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Ecological and Sustainability Assessment of Mangrove Ecosystems in Gili Sulat and Gili Lawang, East Lombok, Indonesia

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Abstract

Small islands in Indonesia hold significant potential for tourism development and biodiversity conservation. However, their sustainability is increasingly threatened by various vulnerabilities. The Gili Sulat and Gili Lawang possess significant ecological, economic, and social potential through the presence of mangrove ecosystems. A balanced approach to managing sustainability across multiple dimensions is therefore essential to preserve protected forests. The gap between mangrove management on small islands and larger islands, in terms of area coverage, community dependence, utilization conflicts, and management strategies, highlights the significance of this study. This research aimed to measure the level of mangrove sustainability from multi-dimensional perspectives using the Rapid Appraisal (RAPFISH) method combined with a remote sensing approach. The RAPFISH analysis resulted in an overall sustainability index of 52.79%, indicating a moderately sustainable status. While the key ecological functions of the mangrove ecosystems remain preserved, further efforts are necessary in areas such as local economic development and institutional capacity to achieve a fully sustainable condition. Leverage analysis identified nine sensitive attributes out of 30 that significantly influence sustainability outcomes and guide future strategies. The Forest Canopy Density (FCD) model shows that coastal mangrove areas maintain high canopy density. Intensified patrols, conservation-based educational ecotourism, mangrove-based livelihoods, ecosystem management plans, and strengthened institutional collaboration are among the strategies to enhance sustainability. The study implies that mangrove sustainability depends on targeted adaptive management of the most influential attributes.

Keywords: forest canopy density (FCD), mangrove ecosystem, multidimensional analysis, small islands, sustainability index

1. Introduction

Small islands are an essential part of Indonesia's geographic and socio-cultural identity as an archipelagic country. Despite their limited area and small populations, these islands hold high ecological importance. Ecosystems such as mangrove forests, coral reefs, and seagrass beds play critical roles in maintaining environmental balance, supporting local livelihoods, and providing natural protection from climate change. According to national policy, small islands are defined as those with an area of 2,000 km^2 or less, including their surrounding ecosystems [1]. However, these islands face multiple challenges, including limited access to clean water, restricted agricultural land, slow ecological recovery, and exposure to environmental change driven by natural and human activities [2–5]. These vulnerabilities are compounded by poverty, marginalization of coastal communities, and increasing population pressure [6]. Addressing these issues requires an integrated management approach that aligns with global climate and sustainability goals, particularly through efforts to conserve biodiversity, promote sustainable fisheries, and enhance blue carbon programs [7]. The sustainable use of small islands must also consider ecological, socio-cultural, economic, and security aspects. In this context, mangrove ecosystems offer valuable contributions to coastal resilience, climate mitigation, and long-term economic sustainability [8].

In West Nusa Tenggara Province, which comprises two main islands and 401 small islands, Gili Sulat and Gili Lawang in East Lombok have been identified as ecologically vulnerable areas [9]. Together with Gili Petagan, they have been designated as protected forest areas since 2002 and are officially registered under the West Nusa Tenggara Forestry Land Register 14, known as *Register Tanah Kehutanan* (RTK) 14 [10]. Land cover data from the Ministry of Environment and Forestry show that these islands are predominantly covered by secondary mangrove forests, indicating ongoing recovery from past degradation caused by natural disturbances and illegal logging [11,12]. Coastal geomorphological pressure, particularly in the northern regions, has been linked to logging activities by external groups in recent years, further intensified by land-use changes and population growth [13,14]. Mangrove ecosystems in Gili Sulat and Gili Lawang, covering 641.63 ha and 369.02 ha respectively, are vital for shoreline stabilization, carbon sequestration, biodiversity habitat, erosion control, and fisheries productivity [15–17]. They also support aquaculture, ecotourism, and the use of natural resources for food, cosmetics, timber, and traditional medicine [16]. Their dense vegetation helps reduce wave energy, saltwater intrusion, and the impacts of extreme weather and tsunamis [18–20].

Data on the biophysical condition of the Mangrove ecosystem in Gili Sulat and Gili Lawang were obtained from the 2023 Wildlife Conservation Society (WCS) and the Marine and Fisheries Office of West Nusa Tenggara Province Research [21]. The type of mangrove forest in the protected forest area of Gili Sulat and Gili Lawang is a combination of fringe and riverine mangrove forests. This is evident in mangroves that are directly exposed to tidal fluctuations and wave action, yet exhibit tree heights exceeding 12 meters and a predominance of the Rhizophoraceae family. There are 10 species of true mangroves from six families, namely *Bruguiera gymnorrhiza*, *Rhizophora mucronata*, *Rhizophora apiculata*, *Rhizophora stylosa*, *Sonneratia alba*, *Aegiceras corniculatum*, *Osbornia octodonta*, *Excoecaria agallocha*, *Pemphis acidula*, *Xylocarpus moluccensis*. In addition, there are five associated mangrove species, namely *Cordia subcordata*, *Ipomoea pes-caprae*, *Clerodendrum inerme*, *Sesuvium portulacastrum*, and *Thespesia populnea*. Based on the standard criteria and guidelines for determining mangrove degradation [22], the mangrove condition in Gili Sulat and Gili Lawang was classified as good (very dense) with a canopy cover percentage of 80% and mangrove density of 1,518 trees/ha [21]. The Mangrove Health Index (MHI) was in the range of moderate to excellent [21]. Several bird species can be found on both islands, such as *Chlidonias sp*., *Alcedo coerulescens*, *Egretta sp*., and *Megapodius reinwardt*. The terrestrial fauna includes *Dendrelaphis pictus*, *Trimeresurus insularis*, *Apis sp*., *Telescopium Telescopium*, *Anguilla sp*., *Ophiocara porocephala*, *Macaca fascicularis,* and *Cynopterus brachyotis* [21].

These islands are also part of a 10,000-hectare marine conservation area, divided into four zones: core, utilization, sustainable fisheries, and mooring [23]. The designation as a forest area and marine conservation area has not yet ensured full ecological protection of the mangrove ecosystem in the Gili Sulat and Gili Lawang protected forests. Destructive fishing and illegal bird hunting persist, and conflicts over resource use between local and non-local fishers remain unresolved. The majority of residents in nearby Sugian Village, located opposite the islands, live below the poverty line, raising concerns about increasing pressure on natural resources [24]. Evaluating the sustainability of mangrove ecosystems in these islands is therefore critical for informing effective management, especially in preserving the ecological aspects of protected forest and marine conservation areas. The gap between mangrove management on small islands and larger islands, in terms of area coverage, community dependence, utilization conflicts, and management strategies, highlights the significance of this study.

Monitoring ecosystem sustainability is vital for preserving ecological functions, maintaining biodiversity, and ensuring the balance of natural resources. Remote sensing has emerged as a crucial tool for observing, evaluating, and supporting the sustainable management of ecosystems across terrestrial and aquatic environments at multiple scales. It enables the efficient assessment of vegetation health, land cover dynamics, and indicators of ecosystem degradation. Satellite platforms such as Sentinel-2 and Landsat are extensively used to monitor biomass, primary productivity, and changes in both forest and agricultural ecosystems [25–29]. Given the complexity of sustainability, assessment approaches should consider environmental, economic, social, and institutional dimensions [30]. In developing country contexts, multi-criteria analysis has been recognized as a suitable method for sustainability evaluation [31]. Mangrove sustainability was assessed from multidimensional perspectives using the Rapid Appraisal (RAPFISH) method combined with a remote sensing approach. Based on the results of the sustainability analysis, appropriate management strategies were formulated with input from relevant policy stakeholders.

2. Materials and Methods

2.1. Research Area

This research was conducted from December 2024 to February 2025 in Gili Sulat and Gili Lawang, located in Sugian Village, Sambelia District, East Lombok Regency, West Nusa Tenggara Province (Figure 1). The study area is located approximately 105 km northeast of Mataram City, the provincial cap

ital of West Nusa Tenggara, and can be accessed via a three-hour drive to Sugian Village, followed by a 15-minute boat trip to Gili Lawang. Geographically, Gili Sulat is situated at 8°19'37.99" S and 116°43'32.00" E, while Gili Lawang lies at 8°17'38.00" S and 116°41'56.00" E. The nearest settlements to these islands are Pekapuran Sub-village and Tekalok Sub-village.

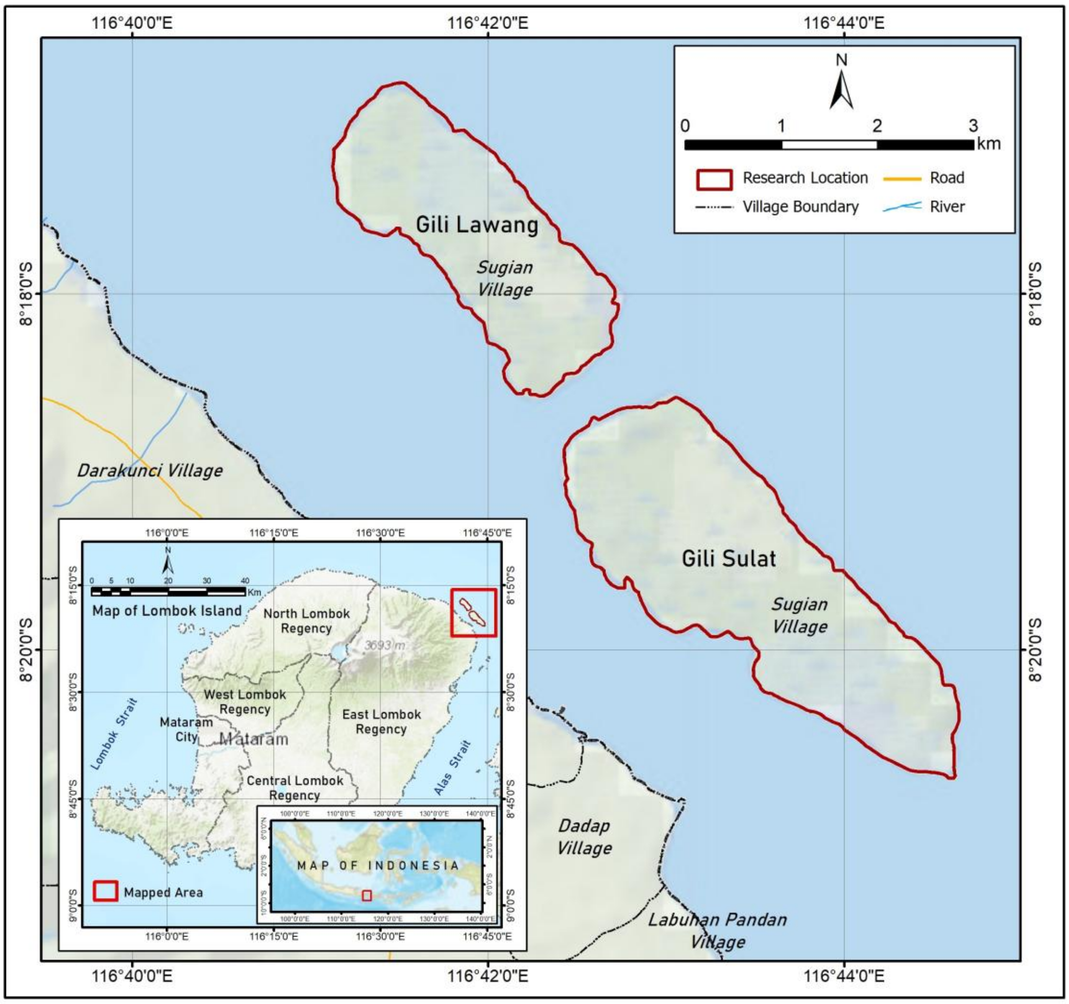


Figure 1. Map of the research area in Gili Sulat and Gili Lawang, East Lombok Regency, West Nusa Tenggara Province, Indonesia.

2.2. Tools

The tools used in this research included both software and supporting instruments. Data collection was facilitated through questionnaires and writing tools, which served as the primary means of recording information. Analytical processes relied on the RAPFISH add-ins for Microsoft Excel and IBM SPSS Statistics 30.0 trial version (subscription ID 513053504) to conduct statistical and sustainability assessments. QGIS 3.34.8 was used for spatial analysis and mapping the research location. The base map for the research location map is the World Topographic Map, and the Landsat satellite imagery was obtained from the USGS Earth Explorer platform. Collectively, these tools provided comprehensive support for data collection, processing, and analysis across multiple dimensions, in combination with the spatial analysis applied in this study.

2.3. Research Methods and Data Collection

This study employs a descriptive design with a mixed-methods approach, utilizing both primary and secondary data. The primary analytical method employed is the Rapid Appraisal for Fisheries (RAPFISH), utilizing a Multi-Dimensional Scaling (MDS) technique. RAPFISH is particularly suitable for evaluating sustainability status through a rapid appraisal framework based on a set of predefined criteria. The attribute criteria used for each dimension are based on relevant regulations and previous studies. This approach enables the numerical analysis of scored attributes, allowing for a structured interpretation of the sustainability dimensions under investigation [30]. Data were collected through field observations and direct data gathering at the research site using a questionnaire based on the rapid appraisal participatory technique. This participatory approach consists of a set of methods designed to engage local communities in identifying, analyzing, and addressing local issues [31,32].

A total of 69 respondents participated in the study, all of whom are residents who live near and utilize the natural resources surrounding the Gili Sulat and Gili Lawang. Community involvement was ensured through participatory approaches, including interviews. These activities enabled community members to share their knowledge, express their perspectives, and offer feedback on the management and utilization of mangrove ecosystems. Based on the result of the sustainability analysis, management strategies were developed with input from relevant policy stakeholders through a purposive sampling approach.

The ecological assessment of mangrove ecosystems in Gili Sulat and Gili Lawang was supported by spatial analysis using vegetation density, particularly the Forest Canopy Density (FCD) model. The FCD model was derived from Landsat 8–9 OLI/TIRS C2 L1 imagery, which has a spatial resolution of 30 meters, complemented by a panchromatic band offering a higher resolution of 15 meters [33]. The spectral resolution of Landsat 8–9 OLI/TIRS C2 L1 imagery consists of the Operational Land Imager (OLI) with nine spectral bands in the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions, plus a panchromatic band, as well as the Thermal Infrared Sensor (TIRS) with two thermal bands for land surface temperature measurements [34–37]. The Landsat satellite imagery used in this study was acquired in July 2025 and obtained from the USGS Earth Explorer platform.

2.4. Analysis Method

The analytical methods employed in this study consisted of two main approaches. First, the index and sustainability status analysis were applied to evaluate the level of mangrove ecosystem sustainability across multiple dimensions. Second, a spatial analysis was conducted to identify, map, and assess the condition of mangrove ecosystems using remote sensing data and geographic information systems. These two methods complement each other in providing a comprehensive understanding of the ecological and spatial aspects of the mangrove ecosystems within the study area.

The sustainability assessment of mangrove ecosystems in Gili Sulat and Gili Lawang employed the RAPFISH (Rapid Appraisal for Fisheries) method developed by the Fisheries Center at the University of British Columbia [38]. This method uses a multi-criteria approach based on the Multidimensional Scaling (MDS) algorithm to map the sustainability position of each unit along a scale from 0% (poor sustainability) to 100% (good sustainability)[39]. Analytical steps for determining the sustainability index and status of mangrove ecosystems in Gili Sulat and Gili Lawang are presented in Figure 2.

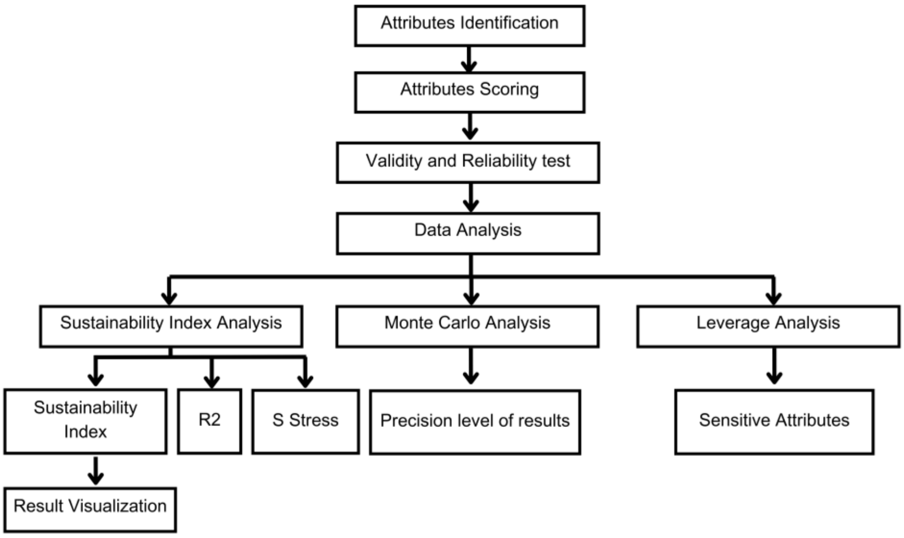


Figure 2. Framework of analytical stages for determining the sustainability index and status of mangrove ecosystems in Gili Sulat and Gili Lawang.

There are 30 attributes selected to represent four sustainability dimensions, namely ecological (7 attributes), economic (7 attributes), social (8 attributes), and institutional (8 attributes). Each attribute was evaluated using an ordinal scale from 0 to 2, based on site-specific conditions. A score of 0 indicates a poor condition, while a score of 2 indicates a good condition. A detailed list, along with brief descriptions, is presented in Tables 1 to 4. The validity and reliability test were assessed using IBM SPSS Statistics software by comparing the calculated correlation coefficient (r) with the critical value of 0.232 and by significance testing (Sig. (2-tailed) < 0.05 with a positive Pearson correlation). The reliability was evaluated with Cronbach's Alpha values greater than 0.5 to determine the internal consistency of the instrument, demonstrating acceptable reliability.

The sustainability index was evaluated using the Multidimensional Scaling (MDS) algorithm, which produced index scores between 0 and 100 for each dimension through the RAPFISH add-ins for Microsoft Excel. The classification of sustainability status based on the RAPFISH index score is presented in Table 5. Sensitive attributes were identified through leverage analysis based on their influence on Root Mean Square (RMS) changes along the ordination axis. Longer bars indicate greater impact on the sustainability score [39]. Monte Carlo analysis was conducted to evaluate the precision and robustness of the MDS results. A difference of less than 5% between the MDS and Monte Carlo results indicates that the sustainability analysis using the RAPFISH technique based on MDS has a high level of confidence in determining sustainability status. Finally, the sustainability index across dimensions was visualized using a kite diagram (also known as a spider chart) generated in Microsoft Excel.

Table 1. Attributes of the ecological dimension for analyzing the sustainability index and status of mangrove ecosystems.

	Attribute	Score	Description	Reference
X1.1	Changes in coastline	0;1;2	0 = coastal erosion 1 = constant 2 = accretion	- [40] - Interview
X1.2	Pressure on mangrove ecosystem	0;1;2	0 = Land-use conversion of Mangrove areas have occurred without due consideration of their ecological functions 1 = Mangrove area changes due to natural processes	- [40] - Interview

	Attribute	Score	Description	Reference
			2 = Mangrove area has remained stable	
X1.3	Mangrove species diversity	0;1;2	0 = low (H' ≤ 1) 1 = moderate (1 < H' ≤ 3) 2 = high (H' > 3)	- Shannon-Wienner Diversity Index [41] - Field Observation
X1.4	Diversity of mangrove-associated fauna	0;1;2	0 = low diversity 1 = moderate diversity 2 = high diversity	- [42] - Interview
X1.5	Mangrove tree density	0;1;2	0 = sparse (< 1,000 trees/ha) 1 = moderate (≥1,000 – <1,500 trees/ha) 2 = high (≥ 1,500 trees/ha)	- [22] - Field Observation
X1.6	Mangrove canopy cover	0;1;2	0 = sparse (cover < 50%) 1 = moderate (cover 50% - < 75%) 2 = high (cover ≥ 75%)	- [22] - Field Observation
X1.7	Utilization of mangrove resources	0;1;2	0 = unsustainable 1 = less sustainable 2 = sustainable	- Field Observation - Interview - [43]

Table 2. Attributes of the economic dimension for analyzing the sustainability index and status of mangrove ecosystems.

	Attribute	Score	Description	Reference
X2.1	Zoning for mangrove utilization	0;1;2	0 = not available 1 = available but not implemented 2 = available and implemented	- [44] - [23] - Interview
X2.2	Economic use of mangrove ecosystems	0;1;2	0 = low (< 25% direct use of forest, fisheries, and ecotourism resources) 1 = moderate (25-50% direct use of forest, fisheries, and ecotourism resources) 2 = high (>50% direct use of forest, fisheries, and ecotourism resources)	- [44] - Interview
X2.3	Accessibility of mangrove areas	0;1;2	0 = access is limited or unavailable 1 = access is available but limited 2 = access is easily available	- Field Observation - Interview - [43]
X2.4	Availability of supporting infrastructure	0;1;2	0 = not available 1 = available but limited 2 = available and adequate	- Field Observation - Interview - [43]
X2.5	Average household income	0;1;2	0 = below minimum wage 1 = at minimum wage 2 = above minimum wage	- [40] - Interview - minimum wage of East Lombok Regency is IDR 2,608,714 [45]
X2.6	Stakeholder participation	0;1;2	0 = no stakeholder involvement 1 = partial stakeholder involvement 2 = full stakeholder involvement	- [44] - Interview
X2.7	Contribution of mangrove-related activities to GDRP	0;1;2	0 = unsustainable 1 = less sustainable 2 = sustainable	- Interview - GDRP East Lombok Regency [46] - [38]

Table 3. Attributes of the social dimension for analyzing the sustainability index and status of mangrove ecosystems.

	Attribute	Score	Description	Reference
X3.1	Social impact of mangrove presence	0;1;2	0 = not available 1 = available but not effective 2 = available and effective	- [44] - [23] - Interview
X3.2	Level of community participation	0;1;2	0 = low (< 50%) 1 = moderate (≥ 50% - <75%) 2 = high (≥ 75%)	- [44] - Interview
X3.3	Educational attainment within the community	0;1;2	0 = never attended school or attended primary school but did not complete 1 = completed primary school and lower secondary school 2 = completed senior secondary school and college	- [40] - Interview
X3.4	Community knowledge of mangrove ecosystem	0;1;2	0 = low 1 = moderate 2 = high	- [44] - Interview
X3.5	Community access to mangrove areas	0;1;2	0 = no access 1 = limited access 2 = full access	- [44] - Interview
X3.6	Conflict over mangrove resource utilization	0;1;2	0 = frequently (> 5 times per year) 1 = occasionally (2-5 times per year) 2 = rarely (< 2 times per year)	- [42] - Interview
X3.7	Community-driven degradation of mangrove ecosystem	0;1;2	0 = extensive 1 = moderate 2 = small area	- [44] - Interview
X3.8	Community awareness of the importance of mangrove conservation	0;1;2	0 = low (< 50%) 1 = moderate (≥ 50% - < 75%) 2 = high (75%)	- [44] - Field observation

Table 4. Attributes of the institutional dimension for analyzing the sustainability index and status of mangrove ecosystems.

	Attribute	Score	Description	Reference
X4.1	Policies and planning for mangrove forest management	0;1;2	0 = not available 1 = available but not implemented 2 = available and implemented	- [44] - Interview
X4.2	Availability of formal and non-formal regulations	0;1;2	0 = not available 1 = available but not effective 2 = available and effective	- [43] - Interview
X4.3	Government commitment to mangrove conservation	0;1;2	0 = not available 1 = available but not effective 2 = available and effective	- [43] - Interview
X4.4	Existence and involvement of farmer, fisher, and community groups	0;1;2	0 = not involved 1 = involved but only procedurally 2 = actively involved	- [40] - Interview
X4.5	Coordination among relevant stakeholders	0;1;2	0 = never implemented 1 = rarely implemented 2 = frequently implemented	- [44] - Interview

	Attribute	Score	Description	Reference
X4.6	Compliance with management regulations	0;1;2	0 = low (> 5 information on violations) 1 = moderate (2-4 information on violations) 2 = high (< 2 information on violations)	- [42] - Interview
X4.7	Enforcement of sanctions for violations	0;1;2	0 = not implemented 1 = implemented but not effective 2 = implemented and effective	- [43] - Interview
X4.8	Monitoring and supervision mechanisms	0;1;2	0 = no supervision and monitoring 1 = inadequate supervision and monitoring 2 = intensive supervision and monitoring	- [43] - Interview

Table 5. Classification of sustainability status based on the RAPFISH index score.

Index Score (%)	Classification
0.00 ≤ IS ≤ 25.00	Poor (Not Sustainable)
25.00 < IS ≤ 50.00	Fair (Less Sustainable)
50.00 < IS ≤ 75.00	Moderate (Moderately Sustainable)
75.00 < IS ≤ 100.00	Good (Highly Sustainable)

Source: [47]

Spatial analysis was conducted to analyze the forest canopy density using Landsat 8-9 OLI/TIRS C2 L1. The Forest canopy density (FCD) serves as a valuable model for assessing forest conditions and monitoring changes over a given period. The parameters applied in the FCD model analysis include the Advanced Vegetation Index (AVI), Bare Soil Index (BSI), Canopy Shadow Index (SI), and Temperature Index (TI) [33]. The study began with the preparation of Landsat 8-9 OLI/TIRS C2 L1 imagery, which included downloading the data and clipping it to match the study area. This was followed by radiometric correction for Bands 2, 3, 4, 5, 7, and 10. It needs to convert into a radiance value to calculate the vegetation indices. This process was performed using equation (1).

$$L_\lambda = M_L Q_{cal} + A_L \tag{1}$$

Note: L_λ = TOA spectral radiance (Watts/(m2 * srad * µm)); M_L = Band-specific multiplicative rescaling factor from the metadata; A_L = Band-specific additive rescaling factor from the metadata; Q_{cal} = Quantized and calibrated standard product pixel values (DN).

Four parameters are utilized to calculate the Forest Canopy Density (FCD). First is the Advanced Vegetation Index (AVI), one of the essential parameters to determine the healthy vegetation index based on the red and near-infrared spectral bands. The AVI is calculated using equation (2). The second parameter is the Bare Soil Index (BSI). The BSI integrates blue, red, near-infrared, and shortwave-infrared spectral bands to detect soil variations. The shortwave infrared and red bands are used to assess soil mineral composition, whereas the blue and near-infrared bands help highlight the presence of vegetation. This index is calculated using equation (3).

$$AVI = \sqrt[3]{((B5+1)*(256-B4)*(B5-B4))} \tag{2}$$

Note: B5 = near infrared; B4 = red band

$$BSI = \frac{(SWIR2+R)-(NIR+B)}{(SWIR2+R)+(NIR+B)} \tag{3}$$

Note: SWIR2 = shortwave infrared band 7; R = red wavelength; NIR = near-infrared; B = blue wavelength

The Canopy Shadow Index (SI) was used as the third parameter. The Shadow Index (SI) is recognized as an important tool in forestry and agricultural monitoring, since canopy shadows provide critical information regarding the structural arrangement of trees and vegetation. The SI is calculated using equation (4)[48]. The last parameter is Temperature Index (TI). High temperatures are found in non-vegetated areas or exposed soil objects. The lower the temperature, the higher the FCD value. This index is calculated using equation (5).

$$SI = \sqrt[3]{((1 - B4) * (1 - B3) * (1 - B2))} \quad (4)$$

Note: B4 = red band; B3 = green band; B2 = blue band

$$TI = Lmin + \left(\frac{(Lmax - Lmin)}{65535}\right) * Q \quad (5)$$

Note: L = infrared thermal radian value; Lmax = radiance maximum band 10; Lmin = radiance minimum band 10; Q = satellite imagery digital value (band 10)

The Forest Canopy Density (FCD) model utilizes forest canopy density as an important parameter for characterizing forest conditions, based on the assumption that there is a relationship between canopy density and forest ecological dynamics. Higher FCD values correspond to a denser forest canopy [49]. A dense canopy may reflect a healthy forest condition, while the absence of a canopy indicates the opposite. The Forest Canopy Density (FCD) is calculated using equation (6) [48]. VD is performed using principal component analysis (PCA) based on two input parameters, AVI and BSI, while SSI is performed using PCA based on two input parameters, SI and TI.

$$FCD = \sqrt{(VD * SSI + 1)} - 1 \quad (6)$$

3. Results and Discussion

3.1. Result

3.1.1. Validity and Reliability Tests

The validity of all 30 attributes was assessed using item-total correlation (r) values, and all attributes were found to be valid, with r values ranging from 0.320 to 0.774. Ecological attributes (X1.1–X1.7) showed r values between 0.424 and 0.722, economic attributes (X2.1–X2.7) ranged from 0.344 to 0.637, social attributes (X3.1–X3.8) ranged from 0.320 to 0.774, and institutional attributes (X4.1–X4.8) ranged from 0.494 to 0.755. These results indicate that all attributes met the validity criteria, where the significance value (2-tailed) was less than 0.05 and the Pearson correlation was positive. This is further supported by the fact that the calculated r values exceeded the critical r value of 0.232.

Reliability testing indicated that all dimensions had Cronbach's Alpha values greater than 0.5, demonstrating acceptable reliability. Specifically, the ecological dimension recorded a Cronbach's Alpha of 0.707, the social dimension 0.707, and the institutional dimension 0.714, all reflecting high reliability, while the economic dimension yielded a Cronbach's Alpha of 0.600, indicating moderate reliability. These results confirm that the instrument is sufficiently reliable for subsequent analyses. All indicators representing the four sustainability dimensions were found to be valid and demonstrated moderate to high reliability, confirming their suitability for assessing sustainability status.

3.1.2. Results of the Sustainability Assessment of the Mangrove Ecosystems

The sustainability assessment of the mangrove ecosystem in Gili Sulat and Gili Lawang yielded an index score of 52.79%, indicating a moderately sustainable status (Figure 3). This contrasts with Haris et al. [43], who found a lower index of 45.79% in Tarumajaya, Bekasi, and Iswahyudi [14], who reported 46.75% in Langsa, both of which are classified as less sustainable. Conversely, the Cengkrong mangrove ecotourism site in East Java achieved a significantly higher index of 76.20%, placing it in the sustainable category [50].

According to Figure 3 and Table 6, the highest index was recorded in the social dimension, reaching 63.80% and categorized as moderately sustainable. In contrast, the economic dimension yielded the lowest index at 43.15% and is categorized as less sustainable. The ecological, social, and institutional dimensions were all classified within the moderately sustainable range. The sustainability index within the moderately sustainable category suggests that the condition and management of the mangrove ecosystems are at an intermediate level. The classification of moderately sustainable implies that, although the key ecological functions of the mangrove ecosystems remain preserved, further efforts are necessary in areas such as community participation, local economic development, and institutional capacity in order to achieve a fully sustainable condition [8,51,52]. Furthermore, this status suggests that without targeted and sustained improvement efforts, mangrove ecosystems are at risk of declining into a less sustainable condition [8, 48].

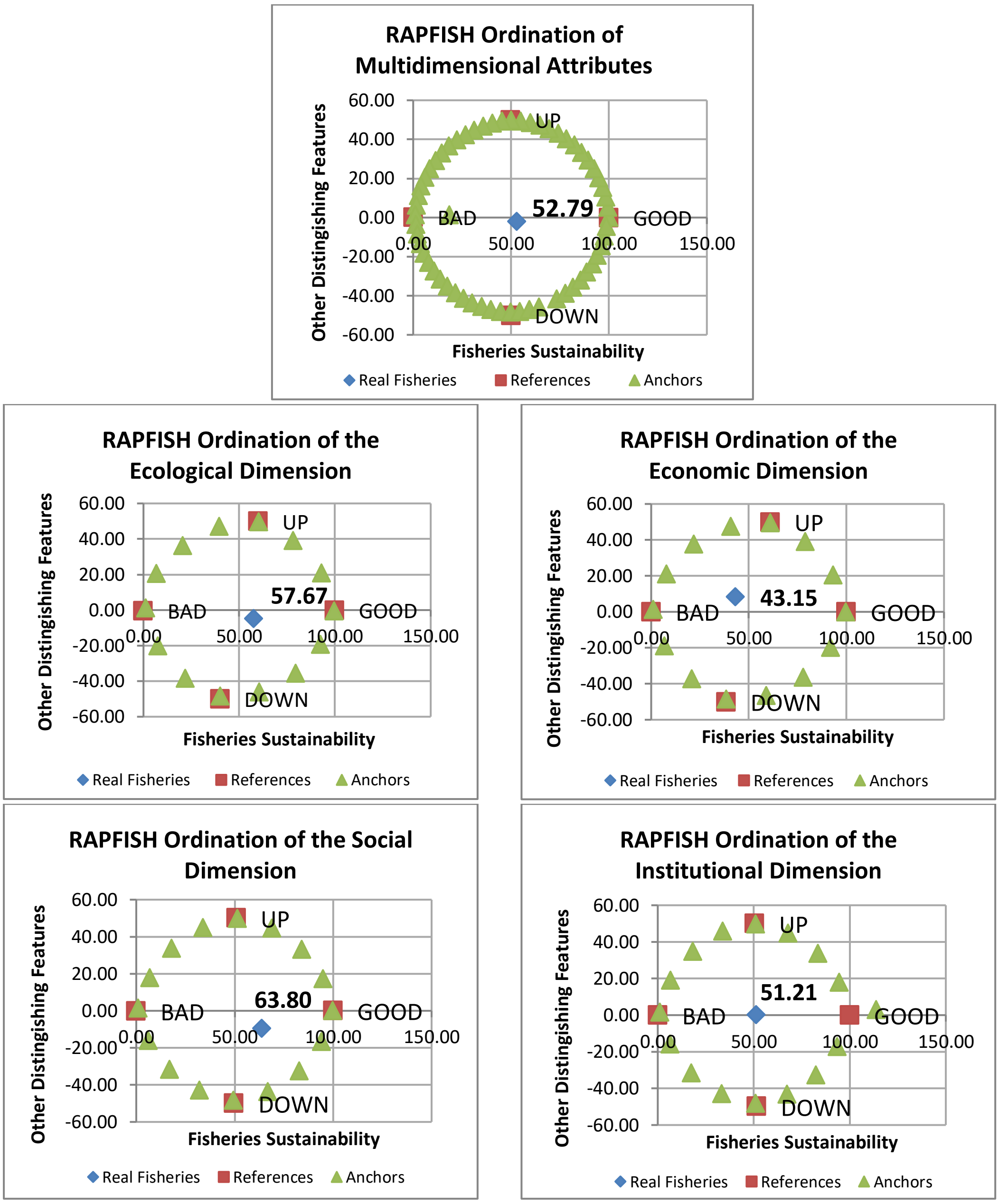


Figure 3. Multidimensional sustainability index for mangrove ecosystem management in the Gili Sulat and Gili Lawang, presenting the overall sustainability status derived from ecological, economic, social, and institutional dimensions. The Horizontal axis represents the sustainability index (0% bad – 100% good).

Table 6. Mangrove ecosystem sustainability in Gili Sulat and Gili Lawang protected forest.

Dimensions	Index Scores (%)		Coefficient of Determination	Stress Value
	MDS	Monte Carlo	R^2	S
Ecological	57.67	56.87	0.9446	0.14
Economic	43.15	43.38	0.9418	0.15
Social	63.80	62.18	0.9451	0.14
Institutional	51.21	50.94	0.9378	0.16
Multidimensional	52.79	52.62	0.9564	0.13

The Stress value, Coefficient of Determination (R^2), and Monte Carlo analysis are outputs from the RAPFISH application, which is used to assess the accuracy of the MDS model. The model is considered reliable when the difference between MDS and Monte Carlo results is less than 5%, indicating precision in estimating the sustainability index. In this research, the differences ranged from 0.17% to 1.62%, with the highest found in the social dimension. R^2 values between 0.9378 and 0.9564 suggest that the data are well represented in the ordination space, with two iterations performed for each dimension. The model's reliability is further supported by Stress values between 0.14 and 0.16 across all dimensions, and 0.13 in the overall analysis, which is well below the acceptable threshold of 0.25, indicating that the data are suitable for further interpretation.

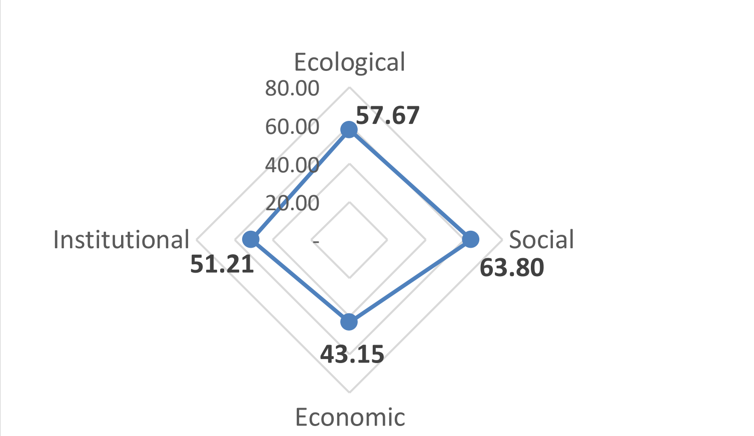
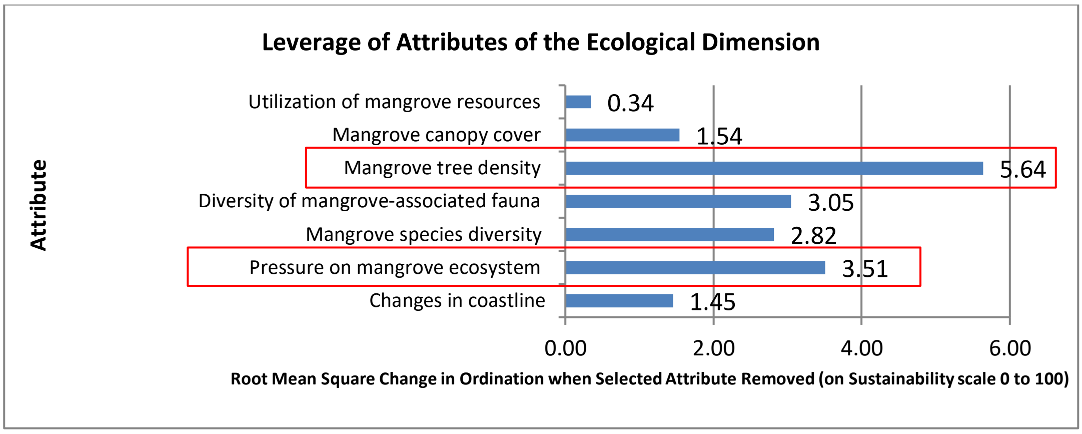
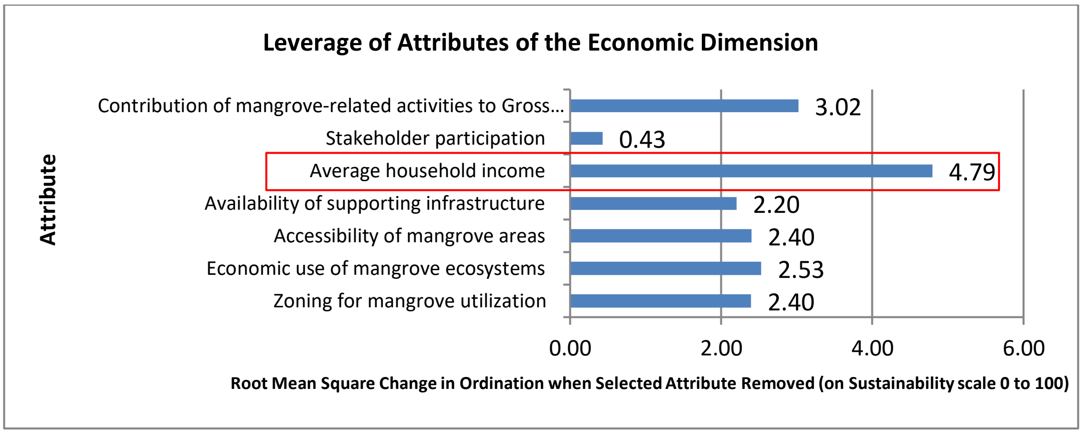


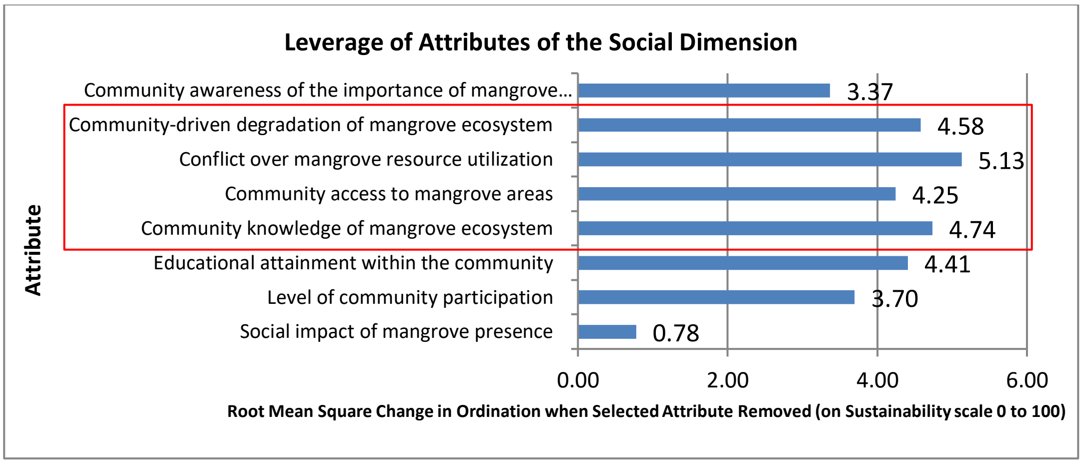
Figure 4. The kite diagram showed the relative position of the sustainability index for each dimension.

Figure 4 shows that mangrove ecosystem management in Gili Sulat and Gili Lawang still requires improvement, particularly in the economic dimension, as indicated by the diagram's contraction toward the lower left quadrant. The social dimension, although not yet optimal, is the strongest, making a significant contribution to current management. The ecological and institutional dimensions are at a moderate level, with potential for further development. Despite relative strengths in these three dimensions, full sustainability has not been achieved due to existing imbalances. Identifying the most influential attributes in each dimension is crucial for guiding targeted strategies and ensuring balanced, sustainable progress.

Seven attributes were assessed for the ecological dimension, yielding a sustainability index of 57.67% (Table 6 and Figure 3), classified as moderately sustainable. This indicates that the management efforts undertaken by local communities and relevant stakeholders have been relatively effective. The mangrove ecosystem in this area has been well preserved ecologically. This is supported by the results of the spatial analysis, which reveal that coastal areas identified as mangrove forests exhibit high density. However, the sustainability of this dimension can still be improved to achieve a higher level of sustainability through enhanced management strategies, given the critical ecological role that mangrove ecosystems play in supporting small islands.







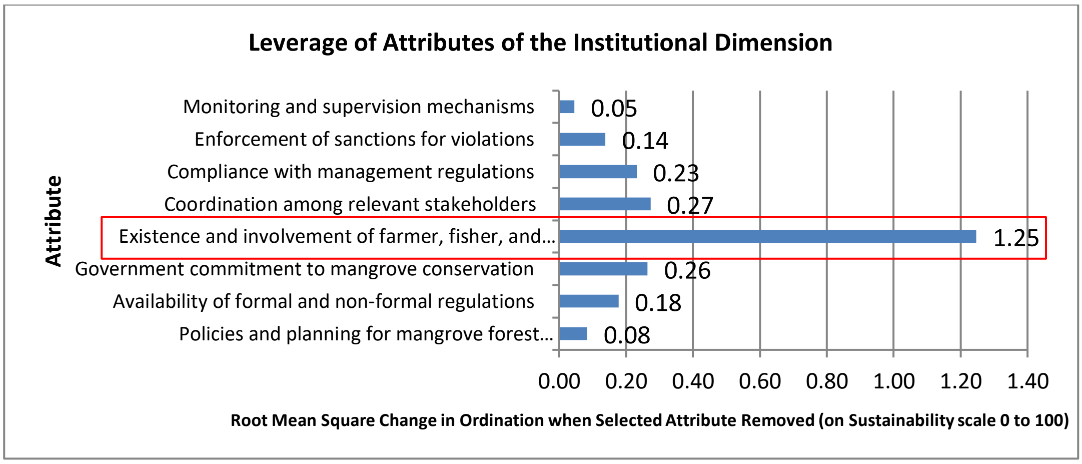


Figure 5. Leverage analysis results showing nine sensitive attributes across four sustainability dimensions.

The results of the leverage analysis for the ecological dimension indicate that mangrove tree density and pressures on the mangrove ecosystem have a significant influence on ecological sustainability (Figure 5). Mangrove density is considered an indicator of ecological balance within mangrove ecosystems [53]. One key indicator that reflects the quality of a mangrove ecosystem is its density. It is closely related to litter production, where higher mangrove forest density leads to increased litter accumulation. The detritus and nutrients derived from this litter serve as a food source for macro-zoobenthos. When food sources are abundant, the benthic fauna population also increases [53].

The economic dimension recorded the lowest sustainability index among all dimensions, with a score of 43.15%, indicating a low level of sustainability (Figure 4). This suggests that current economic practices in Gili Sulat and Gili Lawang have not yet succeeded in supporting sustainable livelihoods, reducing poverty, or promoting long-term community well-being. This is evident from the limited use of resources, which is currently focused on capture fisheries, while ecotourism activities are inactive, and the utilization of non-timber mangrove products has not been developed. As a result, the welfare of the surrounding communities remains suboptimal.

Average household income is a sensitive attribute within the economic dimension (Figure 5). At least 77% of respondents reported an average income below the 2025 Minimum Wage for East Lombok Regency [45]. This condition arises because not all individuals working as fishers have secondary or alternative jobs when they are unable to go to the sea. Of the 69 respondents, only 24 individuals, or 35%, reported having additional employment as farmers. The period from December to March is considered the lean season for fishers [54], during which their income is significantly reduced or even nonexistent.

The social dimension is classified as moderately sustainable, with an index score of 63.80% based on eight assessed attributes (Figure 4). This suggests that the local community has recognized the social benefits of the mangrove ecosystem in Gili Sulat and Gili Lawang. Leverage analysis identified five sensitive attributes: (1) conflicts over mangrove utilization, (2) community knowledge of the mangrove ecosystem, (3) community-driven degradation of the mangrove ecosystem, (4) educational attainment within the community, and (5) community access to mangrove areas (Figure 5). High public awareness of the importance of mangroves is driven by the tangible benefits that local communities experience. Strong community participation in managing and protecting the mangrove ecosystem in Gili Sulat and Gili Lawang often results in conflicts with outsiders, particularly fishers. Environmentally destructive fishing practices persist, especially among fishers from outside the Gili area, including some from Sumbawa Island [54].

The sustainability analysis of eight institutional attributes resulted in an index score of 51.21%, indicating a moderately sustainable status (Figure 4). This suggests that institutional systems are functioning but require improvement, especially in stakeholder collaboration. The most sensitive attribute is the existence and involvement of farmer, fisher, and community groups (Figure 5). In Sugian Village, 20 active fisher groups address local fisheries issues and help protect the surrounding marine area. However, stronger protection and enforcement, including the role of law enforcement officers, remain necessary. Tourism awareness and community monitoring groups also support conservation efforts and participate in mangrove rehabilitation programs led by non-governmental organizations.

3.1.3. Result of the Spatial Analysis

The result of the Advanced Vegetation Index (AVI), computed using equation (2), is illustrated in Figure 6. Higher AVI values signify the presence of vegetation cover, represented in bright green, whereas lower AVI values indicate non-vegetated areas or open land, represented in pale green. The results of the Bare Soil Index (BSI), calculated using equation (3), are presented in Figure 6. Higher BSI values indicate areas dominated by open land or non-vegetated areas, represented in red. Conversely, lower BSI values denote areas covered by vegetation, represented in green, and are associated with higher FCD values. Based on equation (4), Figure 6 also shows the result of the Shadow Index (SI) calculation. A high SI value in the study area indicates the presence of vegetation, represented by darker tones. In contrast, lower SI values correspond to grassland or open land and are characterized by relatively brighter hues. Based on equation (5), Thermal Index (TI) results are obtained as shown in Figure 6. High temperatures are associated with non-vegetated or exposed soil areas, represented in red. The results of the Forest Canopy Density (FCD), calculated using equation (6), are presented in Figure 7. Higher Forest Canopy Density (FCD) values indicate a denser forest canopy [49]. The Forest Canopy Density (FCD) shows that coastal areas identified as mangrove forests exhibit high density.

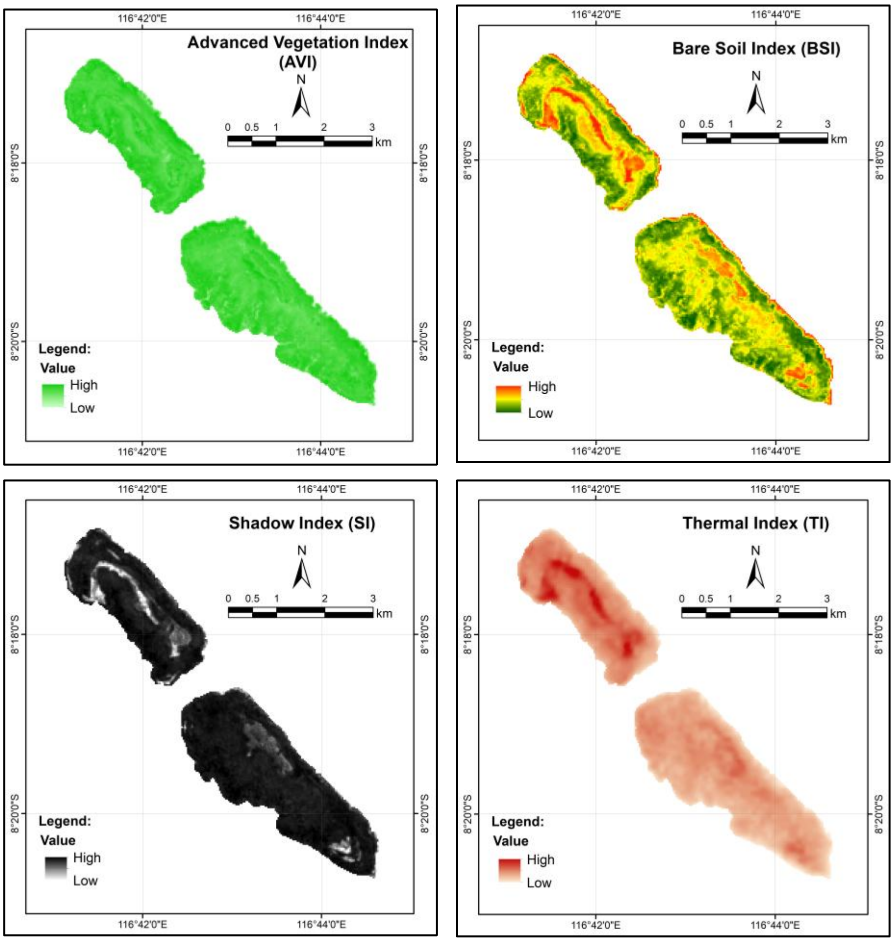


Figure 6. The Advanced Vegetation Index (AVI), Bare Soil Index (BSI), Shadow Index (SI), and Thermal Index (TI) outputs are utilized as fundamental parameters in the formulation of the FCD model.

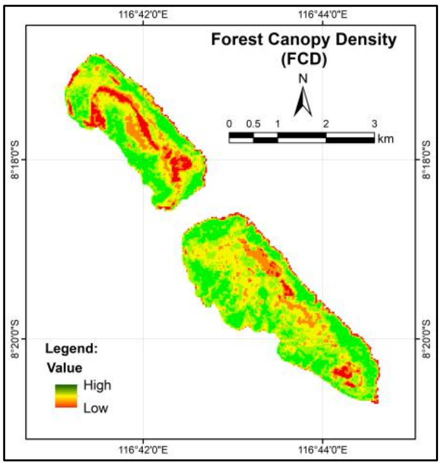


Figure 7. Forest Canopy Density (FCD) model illustrating the spatial distribution of canopy density in Gili Sulat and Gili Lawang, where areas with high canopy density are represented in green and areas with low canopy density are represented in red.

3.2. Discussion

The Sustainability Assessment indicates moderately sustainable mangrove ecosystems, supported by Forest Canopy Density (FCD) results showing areas of high vegetation density. These healthy, dense mangroves reflect effective conservation efforts and provide practical benefits for climate change mitigation, including carbon sequestration, shoreline protection, and support for local communities and their livelihoods. Maintaining and restoring high canopy density through community-based management directly enhances ecological resilience and contributes to climate adaptation. These findings can guide policymakers in implementing targeted actions such as zoning for conservation and restoration, integrating mangrove management into local development plans, supporting community stewardship programs, and allocating resources to areas with degraded forests.

The biodiversity of mangrove ecosystems is closely linked to their ecological condition. A decline in mangrove density occurred across all three zoning categories, with the most significant decrease observed in the sustainable fisheries zone, where density dropped from 2,100 individuals/ha to 1,622 individuals/ha [21]. Sustainable utilization must remain within the ecosystem's carrying capacity and comply with the existing zoning regulations [23]. Strengthening forest and marine patrols is a key strategy for protecting mangrove density and biodiversity. However, enforcement is hampered by limited personnel and logistical constraints, including high fuel costs for patrols in Gili Sulat and Gili Lawang.

Fishery resource extraction in these areas must adopt sustainable practices. Non-timber forest products offer low-impact economic opportunities, while ecotourism can be revitalized if ecological limits are respected. Both avenues have the potential to improve local livelihoods. A comprehensive economic valuation of mangrove ecosystems would inform stakeholders in future resource management decisions. Economic sustainability in Cengkrong, East Java, achieved a higher index (73.46%). This success is linked to diverse economic activities, including tourism services and sustainable resources [50].

In Gili Sulat and Gili Lawang, community-led ecotourism, facilitated through the POKDARWIS Gili Sulang group, declined following the 2018 earthquake and the COVID-19 pandemic. Ecotourism activities are managed under the Social Forestry scheme, and POKDARWIS Gili Sulang is currently pursuing legal recognition through a Community Forest decree, due to the protected forest status of Gili Sulat and Gili Lawang. Tourism infrastructure, including the wooden walkway in Gili Sulat, was destroyed by the earthquake and remains unrestored. Enhancing access and linking the area with nearby tourism destinations, such as the Gili Matra islands, could attract more visitors. According to Hilyana et al. [13], the area could accommodate up to 17,526 visitors annually based on spatial optimization.

Based on input from the Marine and Fisheries Department of West Nusa Tenggara Province, the development of ecotourism in the Gili Sulat and Gili Lawang areas is directed toward becoming conservation-based educational ecotourism. This finding is also in line with the results shown by the Forest Canopy Density (FCD), which quantifies the proportion of ground covered by tree crowns and is widely used as an indicator of forest health, structure, and ecological status. High FCD typically reflects healthy, undisturbed forests, while lower FCD may indicate degradation, fragmentation, or the need for rehabilitation interventions [50–53]. Areas with high FCD are prioritized for conservation, whereas zones with low FCD may be targeted for rehabilitation or management interventions [52,54].

Contrary to initial expectations, which posited a positive correlation between educational attainment and community knowledge of mangrove ecosystems, empirical observations and research findings reveal that the community demonstrates a relatively high level of mangrove knowledge despite generally low to moderate educational backgrounds. Notably, while 38% of residents have completed only elementary education and merely 1% hold university degrees, awareness and understanding of mangrove ecosystems remain comparatively high. This is likely driven by local campaigns, rehabilitation efforts, and the involvement of NGOs. These findings differ from studies linking low education levels to inequality and unsustainable resource use [55,56]. Residents of nearby sub-villages avoid destructive practices despite modest education and income. However, limited educational access remains a constraint. Expanding educational opportunities could strengthen resilience and environmental responsibility [56,57]. Compliance with regulations is generally strong among communities closest to Gili Sulat and Gili Lawang but weaker in more distant sub-villages and among outsiders. This may reflect inadequate enforcement, as initial violations are typically met with verbal warnings, reducing deterrence.

National level commitment is reflected in Government Regulation Number 27 of 2025 [58]. This regulation outlines the preparation and implementation of Mangrove Ecosystem Protection and Management Plans at the national, provincial, and district levels. These plans are based on ecosystem function mapping, baseline assessments, and alignment with the National Mangrove Ecosystem Plan. By guiding the development of relevant policies, strategies, and targets, these plans aim to structure sustainable utilization, monitoring, control, and climate adaptation efforts. Local governments are encouraged to promptly formulate and adopt the Mangrove Ecosystem Protection and Management Plan. This approach ensures that the use of mangrove ecosystems aligns with their designated functions, whether for protection or sustainable development.

Engaging local communities is essential for effective mangrove conservation, as residents possess first-hand knowledge of environmental changes and depend on mangroves for livelihoods such as fishing, aquaculture, and ecotourism. Active participation in activities such as monitoring, reforestation, and sustainable resource management enhances the practicality and long-term success of conservation initiatives. Collaboration among stakeholders enhances outcomes, with local governments providing regulatory support, funding, and technical guidance; NGOs delivering training, awareness campaigns, and facilitating community-led programs; and community members contributing to implementation and monitoring. Additionally, Forest Management Units play a vital role as facilitators of community development through social forestry programs, supporting sustainable livelihoods while promoting ecological restoration. Coordinated efforts, including joint planning, restoration projects, and shared monitoring programs, promote compliance, improve ecological integrity, and generate socio-economic benefits through sustainable livelihoods.

This study is limited by the use of medium-resolution FCD data, which may not capture fine-scale or seasonal variations in canopy structure, and by a sustainability assessment that does not fully incorporate the economic valuation of mangrove ecosystem services, such as fisheries, ecotourism, and carbon sequestration. Future research should employ higher-resolution, multi-temporal FCD analyses and assess the economic valuation of mangrove ecosystem services in Gili Sulat and Gili Lawang.

4. Conclusions

This research concludes that mangrove ecosystem management in Gili Sulat and Gili Lawang is moderately sustainable, with an overall index of 52.79%. The ecological (57.76%), social (63.80%), and institutional (51.21%) dimensions are also moderately sustainable, while the economic dimension is less sustainable (43.15%). Leverage analysis identified nine sensitive attributes across these dimensions. The Forest Canopy Density (FCD) shows that coastal areas identified as mangrove forests exhibit high density. Improving ecological sustainability in protected forests requires several strategic actions, including strengthening forest and marine patrols, developing conservation-based educational ecotourism within ecological limits, and promoting mangrove-based livelihoods. Local governments are encouraged to promptly formulate and adopt the Mangrove Ecosystem Protection and Management Plan. Future research should include multi-temporal FCD analyses and comprehensive economic valuation to support integrated evidence-based planning.

Author Contributions

ASP: Conceptualization, Methodology, Analysis, Software, Investigation, Writing – Original Draft & Editing; **MK**: Review, Supervision, Validation; **WA**: Review, Supervision & Validation.

Conflicts of interest

There are no conflicts to declare

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