-scale fishermen who rely on the functions of mangroves as nursery and feeding grounds for various aquatic biota [14][77]. In addition to ecological and economic impacts, the expansion of shrimp farms also has the potential to diminish the community's sense of ownership over the mangrove ecosystem. However, a sense of ownership is an important form of social capital in supporting the success of long-term conservation [78]. The decline in social attachment to natural resources can trigger apathy, management uncertainty, and even horizontal conflicts, which may undermine community efforts to engage in conservation practices and protect the mangrove ecosystem.

### *3.5. Sustainability*

Based on the sustainability assessment results in each domain (Table 10 and Figure 4), the highest score was obtained in the ecological domain at 57.85% (good), followed by the social domain at 53.90% (good), and the institutional domain at 49.64% (bad to good). Monte Carlo analysis shows that the sustainability index value of the mangrove ecosystem at a 95% confidence level is not significantly different from the MDS analysis results (Table 10). The RapFish analysis results yield stress values ranging from 0.14 to 0.20 and a coefficient of determination ($R^2$) between 0.91 and 0.94 (Table 10), indicating a good model accuracy level.

According to previous reports [37][38], the potential for errors in Monte Carlo analysis can be caused by scoring uncertainty due to limited information, differences in evaluation among evaluators, data input errors, and high stress values. However, the results of this study indicate that the error rate is relatively small, making the RapFish method reliable as a tool for evaluating the sustainability of mangrove ecosystem management. Previous work [37] state that a good stress value is below 0.25 with an $R^2$ value approaching 1, which confirms that the analyzed attributes have a high level of accuracy and can be scientifically justified.

If compared to similar research, the sustainability status in the ecological, social, economic, and institutional domains shows varying results across locations. In Karangsong Village, Indramayu, the sustainability status in all four domains is generally still considered less sustainable [79]. In Pangkep Regency, the ecological and institutional domains show a moderate level of sustainability, while the economic and social domains show a lower level of sustainability [80]. Meanwhile, another research [81] classify the ecological and social domains of mangrove rehabilitation in Natuna Regency as sustainable.

Based on the leverage analysis of 14 indicators distributed across three domains, each domain shows one attribute that is the most sensitive and needs to be considered as a key leverage factor in supporting the sustainability of the mangrove ecosystem, namely, fragmentation, sense of belonging, and cooperation (Figure 4). Fragmentation not only signifies the disruption of ecological connectivity but also denotes a transformation in the reciprocal relationship between humans and the resources they oversee. To understand this phenomenon, the analysis begins by examining the relationship between the sense of ownership indicator and the cooperation indicator, as both indicators play a crucial role in determining the community's response to ecosystem changes. Table 11 explains the pattern of interaction between the ecological, social, and institutional domains in the context of fragmentation.

Table 11 shows that mangrove fragmentation is not solely due to ecological changes but rather the result of a reciprocal interaction between ecosystem degradation and changes in community social behavior. When the mangrove cover continues to shrink, ecological functions such as fish habitats, coastal protection, and environmental quality regulation also decline. This condition drives the community to seek alternative sources of livelihood, which often actually increases the pressure on mangroves. On the contrary, the weakening sense of ownership and low social cooperation lead to a decline in community-based protective functions, causing the fragmentation process to repeat, forming a feedback loop that can accelerate ecosystem degradation.

### *3.6. Integrated Coastal Zone Management*

The results of the two-step matrix cross indicate that the overall mangrove ecosystem is in a vulnerable final status. This status is obtained through two complementary stages of analysis. In the first step, the intersection between the viability score classified as fair (Table 8) and the threats score classified as medium (Table 9) within the CAP framework results in a Vulnerable status. This result indicates that ecologically, the mangrove ecosystem is in a suboptimal condition, characterised by a viability condition that is only sufficient. On the other hand, this area also still faces pressure that cannot be ignored, although it has not yet reached a high or very high level. The combination of suboptimal ecological conditions and moderate pressure places the ecosystem in a vulnerable position, as ecosystems with insufficient viability have a more limited recovery capacity against ongoing pressure, even though this pressure is not yet classified as extreme.

The second step was to compare the Rapfish analysis's sustainability index, which was rated as good, with CAP's vulnerable status. This crossover nevertheless yields a final status of Vulnerable, indicating one crucial conclusion: the persistent pressure is the primary source of the issue. Because of its vulnerable position, the mangrove ecosystem in the study area falls into a category that calls for immediate management intervention (early intervention) as a priority, just below the critical category, to prevent the ecological situation from getting worse.

Despite the strengths of the integrative CAP and

**Table 12.** Formulation of management programs, missions, and action strategies for mangrove ecosystem conservation based on the integration of CAP-Rapfish analysis and FGD.

| Management Program | Missions | Actionable strategy | Institutions/Related Stakeholders |
|---|---|---|---|
| Drafting a participatory zoning agreement to limit the expansion of settlements, agriculture, and aquaculture through community participation and extensions. | Maintaining the integrity of the mangrove ecosystem | Establishing a village-based mangrove management body for supervision | Village key persons; Village government; District Planning Board; and Natural Resources Conservation Agency |
| Developing local (community-based) regulations related to the utilization of coastal areas and the protection of mangrove zones | Maintaining the sustainability of mangrove ecological functions | Creating village regulations about mangroves | Village government and District representative board |
| Community-based mangrove rehabilitation with the determination of location and type of plants | Restoring the connectivity of the mangrove ecosystem | Conducting mangrove planting and regular monitoring by involving all stakeholders. | The Central Sulawesi Provincial Marine and Fisheries Service; Natural Resources Conservation Agency; and Non government organization |
| Environmental education and awareness program based on local experiences and traditional community knowledge | Increasing public awareness and emotional bonds toward mangroves | Create sign boards about mangrove conservation in strategic locations; Conduct environmental education and awareness | Natural Resources Conservation Agency; District education services; and Community groups (including women) |
| Strengthening the value of collective resource ownership through mutual cooperation activities, joint patrols, and monitoring. | Encouraging a sense of ownership and shared responsibility in management | Conducting a pride campaign in the village and in schools | Private sectors; Community groups; and Village government |
| The formation of a multi-stakeholder collaboration forum involving the community as the main decision-making actor. | Enhancing equitable partnerships among stakeholders | Institutionalizing cooperation among parties so that decisions related to mangroves are routine and systematic. | Village government; District representative board; and Non government organization |
| Strengthening local institutional capacity through governance training and partnership negotiation | Encouraging independent and inclusive community institutions | Conducting environmentally friendly community economic empowerment | Non government organization; and Village government |

Rapfish approaches in producing more comprehensive sustainability evaluations, these approaches also have several limitations that need to be considered, particularly regarding the subjectivity of assessments, observational scale limitations, and their transferability to other mangrove ecosystems. The scoring determination in RapFish remains subjective and reflects the interests of stakeholders, and the viability-threat assessment in CAP also involves a similar degree of subjectivity, as it depends on the interpretation of the research team. Although CAP is designed to be flexibly applied at various scales, its application to other mangrove ecosystems still requires the adaptation of threat taxonomies, viability criteria, and socio-institutional indicators according to the local context, rather than direct replication without modification.

Nevertheless, these limitations do not diminish the importance of this integrated approach; rather, they emphasize that the sustainability evaluation of mangrove ecosystems needs to be conducted carefully and contextually. An integrated study of viability and sustainability becomes very important because it captures the situation holistically. This is very important in order to improve the management and conservation patterns of mangroves, especially in Indonesia, regardless of the size of the area, because it touches on the fundamental aspects of management, namely the human dimension. Research that focuses only on one aspect, such as viability, tends to result in haphazard or short-lived management. This can happen because local communities should be made the primary partners in management [82][83].

In terms of mangrove conservation, restoration is an expensive and difficult task, unless social and institutional aspects receive attention. As previously described, there are four important aspects in the discussion of mangrove ecosystem sustainability. Two aspects concerning humans are mangrove resource actors (social aspect) and mangrove resource governance (institutional aspect). These two aspects interact with each other, both specifically within each aspect and generally with the ecological system. This interaction occurs continuously as long as there are humans. The relationship between the two can be mutually beneficial or mutually detrimental [84], depending on factors such as resource availability and environmental conditions. The relationship is illustrated in Figure 5.

Management efforts are focused on enhancing ecological viability by reducing key threat factors while simultaneously strengthening social capacity and the effectiveness of institutional governance, which are prerequisites for long-term sustainability. The strategy is formulated in the form of a mangrove ecosystem management action plan based on the identification of threats and key leverage factors in each sustainability domain. This approach places management interventions in an adaptive and prioritized manner, and they are actionable so that each planned action has direct relevance to the root of the problem. The resulting strategic plan synthesizes the focus group discussions that involved stakeholders, as detailed Table 12.

## 4. CONCLUSIONS

As a relatively small mangrove ecosystem area, the Sausu Tambu mangrove area has a moderate viability level with a moderate threat level as well. This means that, up to now, the area is sufficiently viable to maintain its ecological functions, but it requires management efforts to prevent a decline in ecosystem quality in the future. Meanwhile, the sustainability index of the ecological and social domains is at a moderate level (57.85% and 53.90%), with only the institutional domain being slightly lower (bad to good) at 49.64%. To keep the mangrove ecosystem healthy and sustainable, local management can be done by creating a community group for mangrove care, making village regulation about mangroves, planting mangroves and monitoring on them regularly, conducting environmental awareness campaigns, promoting pride in the mangroves, working together with different groups, and helping the local economy.

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## Conflicts of Interest

The author states that they have no financial interests or personal relationships that could create a conflict of interest affecting this research.

## ACKNOWLEDGEMENT

We acknowledge the contribution of Fahry Ramadhan Thamrin, Sri Herlina, and Ali Akbar for data collections.

## DECLARATION OF GENERATIVE AI

Not applicable.

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