



## Ecological Condition, Degradation Status, and Restoration Priorities for Sustainable Mangrove Conservation in the Kepetingan Coastal Landscape, East Java, Indonesia

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### ABSTRACT

**Purpose of the study:** This study aimed to assess the ecological condition, degradation status, and environmental suitability of mangrove ecosystems in the Kepetingan Coastal Area, East Java, Indonesia, and to identify stakeholder-based restoration priorities to support sustainable mangrove landscape conservation and ecosystem recovery.

**Methodology:** Field surveys were conducted at three sampling stations representing settlement, estuarine, and abandoned aquaculture pond areas. Mangrove vegetation was assessed using the line transect–plot method. Vegetation density, frequency, dominance, and Importance Value Index (IVI) were analyzed. Water temperature, salinity, dissolved oxygen, and pH were measured using field instruments. Mangrove degradation status was evaluated using critical mangrove land assessment criteria, while restoration priorities were determined through SWOT analysis based on stakeholder interviews and questionnaires.

**Main Findings:** Five mangrove species were identified, with *Rhizophora stylosa*, *Avicennia marina*, and *Bruguiera gymnorrhiza* showing the highest ecological importance. Tree density ranged from 300–600 trees ha<sup>-1</sup>, indicating degraded ecosystem conditions. The critical land assessment produced a score of 285, classifying the area as critical mangrove land. Mangrove cover declined from 140.54 ha in 2010 to 109.20 ha in 2015. Environmental parameters remained suitable for restoration, and SWOT analysis identified the Weakness–Opportunity (WO) strategy as the highest restoration priority.

**Novelty/Originality of this study:** This study integrates ecological condition assessment, environmental quality evaluation, mangrove degradation analysis, and stakeholder-based SWOT planning within a single restoration framework. The approach provides a comprehensive basis for determining restoration priorities and contributes to the development of integrated mangrove landscape conservation strategies in degraded tropical coastal ecosystems.

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## 1. INTRODUCTION

Mangrove ecosystems are among the most productive and valuable coastal ecosystems in the world because they provide a wide range of ecological, economic, and social benefits [1]-[3]. These ecosystems support shoreline stabilization, nutrient cycling, biodiversity conservation, fisheries productivity, and carbon sequestration. In addition, mangrove forests function as natural barriers that protect coastal areas from erosion, storm surges, and extreme weather events [4]-[6]. Through these ecological functions, mangroves contribute significantly to the resilience of coastal communities facing environmental and climate-related challenges [7]-[9]. Consequently, mangrove conservation has become an important component of sustainable coastal management and global environmental protection efforts.

Despite their ecological importance, mangrove ecosystems continue to experience severe degradation in many tropical and subtropical regions. Rapid coastal development, aquaculture expansion, urbanization, pollution, and unsustainable resource exploitation have accelerated mangrove loss worldwide [10]-[12]. This degradation has resulted in declining biodiversity, reduced ecosystem services, increased shoreline vulnerability, and the disruption of ecological processes [13], [14]. Furthermore, the conversion and degradation of mangrove forests may release large amounts of stored carbon into the atmosphere, thereby contributing to climate change [15], [16]. These environmental consequences have increased international concern regarding the long-term sustainability of mangrove ecosystems.

Indonesia possesses the largest mangrove area in the world and plays a crucial role in global mangrove conservation. Mangrove ecosystems in Indonesia support diverse flora and fauna while providing essential resources and livelihood opportunities for coastal communities [17]-[19]. However, many Indonesian mangrove areas are currently experiencing degradation due to land-use change, aquaculture development, illegal harvesting, and environmental pollution. The continued decline of mangrove ecosystems threatens ecological stability and reduces the ability of coastal environments to provide essential ecosystem services [20], [21]. Therefore, effective conservation and restoration strategies are urgently needed to ensure the sustainability of mangrove ecosystems in Indonesia.

Mangrove restoration has emerged as a widely recognized approach for addressing ecosystem degradation and promoting environmental sustainability [22]-[24]. Modern restoration practices have shifted beyond conventional tree planting and increasingly emphasize ecological restoration principles, including the recovery of ecosystem functions, biodiversity, hydrological processes, and habitat quality. Successful restoration requires not only suitable environmental conditions but also the active participation of stakeholders and effective governance mechanisms [25]-[27]. In recent years, mangrove restoration has also been promoted as a Nature-based Solution (NbS) capable of simultaneously supporting biodiversity conservation, climate adaptation, and disaster risk reduction [28]-[30]. As a result, restoration initiatives are increasingly viewed as strategic investments for achieving sustainable coastal development.

The growing interest in mangrove restoration is closely linked to its contribution to climate change mitigation and adaptation. Healthy mangrove ecosystems can store substantial amounts of carbon in both vegetation biomass and sediments, a function commonly referred to as blue carbon sequestration [31]-[33]. At the same time, mangroves enhance coastal resilience by reducing wave energy, stabilizing shorelines, and protecting communities from coastal hazards. These multifunctional benefits position mangrove restoration as a key component of several international environmental agendas, including the Sustainable Development Goals (SDGs) [34], [35]. Specifically, mangrove restoration contributes to SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Therefore, understanding factors that influence restoration success is becoming increasingly important for both local and global conservation efforts.

The Kepetingan Coastal Area in Sawohan Village, Buduran District, Sidoarjo Regency, East Java, represents an important mangrove landscape that provides ecological and socio-economic benefits for surrounding communities. The area supports various coastal organisms, contributes to fisheries productivity, and possesses considerable potential for ecotourism development. Nevertheless, increasing anthropogenic pressures, including aquaculture activities, land conversion, environmental pollution, and unsustainable resource use, have contributed to the degradation of mangrove habitats in the region [12], [36], [37]. Evidence of declining mangrove cover and deteriorating ecosystem conditions indicates that the ecological integrity of the area is under threat. Consequently, effective restoration and conservation measures are required to support the long-term sustainability of the Kepetingan coastal landscape.

Several previous studies have investigated mangrove ecosystems by focusing on specific aspects such as vegetation structure, species composition, environmental quality, or restoration techniques [38]-[40]. These studies have generated important ecological information that supports mangrove conservation and management. However, most previous research has examined these aspects separately and has not comprehensively integrated ecological condition, environmental suitability, ecosystem degradation status, and stakeholder perspectives within a single restoration framework. Such integration is essential because restoration outcomes are strongly influenced by ecological, environmental, social, and institutional factors that interact simultaneously. The limited

integration of these dimensions represents an important research gap in the development of effective mangrove restoration strategies.

To address this gap, the present study adopts an integrated approach that combines ecological assessment, environmental quality evaluation, degradation analysis, and stakeholder-based restoration planning. Unlike previous studies that primarily focused on ecological or environmental characteristics alone, this research incorporates SWOT-based stakeholder analysis to identify restoration priorities within a degraded mangrove landscape. The integration of ecological and socio-institutional dimensions provides a more comprehensive understanding of restoration opportunities and constraints [41]-[43]. This approach constitutes the novelty of the study because it links ecosystem condition assessment directly with restoration planning and landscape conservation strategies. Consequently, the study contributes to the growing body of knowledge on integrated mangrove restoration and Nature-based Solutions for coastal ecosystem management.

Therefore, this study aims to (1) assess the ecological condition of mangrove vegetation in the Kepetingan Coastal Area, (2) evaluate the degradation status and environmental suitability of mangrove habitats, and (3) identify restoration priorities through stakeholder-based SWOT analysis. The results are expected to provide scientific evidence for developing sustainable mangrove restoration strategies in degraded coastal ecosystems. Furthermore, the findings may support decision-making processes related to biodiversity conservation, climate adaptation, and ecosystem-based coastal management. The study also offers practical recommendations for integrating ecological restoration with stakeholder participation in mangrove conservation programs. Ultimately, the proposed restoration framework may serve as a reference for sustainable mangrove landscape conservation in other tropical coastal regions experiencing similar environmental challenges.

## 2. RESEARCH METHOD

### 2.1 Study Area

This study was conducted in the mangrove ecosystem of Kepetingan Coastal Area, located in Sawohan Village, Buduran District, Sidoarjo Regency, East Java, Indonesia (Figure 1). The study area represents one of the remaining mangrove ecosystems along the eastern coast of Sidoarjo and provides important ecological functions, including shoreline protection, nursery habitat for aquatic organisms, biodiversity conservation, and support for local livelihoods.

The Kepetingan coastal landscape is characterized by the interaction of marine and riverine processes and comprises various land-use types, including natural mangrove stands, estuarine habitats, residential areas, and abandoned aquaculture ponds. The area has experienced increasing anthropogenic pressures, particularly from aquaculture expansion, settlement development, and resource utilization, which have contributed to mangrove degradation.

Field data collection was conducted from December 2015 to January 2016 at three sampling stations selected purposively to represent different environmental conditions and levels of disturbance. Station 1 is Mangrove area adjacent to residential settlements; Station 2 is Estuarine zone near the river mouth; Station 3 is Mangrove area associated with abandoned aquaculture ponds. The selected stations were intended to represent the variability of ecological conditions within the Kepetingan coastal landscape and to support the assessment of restoration priorities.

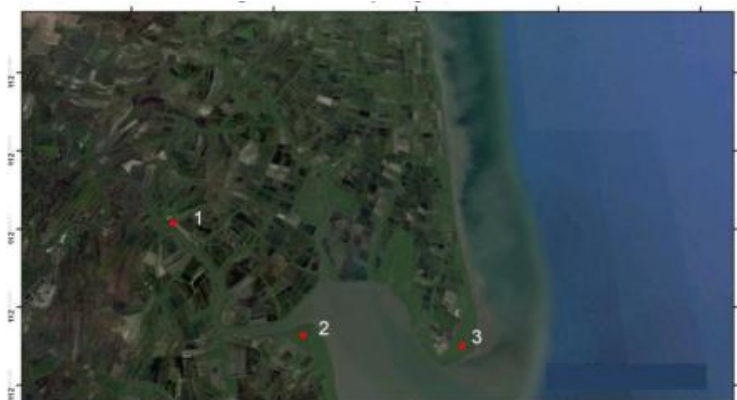


Figure 1. Research Location

The first station is located at Latitude: 7°48'063''S and Longitude: 112°81'637''E. The second station is located at Latitude: 7°47'2833''S and Longitude: 112°82'219''E. S. The third station is located at Latitude: 7°48'405''S and Longitude: 112°83'691''E.

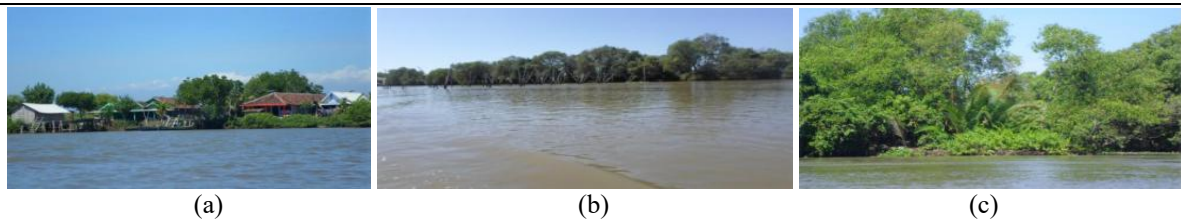


Figure 2. Station 1 (a), Station 2 (b), Station 3 (c)

## 2.2 Research Design

This study employed a descriptive-survey approach integrating ecological assessment, environmental quality evaluation, and stakeholder-based restoration analysis. Ecological data were collected through field observations and vegetation surveys, while social and management-related information was obtained through interviews and questionnaires administered to relevant stakeholders. The research framework consisted of three main stages:

1. Assessment of mangrove ecological conditions;
2. Evaluation of mangrove degradation status and environmental suitability;
3. Formulation of restoration priorities using SWOT analysis.

The integration of ecological and socio-institutional assessments was used to develop recommendations for sustainable mangrove landscape conservation.

## 2.3 Mangrove Vegetation Assessment

Mangrove vegetation was assessed using the line transect–plot method. Transects were established perpendicular to the coastline at each sampling station to capture variations in vegetation structure along the tidal gradient. Vegetation observations were conducted for three growth stages: seedlings, saplings, and trees. For each species encountered, the following parameters were recorded: Species composition, Density, Frequency, Dominance, and Importance Value Index (IVI). Species density was calculated using:

$$D = \frac{N}{A} \quad \dots(1)$$

where:

- $D$  = density (individuals  $\text{ha}^{-1}$ );
- $N$  = number of individuals recorded;
- $A$  = sampled area (ha).

Relative density (RD), relative frequency (RF), and relative dominance (RDo) were subsequently calculated to determine species ecological importance. The Importance Value Index (IVI) was obtained as:

$$IVI = RD + RF + RDo \quad \dots(2)$$

IVI values were used to identify dominant species and evaluate the ecological structure of the mangrove community. Mangrove condition was further evaluated based on vegetation density criteria established in the Decree of the Indonesian Minister of Environment No. 201 of 2004 concerning mangrove damage assessment.

## 2.4 Assessment of Mangrove Degradation Status

The degradation status of mangrove ecosystems was evaluated using the criteria established by the Directorate General of Reforestation and Land Rehabilitation and the Indonesian Ministry of Forestry for critical mangrove land assessment. The assessment incorporated three primary indicators:

1. Mangrove land cover condition;
2. Vegetation density;
3. Land-use pressure.

Each indicator was assigned a score according to the national critical mangrove assessment guidelines. The total score was used to classify mangrove conditions into the following categories: Very Critical; Critical; Moderately Critical; Good. This approach enabled the identification of degradation levels and restoration needs within the study area.

## 2.5 Environmental Quality Assessment

Environmental suitability for mangrove restoration was evaluated through in situ measurements of water quality parameters at each sampling station. The measured parameters included: temperature ( $^{\circ}\text{C}$ ); salinity

(‰); dissolved oxygen (DO, mg L<sup>-1</sup>); pH. Measurements were conducted using calibrated field instruments, including a digital thermometer, refractometer, dissolved oxygen meter, and portable pH meter. Water quality values were compared with ecological requirements for mangrove growth and relevant Indonesian marine water quality standards to evaluate habitat suitability for restoration activities.

## 2.6 Stakeholder-Based SWOT Analysis

Stakeholder perceptions regarding mangrove conservation and restoration were assessed through structured interviews and questionnaire surveys involving local community members, government representatives, and stakeholders associated with mangrove management in the Kepetingan Coastal Area. The SWOT framework was applied to identify internal and external factors influencing restoration success: Strengths (S); Weaknesses (W); Opportunities (O); Threats (T).

Each factor was assigned a weight reflecting its relative importance and a rating representing its influence on restoration outcomes. Weighted scores were subsequently calculated to develop: Internal Factor Analysis Summary (IFAS); External Factor Analysis Summary (EFAS). The resulting IFAS and EFAS matrices were used to formulate four strategic alternatives: SO (Strength–Opportunity); WO (Weakness–Opportunity); ST (Strength–Threat); WT (Weakness–Threat). The strategy obtaining the highest composite score was selected as the priority restoration strategy.

## 2.7 Data Analysis

Vegetation data were analyzed to determine species composition, density, frequency, dominance, and Importance Value Index (IVI). Environmental quality data were summarized descriptively and compared among sampling stations. Mangrove degradation status was evaluated through the critical land assessment scoring system, while restoration priorities were determined using SWOT matrix analysis based on IFAS and EFAS scores. Finally, the results of ecological assessment, environmental quality evaluation, and stakeholder analysis were integrated to identify restoration priorities and formulate recommendations for sustainable mangrove landscape conservation in the Kepetingan Coastal Area.

# 3 RESULTS AND DISCUSSION

## 3.1 Ecological Condition of Mangrove Vegetation

The mangrove ecosystem in the Kepetingan Coastal Area consisted of five mangrove species, namely *Avicennia marina*, *Rhizophora stylosa*, *Rhizophora mucronata*, *Sonneratia alba*, and *Bruguiera gymnorrhiza*. Species composition varied among sampling stations, reflecting differences in habitat characteristics and disturbance intensity [44]–[46]. Station 1 was dominated by *Rhizophora stylosa* and *Avicennia marina*, Station 2 by *Rhizophora mucronata*, *Avicennia marina*, and *Sonneratia alba*, whereas Station 3 was dominated by *Bruguiera gymnorrhiza* and *Sonneratia alba*.

Mangrove density analysis revealed substantial variation among stations (Table 1). Tree density ranged from 300 to 600 trees ha<sup>-1</sup>, with the highest density recorded at Station 2 (600 trees ha<sup>-1</sup>) and the lowest at Station 3 (300 trees ha<sup>-1</sup>). Station 1 exhibited an intermediate density of 500 trees ha<sup>-1</sup>. According to the Indonesian Ministerial Decree No. 201 of 2004, all stations were classified as degraded because tree density remained below the threshold of 1,000 trees ha<sup>-1</sup> for healthy mangrove stands.

Table 1. Mangrove Tree Density at the Study Sites

Station	Site characteristics	Density (trees ha <sup>-1</sup> )	Category
Station 1	Settlement area	500	Degraded
Station 2	Estuarine area	600	Degraded
Station 3	Abandoned pond area	300	Degraded

The relatively higher density observed in the estuarine zone associated with favorable hydrological conditions and continuous sediment deposition that support mangrove establishment and growth [47], [48]. In contrast, the low density recorded in the abandoned aquaculture area indicates long-term ecological impacts of land conversion and habitat degradation [49], [50]. Similar patterns have been reported in tropical coastal ecosystems where aquaculture development represents one of the primary drivers of mangrove loss and fragmentation.

The analysis of relative cover further confirmed the degraded condition of the mangrove ecosystem. Most species exhibited relative cover values below 50%, indicating sparse canopy development. Only *Rhizophora stylosa* at Station 1 and *Bruguiera gymnorrhiza* at Station 3 showed cover values exceeding 50%, suggesting localized dominance and better adaptation to site-specific environmental conditions.

Species dominance was evaluated using the Importance Value Index (IVI). At Station 1, *Rhizophora stylosa* exhibited the highest IVI (165%), followed by *Avicennia marina* (135%). At Station 2, *Avicennia marina*

showed the highest IVI (106%), while *Rhizophora mucronata* and *Sonneratia alba* each recorded IVI values of 97%. At Station 3, *Bruguiera gymnorrhiza* demonstrated the highest ecological importance with an IVI of 172%, followed by *Sonneratia alba* (128%) (Table 2).

Table 2. Importance Value Index (IVI) of Mangrove Species

Station	Species	Tree IVI (%)
1	<i>Rhizophora stylosa</i>	165
1	<i>Avicennia marina</i>	135
2	<i>Avicennia marina</i>	106
2	<i>Rhizophora mucronata</i>	97
2	<i>Sonneratia alba</i>	97
3	<i>Bruguiera gymnorrhiza</i>	172
3	<i>Sonneratia alba</i>	128

The dominance of *Rhizophora*, *Avicennia*, and *Bruguiera* species indicates their ecological adaptability to local environmental conditions, including fluctuating salinity, tidal inundation, and muddy substrates [51], [52]. These species are commonly utilized in mangrove restoration programs due to their high survival capacity and important ecological functions in shoreline stabilization and habitat formation. Interestingly, vegetation observations revealed relatively abundant sapling and seedling stages at several stations despite the low density of mature trees. This condition suggests that the mangrove ecosystem still possesses natural regeneration potential [53], [54]. The presence of natural regeneration is an important ecological indicator because it reflects the capacity of the ecosystem to recover following disturbance and may reduce restoration costs through natural recruitment processes.

Beyond vegetation structure, field observations indicated that the mangrove ecosystem continues to provide habitat for a variety of associated fauna, including crustaceans, mollusks, fish, reptiles, and birds. These findings suggest that although ecological degradation has occurred, important ecosystem functions remain partially intact. Therefore, conservation efforts should prioritize both vegetation recovery and habitat protection to maintain biodiversity and ecosystem resilience within the Kepetingan coastal landscape [55]-[57].

### 3.2 Mangrove Degradation Status and Landscape Change

Assessment of mangrove degradation revealed that the Kepetingan Coastal Area is currently experiencing critical ecological conditions. Based on the mangrove critical land assessment, the ecosystem obtained a Total Scoring Value (TNS) of 285, categorizing the area as critical mangrove land. This classification indicates that the ecological condition of the mangrove ecosystem has declined beyond the threshold required to maintain optimal ecosystem functions and services.

The critical status is closely associated with the low density of mature mangrove trees observed across all sampling stations. Tree densities ranged from only 300–600 trees ha<sup>-1</sup>, which fall below the threshold for healthy mangrove ecosystems according to Indonesian environmental standards. Although natural regeneration was observed in some locations, the current vegetation structure suggests that ecosystem recovery is not sufficient to compensate for ongoing degradation pressures.

In addition to vegetation assessment, changes in mangrove extent were analyzed to evaluate landscape-level degradation. The results showed a substantial decline in mangrove cover between 2010 and 2015. Mangrove area decreased from 140.54 ha in 2010 to 109.20 ha in 2015, representing a net loss of 31.34 ha over a five-year period (Table 3). This reduction reflects significant land-cover transformation and indicates that degradation processes have continued to exceed the natural recovery capacity of the ecosystem [58], [59].

Table 3. Changes in Mangrove Extent in the Kepetingan Coastal Area

Year	Mangrove Area (ha)
2010	140.54
2015	109.20
Change	-31.34

The observed decline in mangrove cover is likely associated with multiple anthropogenic pressures, including aquaculture expansion, land conversion, resource extraction, and increasing human activities along the coastal zone. Similar patterns have been reported throughout Southeast Asia, where conversion of mangrove forests into aquaculture ponds remains one of the principal drivers of mangrove degradation [60], [61]. In the Kepetingan coastal landscape, abandoned aquaculture ponds observed at Station 3 provide evidence of historical land-use changes that have altered natural ecological processes and reduced vegetation density.

The critical condition of the mangrove ecosystem is further reflected by several indicators incorporated in the critical land assessment, including vegetation cover, land use, and ecological condition. The relatively low

vegetation cover observed in several species, combined with the fragmented distribution of mangrove stands, suggests a decline in ecosystem integrity. Habitat fragmentation may reduce ecological connectivity among mangrove patches, limiting species movement and decreasing ecosystem resilience to environmental disturbances [62], [63].

Mangrove degradation has important ecological implications for coastal sustainability. Reduced mangrove cover diminishes the ecosystem's capacity to protect shorelines from erosion, stabilize sediments, and buffer coastal communities against extreme weather events [64], [65]. Furthermore, the loss of mangrove habitat may negatively affect biodiversity because mangrove forests provide breeding, nursery, feeding, and shelter habitats for numerous aquatic and terrestrial organisms [66], [67]. The decline in habitat quality can ultimately reduce fisheries productivity and weaken ecosystem services that support local livelihoods.

From a landscape conservation perspective, the loss of 31.34 ha of mangrove cover represents more than a reduction in vegetation area; it reflects the gradual decline of ecological functions operating across the coastal landscape. Degraded and fragmented mangrove habitats are generally less capable of maintaining biodiversity, storing carbon, and adapting to climate-related disturbances such as sea-level rise and increased storm intensity [68], [69]. Consequently, restoration efforts in Kepetingan should prioritize not only the recovery of vegetation cover but also the restoration of ecological connectivity and ecosystem functionality across the broader coastal landscape.

The findings indicate that while the mangrove ecosystem remains under considerable ecological pressure, the presence of remnant mangrove stands and natural regeneration provides an opportunity for ecological recovery. Therefore, immediate restoration and conservation interventions are required to prevent further habitat loss and to support the long-term sustainability of the Kepetingan mangrove landscape.

### 3.3 Environmental Suitability for Mangrove Restoration

Environmental quality assessment indicated that the Kepetingan Coastal Area generally remains suitable for mangrove restoration despite the degraded condition of its vegetation structure. Water quality parameters measured at the three sampling stations showed values that largely fall within the ecological tolerance ranges for mangrove growth and development. These findings suggest that environmental conditions are not the primary constraint to ecosystem recovery and that restoration interventions have a high probability of success if accompanied by appropriate management measures.

Table 4. Water Quality Parameters at the Study Sites

Parameter	Station 1	Station 2	Station 3
Temperature (°C)	28 ± 0.1	30 ± 0.5	27 ± 0.2
Salinity (‰)	27 ± 0.17	25.3 ± 0.18	30 ± 0.57
Dissolved Oxygen (mg L <sup>-1</sup> )	4.8 ± 0.17	7.5 ± 0.30	5.1 ± 0.31
pH	7.3 ± 0.1	8.3 ± 0.2	7.4 ± 0.2

Water temperature ranged from 27°C to 30°C across sampling stations. The highest temperature was recorded at Station 2, while the lowest was observed at Station 3. These values are considered favorable for mangrove growth because tropical mangrove species generally thrive under temperatures between 25°C and 35°C. Temperature influences several physiological processes, including photosynthesis, respiration, nutrient absorption, and seedling establishment [70], [71]. Therefore, the observed temperature range indicates that thermal conditions in the study area remain suitable for restoration activities.

Salinity values varied from 25.3‰ to 30‰, reflecting typical estuarine and coastal conditions influenced by interactions between seawater and freshwater inputs. The lowest salinity was recorded at Station 2, which is located near the estuarine zone, whereas the highest salinity occurred at Station 3 in the abandoned pond area. The dominant mangrove species identified in this study, including *Rhizophora mucronata*, *Avicennia marina*, and *Bruguiera gymnorhiza*, are known for their adaptability to moderate and fluctuating salinity conditions. Consequently, salinity levels in the Kepetingan Coastal Area are unlikely to limit mangrove establishment or regeneration.

Dissolved oxygen (DO) concentrations ranged from 4.8 to 7.5 mg L<sup>-1</sup>. Station 2 exhibited the highest DO concentration, while Station 1 recorded the lowest value. The relatively high dissolved oxygen levels observed in the estuarine area associated with greater water circulation and hydrological exchange. In general, all measured values remained within acceptable ranges for supporting aquatic organisms associated with mangrove ecosystems. Adequate oxygen availability contributes to maintaining ecological functions, including nutrient cycling, organic matter decomposition, and habitat quality for fish, crustaceans, and other aquatic fauna [72], [73].

The pH values ranged from 7.3 to 8.3, indicating neutral to slightly alkaline conditions. Such values are commonly found in healthy tropical coastal ecosystems and are considered favorable for mangrove growth. Stable pH conditions facilitate nutrient availability and support microbial processes that are essential for

maintaining ecosystem productivity [74], [75]. The relatively narrow pH range observed among stations suggests that water chemistry remains stable despite ongoing anthropogenic disturbances.

Although most environmental parameters were within suitable ranges for mangrove development, the study identified localized signs of environmental degradation associated with human activities. Waste accumulation, aquaculture-related disturbances, and land-use changes may influence water quality over time if not properly managed. Nevertheless, the current environmental conditions indicate that ecological restoration efforts are unlikely to be constrained by abiotic factors.

The favorable environmental conditions observed in the study area provide important evidence that restoration initiatives can focus primarily on addressing ecological degradation and management deficiencies rather than overcoming environmental limitations. Similar findings have been reported in other degraded mangrove ecosystems where hydrological and physicochemical conditions remained suitable despite substantial reductions in vegetation cover. Under such circumstances, restoration success is often determined more by effective governance, stakeholder participation, and protection from further disturbance than by environmental constraints alone.

The combination of suitable temperature, salinity, dissolved oxygen, and pH conditions suggests that the Kepetingan Coastal Area retains a high ecological capacity for recovery. When coupled with the natural regeneration potential observed in several sampling stations, these environmental characteristics provide a strong foundation for implementing restoration programs aimed at restoring ecosystem structure, enhancing biodiversity, and improving long-term landscape resilience. Furthermore, maintaining environmental quality will be essential for ensuring the sustainability of restoration outcomes and supporting broader coastal conservation objectives [76], [77].

### 3.4 Stakeholder-Based Restoration Priorities

Effective mangrove restoration requires not only favorable environmental conditions but also strong institutional support, stakeholder participation, and appropriate management strategies. To identify restoration priorities in the Kepetingan Coastal Area, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted by integrating ecological observations with stakeholder perspectives.

The Internal Factor Analysis Summary (IFAS) revealed a total score of 2.931, consisting of a strength score of 0.969 and a weakness score of 1.962. Meanwhile, the External Factor Analysis Summary (EFAS) produced a total score of 3.590, comprising an opportunity score of 2.495 and a threat score of 1.095. These results indicate that external opportunities for mangrove restoration are relatively high, whereas internal weaknesses remain a major challenge that must be addressed.

#### *Internal and External Factors Affecting Mangrove Restoration*

Several strengths were identified within the Kepetingan mangrove ecosystem. These include the ecological importance of mangroves as habitats for various organisms such as birds, crabs, mollusks, and reptiles, relatively good regeneration potential reflected by the distribution of sapling-stage vegetation, community involvement in mangrove management, and the high diversity of natural resources associated with the coastal ecosystem. These strengths provide a valuable foundation for future restoration initiatives.

Despite these strengths, several weaknesses were also identified. The absence of seedling-stage vegetation in certain areas indicates limitations in natural recruitment processes. In addition, some water quality parameters did not fully meet environmental quality standards, while the overall mangrove ecosystem was categorized as critical. Limited public understanding of environmental regulations and conservation policies further constrains effective ecosystem management.

The analysis also revealed several opportunities that could support restoration efforts. These include the potential development of ecotourism and religious tourism, increasing government commitment to environmental awareness and conservation programs, the existence of legal frameworks protecting mangrove ecosystems, and government-supported mangrove restoration initiatives. Such opportunities can provide both financial and institutional support for long-term conservation efforts.

Conversely, several threats may hinder restoration success if not adequately addressed. These include shoreline changes, unsustainable expansion of aquaculture activities, illegal mangrove harvesting, and the gradual loss of biodiversity. These pressures continue to contribute to ecosystem degradation and may reduce the effectiveness of restoration programs in the future [78]-[80].

#### *Strategic Prioritization for Mangrove Restoration*

The combination of IFAS and EFAS scores was used to formulate restoration strategies through the SWOT matrix. Four strategic alternatives were generated: Strength–Opportunity (SO), Weakness–Opportunity (WO), Strength–Threat (ST), and Weakness–Threat (WT). The resulting scores are presented in Table 5.

Table 5. SWOT Strategic Priority Scores for Mangrove Restoration

Strategy	Score
SO (Strength–Opportunity)	3.464
WO (Weakness–Opportunity)	4.457
ST (Strength–Threat)	2.064
WT (Weakness–Threat)	3.057

Among the four alternatives, the Weakness–Opportunity (WO) strategy obtained the highest score (4.457), indicating that restoration efforts should prioritize reducing existing weaknesses while simultaneously maximizing available opportunities. This result suggests that although the ecosystem possesses significant restoration potential, successful implementation depends largely on overcoming current ecological and institutional limitations.

Based on the SWOT matrix, the primary restoration actions include improving human resource capacity and strengthening community participation in mangrove management, conducting ecological rehabilitation and restoration activities in degraded areas, increasing environmental education and awareness programs, and enhancing collaboration among government agencies, local communities, and other stakeholders. These measures are expected to address both ecological degradation and governance-related challenges that currently limit restoration effectiveness. The prioritization of community capacity development is particularly important because local communities represent the primary actors responsible for long-term ecosystem stewardship [81], [82]. Strengthening local participation can improve monitoring activities, reduce illegal resource exploitation, and increase public support for conservation initiatives. Furthermore, integrating restoration activities with ecotourism development may provide alternative livelihood opportunities that encourage sustainable resource use while generating economic benefits for local residents.

From a restoration ecology perspective, the dominance of the WO strategy highlights the importance of combining ecological rehabilitation with social and institutional interventions. Restoration success is unlikely to be achieved through tree planting alone. Instead, it requires a comprehensive approach that integrates habitat restoration, environmental education, community empowerment, and policy implementation. Such an approach can enhance both ecological resilience and social sustainability, thereby increasing the likelihood of long-term restoration success. Overall, the SWOT analysis demonstrates that the Kepetingan Coastal Area possesses substantial opportunities for mangrove recovery despite its current degraded condition. By addressing identified weaknesses and capitalizing on available opportunities, restoration initiatives can contribute significantly to biodiversity conservation, ecosystem resilience, and sustainable coastal landscape management.

### 3.5 Implications for Sustainable Mangrove Landscape Conservation

The findings of this study demonstrate that mangrove restoration in the Kepetingan Coastal Area should be implemented within a broader landscape conservation framework. The ecological assessment revealed that the mangrove ecosystem is currently in a degraded condition, characterized by low tree density, critical land status, and a substantial reduction in mangrove cover over time. Nevertheless, the presence of suitable environmental conditions and natural regeneration potential indicates that the ecosystem retains the capacity for recovery if appropriate restoration measures are implemented.

One of the most significant findings of this study is the contrast between ecological degradation and environmental suitability. Although the mangrove ecosystem was classified as critical and experienced a loss of approximately 31.34 ha of mangrove cover between 2010 and 2015, water quality parameters remained within ranges generally suitable for mangrove growth and development. This finding suggests that ecosystem degradation in Kepetingan is primarily driven by anthropogenic pressures rather than unfavorable environmental conditions. Consequently, restoration efforts should focus on addressing human-induced disturbances while maintaining environmental quality to facilitate natural recovery processes [83], [84].

The relatively high abundance of saplings and pole-stage vegetation observed at several stations further supports the possibility of ecological recovery. Natural regeneration represents an important component of restoration because it reflects the inherent resilience of the ecosystem [85], [86]. Ecosystems that retain natural recruitment processes generally require lower restoration costs and exhibit higher long-term sustainability compared with areas where regeneration has completely ceased. Therefore, restoration planning in Kepetingan should prioritize the protection of naturally regenerating areas while complementing them with active rehabilitation in severely degraded sites.

From a landscape conservation perspective, the decline in mangrove cover has implications that extend beyond vegetation loss alone. Mangrove ecosystems function as interconnected ecological networks that support biodiversity, fisheries productivity, nutrient cycling, and coastal protection [87], [88]. The reduction and fragmentation of mangrove habitats may disrupt ecological connectivity among estuarine, coastal, and marine ecosystems, thereby reducing ecosystem resilience. Maintaining and restoring connectivity among remnant mangrove patches should therefore be considered a key objective of future conservation programs.

The SWOT analysis further demonstrated that successful restoration depends on both ecological and socio-institutional factors. The identification of the Weakness–Opportunity (WO) strategy as the highest-priority restoration approach highlights the need to strengthen community capacity, improve stakeholder participation, and enhance environmental governance. These findings indicate that ecological restoration cannot be separated from social and institutional dimensions. Restoration programs that actively involve local communities are more likely to achieve long-term success because they foster local stewardship, increase compliance with conservation regulations, and promote sustainable resource management practices.

The opportunities identified through stakeholder analysis, particularly ecotourism development and government-supported conservation programs, provide important mechanisms for integrating conservation objectives with local economic development. Sustainable ecotourism initiatives can generate alternative income sources for coastal communities while simultaneously increasing public awareness of mangrove conservation [89]-[91]. Such approaches can create positive feedback between environmental protection and community welfare, thereby enhancing the sustainability of restoration outcomes.

Furthermore, mangrove restoration in Kepetingan has broader relevance to climate change adaptation and mitigation efforts. Healthy mangrove ecosystems play a critical role in reducing coastal vulnerability by stabilizing shorelines, attenuating wave energy, and protecting coastal communities from erosion and extreme weather events. At the same time, mangroves are recognized as important blue carbon ecosystems due to their ability to sequester and store large amounts of carbon in both biomass and sediments. Restoring degraded mangrove habitats can therefore contribute simultaneously to biodiversity conservation, climate resilience, and carbon management objectives [92], [93].

The results of this study also support the growing recognition of ecosystem-based management approaches in coastal conservation. Rather than focusing solely on reforestation activities, restoration initiatives should incorporate habitat protection, hydrological maintenance, environmental monitoring, community participation, and adaptive management. Such an integrated approach is essential for ensuring that restoration efforts generate long-term ecological benefits and remain resilient to future environmental and socio-economic changes.

Overall, the integration of ecological assessment, environmental quality evaluation, and stakeholder-based planning provides a comprehensive foundation for sustainable mangrove landscape conservation in the Kepetingan Coastal Area. The study highlights that effective restoration requires a balance between ecological recovery and socio-economic considerations. By combining habitat rehabilitation, community engagement, and institutional support, restoration programs can enhance ecosystem resilience and contribute to the long-term sustainability of tropical coastal landscapes.

### **3.6 Relevance of Mangrove Restoration to Contemporary Conservation Challenges**

Mangrove restoration has increasingly become a global conservation priority due to its capacity to address multiple environmental challenges simultaneously. The ecological degradation identified in the Kepetingan Coastal Area reflects broader patterns observed throughout tropical coastal regions, where rapid land-use change, population growth, aquaculture expansion, pollution, and climate-related disturbances continue to threaten the integrity of mangrove ecosystems. Consequently, the restoration of degraded mangrove landscapes is now recognized as a critical strategy for achieving both biodiversity conservation and sustainable development goals.

The substantial decline in mangrove cover documented in this study highlights the vulnerability of coastal ecosystems to human-induced disturbances. The loss of 31.34 ha of mangrove habitat between 2010 and 2015 not only reduced vegetation cover but also diminished the ecological functions that support coastal resilience and local livelihoods. Similar trends have been reported across Southeast Asia, where mangrove conversion for aquaculture and coastal development remains one of the leading causes of habitat degradation [60], [61]. These findings underscore the urgency of implementing restoration measures before ecosystem degradation reaches irreversible levels.

One of the most important contemporary perspectives in ecosystem restoration is the concept of Nature-based Solutions (NbS). Nature-based Solutions refer to actions that protect, restore, and sustainably manage ecosystems while simultaneously addressing societal challenges. In coastal environments, mangrove restoration represents one of the most effective NbS approaches because restored mangrove forests can reduce shoreline erosion, attenuate wave energy, enhance biodiversity, and improve ecosystem services. The favorable environmental conditions observed in the Kepetingan Coastal Area indicate that restoration initiatives can function as effective nature-based solutions for enhancing coastal resilience and reducing environmental risks.

The findings of this study also have important implications for climate change adaptation and mitigation. Coastal communities worldwide are increasingly exposed to sea-level rise, coastal flooding, saltwater intrusion, and extreme weather events. Healthy mangrove ecosystems serve as natural buffers that protect coastlines from these hazards [94], [95]. By stabilizing sediments and reducing wave energy, mangroves can significantly decrease the vulnerability of coastal settlements and infrastructure. Therefore, restoration efforts in

Kepetingan should be viewed not only as ecosystem rehabilitation activities but also as investments in climate adaptation and disaster risk reduction.

In addition to their adaptation benefits, mangrove ecosystems play a significant role in climate change mitigation through blue carbon sequestration. Mangroves are among the most efficient carbon-storing ecosystems on Earth because they accumulate large amounts of carbon in both aboveground biomass and belowground sediments [96], [97]. When mangrove forests are degraded or converted, substantial quantities of stored carbon released into the atmosphere. Conversely, successful restoration can enhance carbon storage capacity and contribute to national and global climate mitigation targets. Although carbon stocks were not directly measured in this study, the restoration of degraded mangrove areas in Kepetingan may provide additional benefits through long-term carbon sequestration and climate regulation.

The study further highlights the importance of community-based conservation in achieving restoration success. Contemporary restoration science increasingly recognizes that ecological interventions alone are insufficient to ensure long-term sustainability. Restoration programs that actively involve local communities generally achieve higher success rates because they foster local stewardship, strengthen environmental awareness, and improve compliance with conservation regulations. The SWOT analysis demonstrated that stakeholder participation, capacity building, and institutional support are critical factors for restoration success in Kepetingan. These findings are consistent with current international restoration frameworks that emphasize participatory governance and collaborative management.

Another important aspect of contemporary conservation is the emphasis on ecosystem resilience. Ecosystem resilience refers to the capacity of ecosystems to resist, recover from, and adapt to environmental disturbances. The presence of natural regeneration observed in the Kepetingan mangrove ecosystem suggests that ecological resilience remains partially intact despite ongoing degradation. Protecting naturally regenerating areas and maintaining environmental quality can therefore strengthen ecosystem resilience and improve the effectiveness of restoration interventions. Such strategies are particularly important under future climate scenarios, where ecosystems will face increasing environmental uncertainty.

The outcomes of this study also contribute to several global sustainability agendas. Mangrove restoration directly supports Sustainable Development Goal (SDG) 13 (Climate Action) through climate adaptation and carbon sequestration, SDG 14 (Life Below Water) through the conservation of coastal and marine habitats, and SDG 15 (Life on Land) through ecosystem restoration and biodiversity conservation. Moreover, restoration initiatives that generate alternative livelihood opportunities through ecotourism and sustainable resource management can contribute indirectly to poverty reduction and community well-being.

Overall, the ecological assessment, environmental evaluation, and stakeholder analysis conducted in this study demonstrate that mangrove restoration in the Kepetingan Coastal Area has significance beyond local conservation efforts. The findings illustrate how integrated restoration planning can simultaneously address biodiversity loss, ecosystem degradation, climate change, and socio-economic challenges. As such, the restoration framework developed in this study may serve as a practical model for other degraded tropical coastal landscapes seeking to balance ecological recovery with sustainable development objectives.

#### 4 CONCLUSION

The mangrove ecosystem in the Kepetingan Coastal Area exhibited degraded ecological conditions, as reflected by low tree density ranging from 300 to 600 trees ha<sup>-1</sup> and the dominance of several species, particularly *Rhizophora stylosa*, *Avicennia marina*, and *Bruguiera gymnorrhiza*. Assessment of mangrove degradation revealed a critical ecosystem status, with a critical land assessment score of 285 and a decline in mangrove cover from 140.54 ha in 2010 to 109.20 ha in 2015. Despite the degraded condition, environmental parameters, including temperature, salinity, dissolved oxygen, and pH, remained within suitable ranges for mangrove growth, indicating favorable conditions for restoration activities.

The study further demonstrated that the Kepetingan mangrove ecosystem retains natural regeneration potential, providing an important foundation for ecosystem recovery. Stakeholder-based SWOT analysis identified the Weakness–Opportunity (WO) strategy as the highest-priority restoration approach, emphasizing ecological rehabilitation, community capacity development, environmental monitoring, stakeholder collaboration, and government-supported conservation programs. These findings indicate that restoration success depends not only on ecological suitability but also on effective institutional support and community participation.

Overall, this study highlights the importance of integrating ecological assessment, environmental quality evaluation, degradation analysis, and stakeholder-based planning to establish restoration priorities for sustainable mangrove landscape conservation. The proposed framework contributes to ecosystem resilience, biodiversity conservation, and climate adaptation efforts, while providing practical guidance for the restoration and management of degraded tropical coastal ecosystems.

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## AUTHOR CONTRIBUTIONS

Conceptualization, I.F. and A.O.; Methodology, I.F. and A.O.; Software, I.F.; Validation, I.F. and A.O.; Formal Analysis, I.F.; Investigation, I.F.; Resources, I.F.; Data Curation, I.F.; Writing – Original Draft Preparation, I.F.; Writing – Review & Editing, A.O.; Visualization, I.F.; Supervision, A.O.; Project Administration, I.F.; Funding Acquisition, I.F.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable.

## REFERENCES

- [1] J. P. S. Gargaran, R. D. Y. Capuno, V. F. P. Novicio, C. C. Petiluna, C. E. T. Catalba, D. A. P. Paras, and J. J. C. Garces, "Mangrove ecosystem in Asia: Review and synthesis of ecosystem services and economic valuation methods," *Environmental & Experimental Biology*, vol. 22, no. 2, 2024, doi: 10.22364/eeb.22.06.
- [2] V. Hagger, T. A. Worthington, C. E. Lovelock, M. F. Adame, T. Amano, B. M. Brown, *et al.*, "Drivers of global mangrove loss and gain in social-ecological systems," *Nature Communications*, vol. 13, no. 1, p. 6373, 2022, doi: 10.1038/s41467-022-33962-x.
- [3] A. Elwin, E. J. Robinson, G. Feola, V. Jintana, and J. Clark, "How is mangrove ecosystem health defined? A local community perspective from coastal Thailand," *Ocean & Coastal Management*, vol. 251, p. 107037, 2024, doi: 10.1016/j.ocecoaman.2024.107037.
- [4] R. Sunkur, K. Kantamaneni, C. Bokhoree, and S. Ravan, "Mangroves' role in supporting ecosystem-based techniques to reduce disaster risk and adapt to climate change: A review," *Journal of Sea Research*, vol. 196, p. 102449, 2023, doi: 10.1016/j.seares.2023.102449.
- [5] N. Asari, M. N. Suratman, N. A. Mohd Ayob, and N. H. Abdul Hamid, "Mangrove as a natural barrier to environmental risks and coastal protection," in *Mangroves: Ecology, Biodiversity and Management*. Singapore: Springer, 2021, pp. 305–322, doi: 10.1007/978-981-16-2494-0\_13.
- [6] C. W. Chang and N. Mori, "Green infrastructure for the reduction of coastal disasters: A review of the protective role of coastal forests against tsunami, storm surge, and wind waves," *Coastal Engineering Journal*, vol. 63, no. 3, pp. 370–385, 2021, doi: 10.1080/21664250.2021.1929742.
- [7] A. Mohanty, A. G. Mohapatra, and S. K. Mohanty, "Climate change impacts on mangroves: Need for resilience mechanisms," in *Mangroves in a Changing World: Adaptation and Resilience*. Cham: Springer Nature Switzerland, 2024, pp. 45–70, doi: 10.1007/978-3-031-67691-8\_4.
- [8] B. I. Kochoni, H. G. G. Avakoudjo, T. M. Kamelan, C. B. L. Sinsin, and E. P. Kouamelan, "Contribution of mangroves ecosystems to coastal communities' resilience towards climate change: A case study in southern Côte d'Ivoire," *GeoJournal*, vol. 88, no. 4, pp. 3935–3951, 2023, doi: 10.1007/s10708-023-10845-2.
- [9] D. T. Gevaña, J. E. Garcia, C. D. Ruzol, F. L. Malabayabas, L. B. Grefalda, E. O'Brien, *et al.*, "Climate change resiliency through mangrove conservation: The case of Alitas farmers of Infanta, Philippines," in *Fostering Transformative Change for Sustainability in the Context of Socio-Ecological Production Landscapes and Seascapes (SEPLS)*. Singapore: Springer Nature Singapore, 2021, pp. 195–214, doi: 10.1007/978-981-33-6761-6\_11.
- [10] A. C. Ferreira, R. Borges, and L. D. de Lacerda, "Can sustainable development save mangroves?," *Sustainability*, vol. 14, no. 3, p. 1263, 2022, doi: 10.3390/su14031263.
- [11] S. R. Dayal, K. Ravuiwasa, and J. A. Bhat, "Deforestation and degradation in the mangrove ecosystem: Implication on environment and livelihoods," in *Land Degradation Neutrality: Achieving SDG 15 by Forest Management*. Singapore: Springer Nature Singapore, 2022, pp. 99–116, doi: 10.1007/978-981-19-5478-8\_6.
- [12] H. Akram, S. Hussain, P. Mazumdar, K. O. Chua, T. E. Butt, and J. A. Harikrishna, "Mangrove health: A review of functions, threats, and challenges associated with mangrove management practices," *Forests*, vol. 14, no. 9, p. 1698, 2023, doi: 10.3390/f14091698.
- [13] P. Ekka, S. Patra, M. Upreti, G. Kumar, A. Kumar, and P. Saikia, "Land degradation and its impacts on biodiversity and ecosystem services," in *Land and Environmental Management Through Forestry*. Hoboken, NJ, USA: Wiley, 2023, pp. 77–101, doi: 10.1002/9781119910527.ch4.
- [14] M. A. Islam, M. M. Billah, M. H. Idris, M. K. A. Bhuiyan, and A. H. M. Kamal, "Mangroves of Malaysia: A comprehensive review on ecosystem functions, services, restorations, and potential threats of climate change," *Hydrobiologia*, vol. 851, no. 8, pp. 1841–1871, 2024, doi: 10.1007/s10750-023-05431-z.
- [15] D. M. Alongi, "Impacts of climate change on blue carbon stocks and fluxes in mangrove forests," *Forests*, vol. 13, no. 2, p. 149, 2022, doi: 10.3390/f13020149.

- [16] S. Sharma, R. A. MacKenzie, T. Tieng, K. Soben, N. Tulyasuwan, A. Resanond, *et al.*, “The impacts of degradation, deforestation and restoration on mangrove ecosystem carbon stocks across Cambodia,” *Science of the Total Environment*, vol. 706, p. 135416, 2020, doi: 10.1016/j.scitotenv.2019.135416.
- [17] M. Basyuni, S. D. Sasmito, K. Analuddin, T. Z. Ulqodry, M. F. Saragi-Sasmito, S. Eddy, and N. Milantara, “Mangrove biodiversity, conservation and roles for livelihoods in Indonesia,” in *Mangroves: Biodiversity, Livelihoods and Conservation*. Singapore: Springer Nature Singapore, 2022, pp. 397–445, doi: 10.1007/978-981-19-0519-3\_16.
- [18] Rahman, F. F. Lokollo, G. D. Manuputty, R. D. Hukubun, Krisye, Maryono, *et al.*, “A review on the biodiversity and conservation of mangrove ecosystems in Indonesia,” *Biodiversity and Conservation*, vol. 33, no. 3, pp. 875–903, 2024, doi: 10.1007/s10531-023-02767-9.
- [19] R. M. Suhardi, W. Rahardi, H. C. Shih, J. A. Mantiquilla, Y. H. Wu, M. S. Shiao, and Y. C. Chiang, “A review of the mangrove ecosystem in Indonesia: Biodiversity, conservation, and challenges in sustainable management,” *Ecological Genetics and Genomics*, vol. 32, p. 100282, 2024, doi: 10.1016/j.egg.2024.100282.
- [20] W. Wang, H. Fu, S. Y. Lee, H. Fan, and M. Wang, “Can strict protection stop the decline of mangrove ecosystems in China? From rapid destruction to rampant degradation,” *Forests*, vol. 11, no. 1, p. 55, 2020, doi: 10.3390/f11010055.
- [21] F. Afonso, P. M. Félix, P. Chainho, J. A. Heumüller, R. F. de Lima, F. Ribeiro, and A. C. Brito, “Community perceptions about mangrove ecosystem services and threats,” *Regional Studies in Marine Science*, vol. 49, p. 102114, 2022, doi: 10.1016/j.rsma.2021.102114.
- [22] S. D. Sasmito, M. Basyuni, A. Kridalaksana, M. F. Saragi-Sasmito, C. E. Lovelock, and D. Murdiyarto, “Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia’s mangroves,” *Nature Ecology & Evolution*, vol. 7, no. 1, pp. 62–70, 2023, doi: 10.1038/s41559-022-01926-5.
- [23] C. E. Lovelock, E. Barbier, and C. M. Duarte, “Tackling the mangrove restoration challenge,” *PLoS Biology*, vol. 20, no. 10, p. e3001836, 2022, doi: 10.1371/journal.pbio.3001836.
- [24] M. E. B. Gerona-Daga and S. G. Salmo, “A systematic review of mangrove restoration studies in Southeast Asia: Challenges and opportunities for the United Nation’s Decade on Ecosystem Restoration,” *Frontiers in Marine Science*, vol. 9, p. 987737, 2022, doi: 10.3389/fmars.2022.987737.
- [25] A. Akhtar-Khavari and A. Telesetsky, “From protection to restoration: A challenge for environmental governance,” in *Research Handbook on Fundamental Concepts of Environmental Law*. Cheltenham, U.K.: Edward Elgar Publishing, 2022, pp. 45–70, doi: 10.4337/9781839108327.00008.
- [26] C. Van Oosten, H. Runhaar, and B. Arts, “Capable to govern landscape restoration? Exploring landscape governance capabilities, based on literature and stakeholder perceptions,” *Land Use Policy*, vol. 104, p. 104020, 2021, doi: 10.1016/j.landusepol.2019.05.039.
- [27] S. Löfqvist, F. Kleinschroth, A. Bey, A. De Bremond, R. DeFries, J. Dong, *et al.*, “How social considerations improve the equity and effectiveness of ecosystem restoration,” *BioScience*, vol. 73, no. 2, pp. 134–148, 2023, doi: 10.1093/biosci/biac099.
- [28] M. A. Rahaman, Mursheduzzaman, G. A. M. Ali Reza, A. M. Chowdhury, A. R. Avi, T. R. Chakraborty, and M. Shamsuzzoha, “Nature-based solutions to promote climate change adaptation and disaster risk reduction along the coastal belt of Bangladesh,” in *The Palgrave Handbook of Climate Resilient Societies*. Cham, Switzerland: Springer International Publishing, 2020, pp. 1–16, doi: 10.1007/978-3-030-32811-5\_49-1.
- [29] M. Vicarelli, K. Sudmeier-Rieux, A. Alsadadi, A. Shrestha, S. Schütze, M. M. Kang, *et al.*, “On the cost-effectiveness of nature-based solutions for reducing disaster risk,” *Science of the Total Environment*, vol. 947, p. 174524, 2024, doi: 10.1016/j.scitotenv.2024.174524.
- [30] S. Lucatello and I. Alcántara-Ayala, “Sustainable synergy: Strengthening disaster risk reduction in Latin America and the Caribbean through nature-based solutions,” *International Journal of Disaster Risk Reduction*, vol. 113, p. 104860, 2024, doi: 10.1016/j.ijdr.2024.104860.
- [31] J. J. Zhu and B. Yan, “Blue carbon sink function and carbon neutrality potential of mangroves,” *Science of the Total Environment*, vol. 822, p. 153438, 2022, doi: 10.1016/j.scitotenv.2022.153438.
- [32] T. C. Jennerjahn, “Relevance and magnitude of ‘Blue Carbon’ storage in mangrove sediments: Carbon accumulation rates vs. stocks, sources vs. sinks,” *Estuarine, Coastal and Shelf Science*, vol. 247, p. 107027, 2020, doi: 10.1016/j.ecss.2020.107027.
- [33] M. S. Azman, S. Sharma, M. L. Hamzah, R. M. Zakaria, K. Palaniveloo, and R. A. MacKenzie, “Total ecosystem blue carbon stocks and sequestration potential along a naturally regenerated mangrove forest chronosequence,” *Forest Ecology and Management*, vol. 527, p. 120611, 2023, doi: 10.1016/j.foreco.2022.120611.
- [34] M. Gong, N. Teller, E. J. Golebie, M. Aczel, Z. Jiang, J. Van Zeghbroeck, and J. Liu, “Unveiling complementarities between mangrove restoration and global sustainable development goals,” *Journal of Cleaner Production*, vol. 474, p. 143524, 2024, doi: 10.1016/j.jclepro.2024.143524.
- [35] S. Obiene, K. Shilabukha, G. Muga, L. Ojwang, and M. A. Owuor, “Understanding of Sustainable Development Goals among communities living adjacent to mangroves in Kenya,” *Western Indian Ocean Journal of Marine Science*, vol. 1, no. 2022, pp. 59–73, 2022.
- [36] J. Okorundu, N. A. Umar, C. O. Ulor, C. G. Onwuagba, B. E. Diagi, S. I. Ajiere, and C. Nwaogu, “Anthropogenic activities as primary drivers of environmental pollution and loss of biodiversity: A review,” *International Journal of Trend in Scientific Research and Development*, vol. 6, no. 4, pp. 621–643, 2022.
- [37] A. Newton, J. Icely, S. Cristina, G. M. Perillo, R. E. Turner, D. Ashan, *et al.*, “Anthropogenic direct pressures on coastal wetlands,” *Frontiers in Ecology and Evolution*, vol. 8, p. 144, 2020, doi: 10.3389/fevo.2020.00144.
- [38] N. N. Md Isa and M. N. Suratman, “Structure and diversity of plants in mangrove ecosystems,” in *Mangroves: Ecology, Biodiversity and Management*. Singapore: Springer, 2021, pp. 361–369, doi: 10.1007/978-981-16-2494-0\_15.

- [39] T. R. Soeprbowati, S. Anggoro, S. Puryono, H. Purnaweni, R. B. Sularto, and R. Mersyah, "Species composition and distribution in the mangrove ecosystem in the city of Bengkulu, Indonesia," *Water*, vol. 14, no. 21, p. 3516, 2022, doi: 10.3390/w14213516.
- [40] K. Maurya, S. Mahajan, and N. Chaube, "Remote sensing techniques: Mapping and monitoring of mangrove ecosystem—A review," *Complex & Intelligent Systems*, vol. 7, no. 6, pp. 2797–2818, 2021, doi: 10.1007/s40747-021-00457-z.
- [41] M. Bardhan, "An empirical study on mangrove restoration in Indian Sundarbans—A community-based environmental approach," in *Modern Cartography Series*, vol. 10. Amsterdam, Netherlands: Academic Press, 2021, pp. 387–405, doi: 10.1016/B978-0-12-823895-0.00012-9.
- [42] M. Mutahara, J. F. Warner, and M. S. A. Khan, "Multi-stakeholder participation for sustainable delta management: A challenge of the socio-technical transformation in the management practices in Bangladesh," *International Journal of Sustainable Development & World Ecology*, vol. 27, no. 7, pp. 611–624, 2020, doi: 10.1080/13504509.2020.1722278.
- [43] I. N. Djenontin, L. C. Zulu, and D. Etongo, "Ultimately, what is forest landscape restoration in practice? Embodiments in sub-Saharan Africa and implications for future design," *Environmental Management*, vol. 68, no. 5, pp. 619–641, 2021, doi: 10.1007/s00267-020-01360-y.
- [44] R. Djameluddin, R. Holmes, and B. Djabar, "Assessing species composition and structural attributes across different habitats to evaluate changes and management effectiveness of protected mangroves," *Forest Ecology and Management*, vol. 561, p. 121857, 2024, doi: 10.1016/j.foreco.2024.121857.
- [45] P. Hajjalizadeh, M. Safaie, R. Naderloo, M. G. Shojaei, J. Gammal, A. Villnäs, and A. Norkko, "Species composition and functional traits of macrofauna in different mangrove habitats in the Persian Gulf," *Frontiers in Marine Science*, vol. 7, p. 575480, 2020, doi: 10.3389/fmars.2020.575480.
- [46] N. B. Toosi, A. R. Soffianian, S. Fakheran, and L. T. Waser, "Mapping disturbance in mangrove ecosystems: Incorporating landscape metrics and PCA-based spatial analysis," *Ecological Indicators*, vol. 136, p. 108718, 2022, doi: 10.1016/j.ecolind.2022.108718.
- [47] J. López-Portillo, A. Zaldívar-Jiménez, A. L. Lara-Domínguez, R. Pérez-Ceballos, M. Bravo-Mendoza, N. N. Álvarez, and L. Aguirre-Franco, "Hydrological rehabilitation and sediment elevation as strategies to restore mangroves in terrigenous and calcareous environments in Mexico," in *Wetland Carbon and Environmental Management*. Hoboken, NJ, USA: Wiley, 2021, pp. 173–190, doi: 10.1002/9781119639305.ch9.
- [48] D. Xie, C. Schwarz, M. G. Kleinhans, Z. Zhou, and B. van Maanen, "Implications of coastal conditions and sea-level rise on mangrove vulnerability: A bio-morphodynamic modeling study," *Journal of Geophysical Research: Earth Surface*, vol. 127, no. 3, p. e2021JF006301, 2022, doi: 10.1029/2021JF006301.
- [49] C. E. van Bijsterveldt, B. K. van Wesenbeeck, D. van der Wal, N. Afiati, R. Pribadi, B. Brown, and T. J. Bouma, "How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds," *Estuarine, Coastal and Shelf Science*, vol. 235, p. 106576, 2020, doi: 10.1016/j.ecss.2019.106576.
- [50] A. K. Bhowmik, R. Padmanaban, P. Cabral, and M. M. Romeiras, "Global mangrove deforestation and its interacting social-ecological drivers: A systematic review and synthesis," *Sustainability*, vol. 14, no. 8, p. 4433, 2022, doi: 10.3390/su14084433.
- [51] S. Acharya, M. Pradhan, G. Mahalik, R. Babu, S. Parida, and P. K. Mohapatra, "Abiotic stress tolerance in mangroves with a special reference to salinity," *Plant Science Today*, vol. 10, no. 2, pp. 58–68, 2023, doi: 10.14719/pst.1925.
- [52] S. Jeffry, M. H. Zakaria, S. D. Ramaiya, and J. S. Bujang, "Morphology and structure adaptation of *Avicennia* and *Sonneratia* growing in lagoon, island, and bay," 2024, doi: 10.21203/rs.3.rs-4273123/v1.
- [53] A. F. Raganas, A. S. Hadsall, N. M. Pampolina, S. Hotes, and D. B. Magcale-Macandog, "Regeneration capacity and threats to mangrove areas on the southern coast of Oriental Mindoro, Philippines: Implications to mangrove ecosystem rehabilitation," *Biodiversitas*, vol. 21, no. 8, pp. 3625–3636, 2020, doi: 10.13057/biodiv/d210827.
- [54] M. S. Azman, S. Sharma, M. A. M. Shahrudin, M. L. Hamzah, S. N. Adibah, R. M. Zakaria, and R. A. MacKenzie, "Stand structure, biomass and dynamics of naturally regenerated and restored mangroves in Malaysia," *Forest Ecology and Management*, vol. 482, p. 118852, 2021, doi: 10.1016/j.foreco.2020.118852.
- [55] C. Tan, B. Xu, G. Hong, and X. Wu, "Integrating habitat risk and landscape resilience in forest protection and restoration planning for biodiversity conservation," *Landscape and Urban Planning*, vol. 248, p. 105111, 2024, doi: 10.1016/j.landurbplan.2024.105111.
- [56] P. Jordan and P. Fröhle, "Bridging the gap between coastal engineering and nature conservation? A review of coastal ecosystems as nature-based solutions for coastal protection," *Journal of Coastal Conservation*, vol. 26, no. 2, art. no. 4, 2022, doi: 10.1007/s11852-021-00848-x.
- [57] I. R. Henud, A. A. Póvoa, M. G. Tavares, and A. Soares-Gomes, "Coastal resilience and adaptation strategies: Natural habitats for coastal protection and Atlantic forest restoration on the coast of the Rio de Janeiro state," *International Journal of Disaster Risk Reduction*, vol. 113, p. 104861, 2024, doi: 10.1016/j.ijdrr.2024.104861.
- [58] P. Chaiklang, D. Karthe, M. Babel, L. Giessen, and C. Schusser, "Reviewing changes in mangrove land use over the decades in Thailand: Current responses and challenges," *Trees, Forests and People*, vol. 17, p. 100630, 2024, doi: 10.1016/j.tfp.2024.100630.
- [59] C. K. Lee, C. Duncan, E. Nicholson, T. E. Fatoyinbo, D. Lagomasino, N. Thomas, *et al.*, "Mapping the extent of mangrove ecosystem degradation by integrating an ecological conceptual model with satellite data," *Remote Sensing*, vol. 13, no. 11, p. 2047, 2021, doi: 10.3390/rs13112047.
- [60] J. Luo, Z. Sun, L. Lu, Z. Xiong, L. Cui, and Z. Mao, "Rapid expansion of coastal aquaculture ponds in Southeast Asia: Patterns, drivers and impacts," *Journal of Environmental Management*, vol. 315, p. 115100, 2022, doi: 10.1016/j.jenvman.2022.115100.
- [61] D. N. Bryan-Brown, R. M. Connolly, D. R. Richards, F. Adame, D. A. Friess, and C. J. Brown, "Global trends in mangrove forest fragmentation," *Scientific Reports*, vol. 10, no. 1, p. 7117, 2020, doi: 10.1038/s41598-020-63880-1.

- [62] J. J. Jaramillo, C. A. Rivas, J. Oteros, and R. M. Navarro-Cerrillo, "Forest fragmentation and landscape connectivity changes in Ecuadorian mangroves: Some hope for the future?," *Applied Sciences*, vol. 13, no. 8, p. 5001, 2023, doi: 10.3390/app13085001.
- [63] L. A. Yeager, J. Estrada, K. Holt, S. R. Keyser, and T. A. Oke, "Are habitat fragmentation effects stronger in marine systems? A review and meta-analysis," *Current Landscape Ecology Reports*, vol. 5, no. 3, pp. 58–67, 2020, doi: 10.1007/s40823-020-00053-w.
- [64] B. D. Angnuureng, R. Adade, E. O. Chuku, S. Dzantor, E. K. Brempong, and P. A. D. Mattah, "Effects of coastal protection structures in controlling erosion and livelihoods," *Heliyon*, vol. 9, no. 10, 2023, doi: 10.1016/j.heliyon.2023.e20633.
- [65] D. Amos and S. Akib, "A review of coastal protection using artificial and natural countermeasures—Mangrove vegetation and polymers," *Eng*, vol. 4, no. 1, pp. 941–953, 2023, doi: 10.3390/eng4010055.
- [66] A. C. Ferreira, E. C. Ashton, R. D. Ward, I. Hendy, and L. D. Lacerda, "Mangrove biodiversity and conservation: Setting key functional groups and risks of climate-induced functional disruption," *Diversity*, vol. 16, no. 7, p. 423, 2024, doi: 10.3390/d16070423.
- [67] D. Arceo-Carranza, X. Chiappa-Carrara, R. Chávez López, and C. Yáñez Arenas, "Mangroves as feeding and breeding grounds," in *Mangroves: Ecology, Biodiversity and Management*. Singapore: Springer Singapore, 2021, pp. 63–95, doi: 10.1007/978-981-16-2494-0\_3.
- [68] C. S. Das, D. Mallick, and R. N. Mandal, "Mangrove forests in changing climate: A global overview," *Journal of the Indian Society of Coastal Agricultural Research*, vol. 38, no. 2, 2020.
- [69] M. Otundo Richard, "Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives among African countries along the Indian Ocean Belt," 2024, doi: 10.2139/ssrn.4912339.
- [70] A. Bhattacharya, "Effect of low-temperature stress on germination, growth, and phenology of plants: A review," in *Physiological Processes in Plants Under Low Temperature Stress*. Singapore: Springer, 2022, pp. 1–106, doi: 10.1007/978-981-16-9037-2\_1.
- [71] K. Y. Crous, J. Uddling, and M. G. De Kauwe, "Temperature responses of photosynthesis and respiration in evergreen trees from boreal to tropical latitudes," *New Phytologist*, vol. 234, no. 2, pp. 353–374, 2022, doi: 10.1111/nph.17951.
- [72] M. E. Benbow, J. P. Receveur, and G. A. Lamberti, "Death and decomposition in aquatic ecosystems," *Frontiers in Ecology and Evolution*, vol. 8, p. 17, 2020, doi: 10.3389/fevo.2020.00017.
- [73] S. K. Mallik, R. Pathak, and N. Shahi, "Sediment microbiology in the aquatic environment," in *Handbook of Aquatic Microbiology*. Boca Raton, FL, USA: CRC Press, 2024, pp. 56–76.
- [74] P. Srivastava, K. Sachan, P. Baskar, D. R. K. Saikanth, W. Lytand, R. K. M. Kumar, and B. V. Singh, "Soil microbes expertly balancing nutrient demands and environmental preservation and ensuring the delicate stability of our ecosystems: A review," *International Journal of Plant & Soil Science*, vol. 35, no. 18, pp. 989–1000, 2023, doi: 10.9734/IJPSS/2023/v35i183363.
- [75] T. R. Sveen, S. E. Hannula, and M. Bahram, "Microbial regulation of feedbacks to ecosystem change," *Trends in Microbiology*, vol. 32, no. 1, pp. 68–78, 2024, doi: 10.1016/j.tim.2023.06.006.
- [76] M. I. Saunders, C. Doropoulos, E. Bayraktarov, R. C. Babcock, D. Gorman, A. M. Eger, *et al.*, "Bright spots in coastal marine ecosystem restoration," *Current Biology*, vol. 30, no. 24, pp. R1500–R1510, 2020, doi: 10.1016/j.cub.2020.10.056.
- [77] I. Kenny, S. D. Connell, G. Drew, A. Wright, S. Carruthers, and D. McAfee, "Aligning social and ecological goals for successful marine restoration," *Biological Conservation*, vol. 288, p. 110357, 2023, doi: 10.1016/j.biocon.2023.110357.
- [78] R. Kumar, A. Kumar, and P. Saikia, "Deforestation and forests degradation impacts on the environment," in *Environmental Degradation: Challenges and Strategies for Mitigation*. Cham, Switzerland: Springer International Publishing, 2022, pp. 19–46, doi: 10.1007/978-3-030-95542-7\_2.
- [79] O. D. Elisha and M. J. Felix, "Destruction of coastal ecosystems and the vicious cycle of poverty in Niger Delta Region," *Journal of Global Agriculture and Ecology*, vol. 11, no. 2, pp. 7–24, 2021.
- [80] S. A. Aransiola, S. L. T. Zobeashia, A. A. Ikhumetse, O. I. Musa, O. P. Abioye, U. J. J. Ijah, and N. R. Maddela, "Niger Delta mangrove ecosystem: Biodiversity, past and present pollution, threat and mitigation," *Regional Studies in Marine Science*, vol. 75, p. 103568, 2024, doi: 10.1016/j.rsma.2024.103568.
- [81] L. K. Cervený, M. M. Derrien, A. B. Miller, and C. Meyer, "Partnership and community engagement models for stewarding national scenic trails: A social-ecological systems perspective," *Tourism Planning & Development*, vol. 19, no. 3, pp. 204–226, 2022, doi: 10.1080/21568316.2021.1987314.
- [82] L. M. Mumaw and C. M. Raymond, "A framework for catalysing the rapid scaling of urban biodiversity stewardship programs," *Journal of Environmental Management*, vol. 292, p. 112745, 2021, doi: 10.1016/j.jenvman.2021.112745.
- [83] M. Zimmer, G. N. Ajonina, A. A. Amir, S. M. Cragg, S. Crooks, F. Dahdouh-Guebas, *et al.*, "When nature needs a helping hand: Different levels of human intervention for mangrove (re-) establishment," *Frontiers in Forests and Global Change*, vol. 5, p. 784322, 2022, doi: 10.3389/ffgc.2022.784322.
- [84] S. Dhyani, J. Shukla, R. Kadaverugu, R. Dasgupta, M. Panda, S. K. Kundu, *et al.*, "Participatory stakeholder assessment for drivers of mangrove loss to prioritize evidence-based conservation and restoration in Bhitarkanika and Mahanadi Delta, India," *Sustainability*, vol. 15, no. 2, p. 963, 2023, doi: 10.3390/su15020963.
- [85] J. W. F. Ren and G. C. Coffman, "Integrating the resilience concept into ecosystem restoration," *Restoration Ecology*, vol. 31, no. 5, p. e13907, 2023, doi: 10.1111/rec.13907.
- [86] R. L. Chazdon, D. A. Falk, L. F. Banin, M. Wagner, S. J. Wilson, R. C. Grabowski, and K. N. Suding, "The intervention continuum in restoration ecology: Rethinking the active–passive dichotomy," *Restoration Ecology*, vol. 32, no. 8, p. e13535, 2024, doi: 10.1111/rec.13535.

- [87] M. Sievers, C. J. Brown, J. McGowan, M. P. Turschwell, C. A. Buelow, B. Holgate, *et al.*, “Co-occurrence of biodiversity, carbon storage, coastal protection, and fish and invertebrate production to inform global mangrove conservation planning,” *Science of the Total Environment*, vol. 904, p. 166357, 2023, doi: 10.1016/j.scitotenv.2023.166357.
- [88] T. R. Athira, K. Jishnu, K. A. Rubeena, A. Abbas, S. B. Muzaffar, A. Nefla, *et al.*, “Mangrove ecosystem: Navigating the crossroads of traditional fishing, misguided conservation, and large wading birds decline,” in *Mangroves in a Changing World: Adaptation and Resilience*. Cham, Switzerland: Springer Nature Switzerland, 2024, pp. 125–144, doi: 10.1007/978-3-031-67691-8\_8.
- [89] F. Musa, N. M. Fozi, and D. M. Hamdan, “Coastal communities’ willingness to pay for mangrove ecotourism in Marudu Bay, Sabah, Malaysia,” *Journal of Sustainability Science and Management*, vol. 15, no. 4, pp. 130–140, 2020, doi: 10.46754/jssm.2020.06.013.
- [90] M. Mardianton, S. Amar, and A. Irianto, “Empowering mangrove ecotourism: Integrating governance, community, and technology for sustainable coastal development,” *Journal of Ecohumanism*, vol. 3, no. 8, pp. 3153–3167, 2024.
- [91] K. Swangjang and P. Kornpiphat, “Does ecotourism in a mangrove area at Klong Kone, Thailand, conform to sustainable tourism? A case study using SWOT and DPSIR,” *Environment, Development and Sustainability*, vol. 23, no. 11, pp. 15960–15985, 2021, doi: 10.1007/s10668-021-01313-3.
- [92] V. B. Arifanti, J. B. Kauffman, Subarno, M. Ilman, A. Tosiani, and N. Novita, “Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia,” *Global Change Biology*, vol. 28, no. 15, pp. 4523–4538, 2022, doi: 10.1111/gcb.16216.
- [93] F. Sidik, A. Lawrence, T. Wagey, F. Zamzani, and C. E. Lovelock, “Blue carbon: A new paradigm of mangrove conservation and management in Indonesia,” *Marine Policy*, vol. 147, p. 105388, 2023, doi: 10.1016/j.marpol.2022.105388.
- [94] A. Kumari and M. S. Rathore, “Roles of mangroves in combating the climate change,” in *Mangroves: Ecology, Biodiversity and Management*. Singapore: Springer Singapore, 2021, pp. 225–255, doi: 10.1007/978-981-16-2494-0\_10.
- [95] S. Mugilan, S. Manivasakan, K. Baranidharan, J. RM, K. P. Ragunath, P. Hemalatha, *et al.*, “Mangroves as natural shields: A comprehensive review of their role in mitigating natural disasters and conservation strategies,” *Asian Journal of Environment and Ecology*, vol. 23, no. 7, pp. 1–10, 2024.
- [96] S. C. Decena, C. Avorque, A. Arribado, and D. Macasait Jr., “Aboveground and belowground carbon stocks in mangrove ecosystems along Carigara Bay in Leyte, Philippines,” 2023, doi: 10.21203/rs.3.rs-2910104/v1.
- [97] A. Chanda and A. Akhand, “Challenges towards the sustainability and enhancement of the Indian Sundarban mangrove’s blue carbon stock,” *Life*, vol. 13, no. 8, p. 1787, 2023, doi: 10.3390/life13081787.