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POLICY STRATEGY DIRECTIONS FOR MANGROVE ECOSYSTEM GOVERNANCE IN CLIMATE CHANGE MITIGATION EFFORTS AT MENIPO NATURE TOURISM PARK

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Abstract

Mangrove ecosystem management plays an important role in achieving the Sustainable Development Goals (SDGs), particularly in protecting coastal and marine ecosystems from environmental degradation. Mangrove forests also contribute to climate change mitigation as blue carbon ecosystems through their capacity to absorb and store large amounts of carbon. This study aimed to analyze mangrove vegetation community structure, carbon potential, and management strategies for climate change mitigation in Menipo Nature Tourism Park (TWA Menipo), Indonesia. Data were collected using both qualitative and quantitative methods. The study identified 15 mangrove species, with Rhizophora mucronata, Bruguiera gymnorrhiza, Rhizophora stylosa, and Bruguiera parviflora as the dominant species. The vegetation exhibited a moderate diversity index, low evenness, and low species richness. Total biomass was estimated at 1,959.27 t/ha, while carbon stock and CO_2 sequestration potential reached 920.86 t/ha and 3,376.48 t/ha, respectively, highlighting the significant ecological role of mangroves as carbon sinks. The main driving factors influencing management direction were the sustainability of mangrove rehabilitation programs and the level of ecosystem degradation. Key stakeholders included Mangrove Farmer Groups, Non-Governmental Organizations (NGOs), the East Nusa Tenggara Natural Resources Conservation Agency (BKSDA NTT), village governments, and traditional leaders. Recommended management strategies include conducting biophysical assessments prior to rehabilitation, strengthening customary regulations, empowering local communities through social forestry programs, allowing sustainable harvesting of fishery resources without damaging mangrove habitats, providing designated boat-parking areas, and developing priority zoning maps for rehabilitation. These measures are expected to support sustainable mangrove conservation and enhance climate change mitigation efforts.

Keywords*: Mangrove Ecosystem, Ecological Conditions, Climate Change*

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INTRODUCTION

Indonesia's engagement in global climate change initiatives formally began with the ratification of the United Nations Framework Convention on Climate Change (UNFCCC) through Law No. 6 of 1994, followed by the ratification of the Kyoto Protocol under Law No. 17 of 2004. Since then, the country has progressively strengthened its climate commitments in line with international agreements. In 2022, Indonesia submitted its Enhanced Nationally Determined Contributions (NDCs), increasing its greenhouse gas (GHG) emission reduction targets compared with the previous Updated NDC. The unconditional target, achieved through domestic efforts, was raised from 29% to 31.89% by 2030, while the conditional target, supported by international cooperation, increased from 41% to 43.2%

(Suratiningsih & Nugrahaningsih, 2024). Greenhouse gases primarily include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), all of which contribute significantly to global warming (Adharani et al., 2024). To achieve these enhanced commitments, Indonesia has implemented a range of mitigation measures across multiple sectors, coordinated by institutions responsible for climate action (Adharani et al., 2024). The increasing concentration of GHG emissions, particularly CO_2 and CH_4 generated from industrial activities, transportation, agriculture, and livestock production, has accelerated global warming and climate change (Azzahra, 2020). Consequently, reducing atmospheric carbon levels requires not only emission reduction strategies but also the conservation of existing carbon stocks and the enhancement of carbon sequestration through sustainable forest management and ecosystem conservation programs, including mangrove ecosystems, which serve as important natural carbon sinks (Amanda et al., 2021).

Mangrove ecosystem management plays a crucial role in achieving several Sustainable Development Goals (SDGs), particularly those related to marine ecosystem conservation, economic development, climate action, and biodiversity protection (Muhammad et al., 2024). Mangrove forests are widely recognized for their significant contribution to climate change mitigation through their capacity to sequester and store substantial amounts of atmospheric carbon dioxide (CO_2) (Tsani & Muhsoni, 2022). Compared with many other forest ecosystems, mangroves possess a remarkably high carbon storage potential, making them one of the most effective natural carbon sinks (Tsani & Muhsoni, 2022). The carbon stock within mangrove ecosystems is primarily determined by their ability to absorb atmospheric CO_2 through photosynthesis, which is subsequently accumulated and stored as plant biomass (Mulani, 2023). Consequently, the assessment of carbon stocks in mangrove forests provides an important indicator of the amount of CO_2 removed from the atmosphere and retained within the ecosystem (Amanda et al., 2021). As one of the countries with the largest mangrove resources globally, Indonesia contains approximately 25% of the world's total mangrove area. The extent of Indonesian mangrove forests is estimated to range from 2.5 to 4.5 million hectares; however, approximately 1.82 million hectares have experienced varying degrees of degradation (KKP, 2020). Indonesia's mangrove ecosystems are characterized by considerable species diversity, although only about 47 true mangrove species have been recorded nationwide (Kusuma et al., 2022). This diversity reflects the ecological importance of mangrove forests and their substantial contribution to national climate change mitigation efforts through carbon sequestration and ecosystem resilience. Such ecological functions are particularly relevant in regions such as East Nusa Tenggara Province, where mangrove ecosystems provide essential environmental services while supporting climate adaptation and mitigation strategies at the local and regional levels (Lestariningsih et al., 2018).

The province of East Nusa Tenggara possesses one of Indonesia's most extensive mangrove resources, highlighting its ecological significance for coastal sustainability (Matatula et al., 2023). According to available records, the province supports approximately 40.61 ha of mangrove forest, of which nearly 9.98 ha have been degraded due to a combination of anthropogenic disturbances and natural environmental pressures, including those observed in Menipo Nature Tourism Park (MNTP). As a protected conservation area, MNTP encompasses 2,449.50 ha, with 998.43 ha dominated by mangrove ecosystems, making mangroves a critical coastal component that supports biodiversity conservation, provides habitat for numerous flora and fauna species, and sustains the socio-economic livelihoods of surrounding communities. Despite its ecological importance, the mangrove ecosystem within MNTP has experienced degradation across approximately 10 ha, primarily driven by land conversion for settlements and agriculture, uncontrolled livestock grazing, boat mooring activities, environmentally unsustainable jetty development, coastal abrasion, and salinity fluctuations. These pressures threaten the ecological integrity and long-term resilience of the mangrove ecosystem. Therefore, comprehensive mitigation measures are required to address ongoing degradation through targeted rehabilitation programs, prevention of further mangrove loss, and enhanced stakeholder engagement. Strengthening collaboration among relevant actors is essential to support sustainable mangrove management and ensure the long-term conservation of ecosystem functions and services (Ariyani et al., 2020).

MATERIAL AND METHOD

a. Study Area and Research Period

The mangrove ecosystem investigated in this study is located within the Menipo Nature Tourism Park, which is administratively situated in Enoraen Village, East Amarasi District, Kupang Regency, East Nusa Tenggara Province, Indonesia. Geographically, the area extends between 10°07′–10°13′ S and 124°05′–124°13′ E. The total area of Menipo Nature Tourism Park covers approximately 2,449.50 ha, of which 998.43 ha are occupied by mangrove ecosystems. Field data collection was conducted between September and October 2025. The spatial distribution of the mangrove ecosystem within the study area is presented in Figure 1.

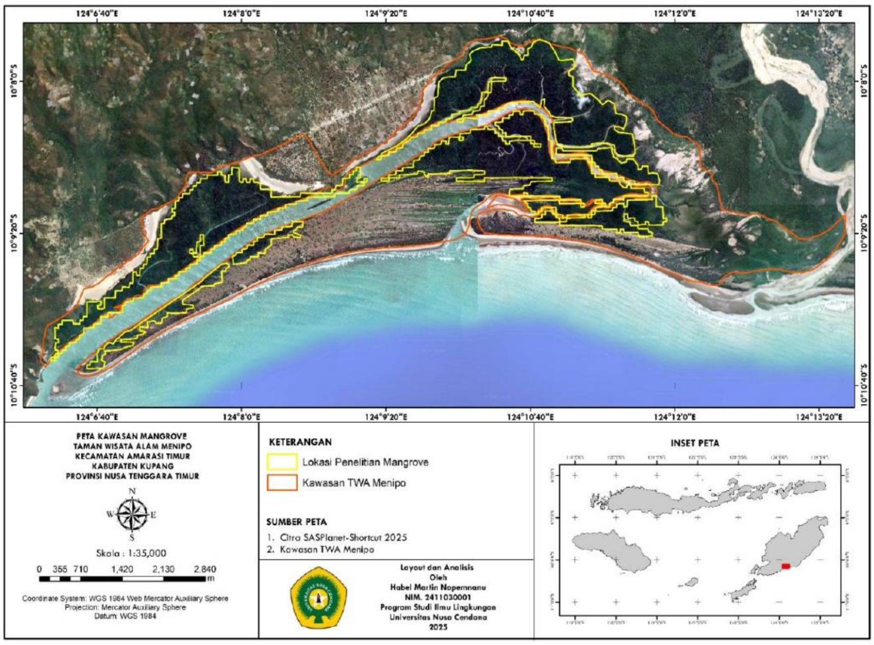

Figure 1. Map of the Mangrove Area in Menipo Nature Tourism Park

b. Materials and Equipment

The materials and equipment used in this study consisted of both hardware and software components. The software employed included ArcGIS 10.8 for spatial analysis and mapping, MICMAC and MACTOR for stakeholder and structural analyses, as well as Microsoft Word and Microsoft Excel for data processing and documentation. The field equipment used during data collection comprised a Global Positioning System (GPS) device for recording geographic coordinates; a shapefile (SHP) map of the mangrove area within Menipo Nature Tourism Park (TWA Menipo); a compass for navigation and orientation; the Avenza Maps application for determining transect lines and sampling plots; measuring tapes for tree diameter at breast height (DBH) measurements and plot establishment; a Haga altimeter and the Trees application for tree height assessment; a pH meter for measuring soil pH and air temperature; a refractometer for determining salinity levels; and a digital camera for photographic and video documentation. Species identification was supported by mangrove identification guides, the PlantNet application, and Google Lens. Standard stationery, including pens, pencils, and rulers, was also utilized throughout the study. The research materials included a shapefile of the TWA Menipo mangrove area obtained from the Indonesian Mangrove Shapefile Database, questionnaires designed to identify key variables for MICMAC analysis and stakeholder interests for MACTOR analysis, and tally sheets used to record mangrove vegetation measurements and field observations.

c. Data Source

The study utilized both primary and secondary data sources. Primary data were collected through direct field observations, measurements, and verification conducted within the Menipo Nature Tourism Park (MNTP). The field survey gathered information on mangrove species composition, diameter at breast height (DBH), tree height, site area, and geographic coordinates delineating the study boundaries. Field data collection was supplemented by information obtained from personnel of the East Nusa Tenggara Natural Resources Conservation Agency (BBKSDA) and relevant mangrove species identification references. In addition, primary data were acquired through in-depth interviews with key stakeholders involved in mangrove ecosystem management within the study area.

Secondary data were compiled from a range of relevant published and unpublished sources, including official reports, policy documents, books, archives, and scientific literature. These data provided supporting information on the general characteristics of the study area, mangrove management practices, and allometric equations used to estimate aboveground biomass, carbon stocks, and carbon sequestration potential in the mangrove ecosystem. The integration of primary and secondary data enabled a comprehensive assessment of mangrove ecological conditions and management strategies in the study area.

d. Sampling Cluster Determination

Sampling plots were selected using a Stratified Random Sampling method based on mangrove stand density categories, namely low, medium, and high density. Given the total inventory area of 9.88 ha, 247 sampling plots were systematically distributed among the density strata to obtain representative ecological data and minimize sampling bias.

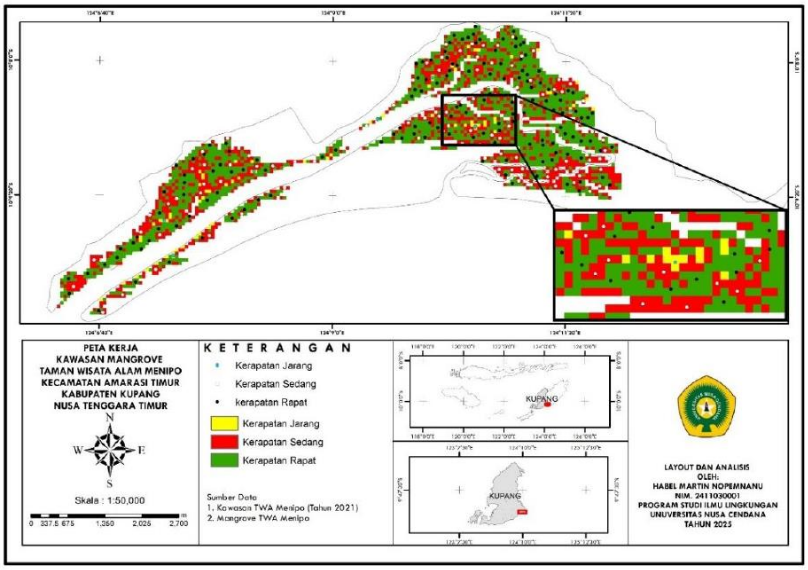

Figure 2. Research Map

e. Key Factors (Variables) in Mangrove Ecosystem Management

The application of the MICMAC (Matrix of Cross-Impact Multiplication Applied to Classification) approach is essential for identifying and evaluating the key variables that influence the sustainable management of mangrove ecosystems. This analytical framework enables a systematic examination of the complex interrelationships among variables by assessing both their direct and indirect influences within the management system. Through this process, it becomes possible to determine the relative importance of each variable and to understand how interactions among factors shape overall system dynamics. In the context of mangrove ecosystem management in Menipo Nature Tourism Park, the selection of variables was based on their relevance to management objectives, the clarity of their operational definitions, and the absence of conceptual overlap. The variables were identified through an integration of literature review findings, field observations, and stakeholder inputs obtained from actors involved in the planning, implementation, and monitoring of management activities. Consequently, the analysis incorporated ecological, social, economic, and institutional dimensions that collectively characterize the management system. The assessment of direct influences was conducted through the construction of an influence matrix, from which key variables were identified according to their positions within the influence–dependence map. Particular attention was given to variables exhibiting high levels of influence, whether associated with low dependence (driver variables) or high dependence (linkage variables), as these factors play a strategic role in governing system behavior and shaping the effectiveness of mangrove ecosystem management. The key variables considered in the MICMAC analysis are described in Table 1.

Table 1. Key Variables Examined in This Study

No.	Key Variable	Description
1	Mangrove Degradation	Natural mangrove degradation is caused by coastal erosion, high sedimentation rates, pests and diseases, flooding, and drought.
2	Sustainability of Rehabilitation	Ensuring that investments of time, resources, and labor in mangrove rehabilitation result in healthy and resilient mangrove forests.
3	Strengthening Customary Regulations	Strengthening customary regulations in mangrove management involves formal recognition of customary laws and institutions, as well as the integration of local wisdom into government policy frameworks.
4	Early Mangrove Education	Introducing mangrove-related concepts through direct experiences in nature, such as visits to mangrove forests and seedling planting activities, as well as through structured educational programs in schools.
5	Enhancing Mangrove Research in Menipo	Aims to develop a comprehensive understanding of mangrove ecosystems to support conservation, restoration, and sustainable utilization. Such research focuses on various aspects, including mangrove ecology, economic benefits, and contributions to climate change mitigation.
6	Availability of Environmental Monitoring Equipment for Mangrove Habitats	Required to monitor and evaluate ecosystem health, support conservation and rehabilitation efforts, and improve understanding of factors influencing mangrove growth and long-term survival.
7	Climate Change Resilience	Mangroves contribute to climate change mitigation by absorbing and storing substantial amounts of carbon (blue carbon), up to 4–5 times more than terrestrial forests. In addition, mangroves serve as vital natural barriers that protect coastal communities from climate-related hazards such as coastal erosion, storm surges, extreme waves, and sea-level rise.

f. Stakeholder Roles in Mangrove Ecosystem Management

Using the MACTOR method, stakeholder strategies, objectives, and recommendations can be systematically mapped into a matrix, providing a comprehensive representation of the relationships, alliances, and potential conflicts among actors involved in mangrove ecosystem management. Respondents were identified through purposive sampling, with selection criteria including their degree of participation, institutional authority, vested interests, and influence on decision-making processes related to mangrove ecosystem governance in Menipo Nature Tourism Park (TWA Menipo).

Table 2. Stakeholders or Actors Involved in the Study

No.	Stakeholder	Description
1	BBKSDA NTT	As the official management authority of Menipo Nature Tourism Park (TWA Menipo), BBKSDA plays a role in implementing conservation policies, protecting biodiversity, and supervising activities within the protected area, including the preservation of mangrove ecosystems.
2	Customary Leaders	Support the formulation of environmental conservation policies and programs as well as forest protection efforts at the provincial level. Their role is important in integrating conservation plans into regional policy frameworks.
3	Mangrove Farmer Group	A local community group actively involved in mangrove rehabilitation and utilization. They serve as the spearhead of community-based conservation activities.
4	Village Government	As the village governing authority, the Village Head has the authority to support local regulations, facilitate community participation, and align conservation programs with village development priorities.
5	NGO Network for Community Care	A non-governmental organization focusing on community empowerment and environmental advocacy. It can act as an intermediary between communities and government institutions while also conducting environmental education activities.
6	PLN (Persero)	As a state-owned enterprise, PLN can contribute through Corporate Social Responsibility (CSR) programs, such as funding conservation initiatives, community empowerment programs, or environmental clean-up activities in surrounding areas.
7	Academics	Lecturers, researchers, or higher education institutions that conduct scientific studies, provide data and analytical support, and serve as partners in developing evidence-based policy models.

RESULTS AND DISCUSSION

a. Overview of the Study Area

Menipo Nature Tourism Park (MNTP) is a coastal conservation area located in Enoraen Village, East Amarasi District, Kupang Regency, East Nusa Tenggara Province, Indonesia. Covering approximately 2,449.5 ha, including Menipo Island with an area of about 571 ha, the park was officially designated through the Decree of the Minister of Forestry No. 23/Kpts-II/1993. The area plays a vital role in conserving biodiversity, safeguarding coastal ecosystems, and supporting sustainable nature-based tourism. Physically, MNTP is characterized by predominantly flat to undulating terrain underlain by limestone formations and alluvial deposits, creating suitable conditions for mangrove establishment while remaining susceptible to coastal erosion and seawater intrusion. The region experiences a tropical semi-arid climate with a prolonged dry season, where tidal fluctuations and salinity gradients significantly influence vegetation dynamics and ecosystem processes. The park encompasses several key ecosystems, including mangrove forests, coastal forests, seagrass beds, and savanna landscapes, which provide habitat for a wide range of ecologically important flora and fauna. Between 2020 and 2024, a series of mangrove rehabilitation initiatives were implemented across the area, including the 2024 *PLN Menanam* Program, which restored approximately 10 ha of mangrove habitat. These restoration efforts were undertaken to enhance mangrove cover, mitigate coastal erosion, strengthen the ecological functions of coastal ecosystems, and promote sustainable ecotourism development while supporting the livelihoods and empowerment of local communities.

b. Mangrove Vegetation Species Composition

The vegetation survey recorded a total of 13,182 individuals across the seedling, sapling, and tree growth stages from 247 sampling plots established within the mangrove ecosystem of Menipo Nature Tourism Park. A total of 15 mangrove-associated species belonging to eight families were identified. These species included *Avicennia alba*, *Avicennia officinalis*, *Bruguiera gymnorrhiza*, *Bruguiera parviflora*, *Ceriops tagal*, *Dodonaea viscosa*, *Excoecaria agallocha*, *Lumnitzera racemosa*, *Osbornia octodonta*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sonneratia alba*, and *Sonneratia caseolaris*. The presence of these species indicates a relatively diverse mangrove community, reflecting the ecological heterogeneity of the study area and its importance for maintaining coastal biodiversity and ecosystem functioning.

Table 3. Mangrove Species Composition and Vegetation Abundance in Menipo Nature Tourism Park

No.	Family	Species Name	Seedlings	Saplings	Trees	Total
1	Rhizophoraceae	*Bruguiera gymnorrhiza*	763	1.248	168	2.179
		Bruguiera parviflora	236	943	663	1.842
		Ceriops tagal	178	535	43	756
		Rhizophora apiculata	10	0	26	36
		Rhizophora mucronata	522	2.168	3.693	6.383
		Rhizophora stylosa	363	169	735	1.267
2	Acanthaceae	*Avicennia alba*	9	61	167	237
		Avicennia officinalis	6	7	0	13
3	Lythraceae	*Sonneratia alba*	2	30	39	71
		Sonneratia caseolaris	4	11	67	82
4	Sapindaceae	*Dodonaea viscosa*	9	7	0	16
5	Euphorbiaceae	*Excoecaria agallocha*	4	4	12	20
6	Combretaceae	*Lumnitzera racemosa*	23	16	18	57
7	Myrtaceae	*Osbornia octodonta*	10	12	0	22
8	Rubiaceae	*Scyphiphora hydrophyllacea*	168	22	11	201
Total			**2.307**	**5.233**	**5.642**	**13.182**

c. Seedling-Level Vegetation Analysis

The analysis revealed a total seedling density of 23,350 individuals ha^{-1} across the study area. Among the recorded species, *Bruguiera gymnorrhiza* exhibited the highest density (7,722.67 individuals ha^{-1}; IVI = 43.55%), followed by *Rhizophora mucronata* (5,283.40 individuals ha^{-1}; IVI = 54.07%) and *Rhizophora stylosa* (3,674.09 individuals ha^{-1}; IVI = 32.77%). The dominance of these species at the seedling stage suggests their significant contribution to natural regeneration and future stand development within the mangrove ecosystem.

Table 4. Vegetation Analysis Results at the Seedling Stage

No.	Species Name	Number	K	KR	FR	IVI
1	*Avicennia alba*	9	91.09	0.39	1.75	2.14
2	*Avicennia officinalis*	6	60.73	0.26	0.87	1.13
3	*Bruguiera gymnorrhiza*	763	7722.67	33.07	10.48	43.55
4	*Bruguiera parviflora*	236	2388.66	10.23	18.34	28.57
5	*Ceriops tagal*	178	1801.62	7.72	9.17	16.89
6	*Dodonaea viscosa*	9	91.09	0.39	1.31	1.70
7	*Excoecaria agallocha*	4	40.49	0.17	0.87	1.05
8	*Lumnitzera racemosa*	23	232.79	1.00	2.18	3.18
9	*Osbornia octodonta*	10	101.21	0.43	1.31	1.74
10	*Rhizophora apiculata*	10	101.21	0.43	1.75	2.18
11	*Rhizophora mucronata*	522	5283.40	22.63	31.44	54.07
12	*Rhizophora stylosa*	363	3674.09	15.73	17.03	32.77
13	*Scyphiphora hydrophyllacea*	168	1700.04	7.28	1.31	8.59
14	*Sonneratia alba*	2	20.24	0.09	1.31	1.40
15	*Sonneratia caseolaris*	4	40.49	0.17	0.87	1.05
Total		**2.307**	**23.350**	**100**	**100**	**200**

Moderate tidal inundation combined with fine muddy substrates provides favorable conditions for the establishment of *Rhizophora* propagules. Unlike many mangrove species, *Rhizophora* exhibits vivipary, whereby seeds germinate while still attached to the parent tree. Consequently, the propagules are dispersed with sufficient energy reserves and an initial root structure that enhances their survival potential. Their elongated, pointed, and relatively heavy morphology enables them to penetrate soft sediment rapidly upon dispersal, facilitating successful establishment and reducing the likelihood of being washed away by tidal currents. In contrast, *Avicennia alba* and *Sonneratia alba* exhibited relative densities of less than 1%, indicating limited distribution and low population abundance within the study area. The reduced occurrence of these species is likely associated with coastal abrasion and habitat disturbance resulting from environmentally unsustainable shoreline developments, including the construction of small-scale jetties and other coastal infrastructure.

d. Vegetation Analysis Results at the Sapling Stage

The Importance Value Index (IVI) of sapling-stage vegetation varied considerably among species, indicating differences in their relative ecological significance and contribution to community structure. The vegetation analysis results for the sapling layer within the mangrove forest ecosystem of Menipo Nature Tourism Park are summarized in Table 5.

Table 5. Vegetation Analysis Results for the Sapling Growth Stage

No.	Species Name	Number	K	KR	FR	IVI
1	*Avicennia alba*	61	98.79	1.17	1.42	2.59
2	*Avicennia officinalis*	7	11.34	0.13	0.41	0.54
3	*Bruguiera gymnorrhiza*	1248	2021.05	23.85	10.77	34.62
4	*Bruguiera parviflora*	943	1527.13	18.02	29.88	47.90
5	*Ceriops tagal*	535	866.40	10.22	8.74	18.96
6	*Dodonaea viscosa*	7	11.34	0.13	0.41	0.54
7	*Excoecaria agallocha*	4	6.48	0.08	0.20	0.28
8	*Lumnitzera racemosa*	16	25.91	0.31	2.03	2.34
9	*Osbornia octodonta*	12	19.43	0.23	0.81	1.04
10	*Rhizophora mucronata*	2168	3510.93	41.43	38.82	80.25
11	*Rhizophora stylosa*	169	273.68	3.23	3.86	7.09
12	*Scyphiphora hydrophyllacea*	22	35.63	0.42	1.02	1.44
13	*Sonneratia alba*	30	48.58	0.57	1.02	1.59
14	*Sonneratia caseolaris*	11	17.81	0.21	0.61	0.82
	Total	**5233**	**8474.49**	**100**	**100**	**200**

The species exhibiting the highest density was *Rhizophora mucronata* (3,510.93 individuals ha^{-1}; IVI = 80.25%), followed by *Bruguiera gymnorrhiza* (2,021.05 individuals ha^{-1}; IVI = 34.62%) and *Bruguiera parviflora* (1,527.13 individuals ha^{-1}; IVI = 47.90%). These species were the dominant components of the sapling community, indicating their strong adaptation to local environmental conditions and their substantial contribution to the structure and regeneration dynamics of the mangrove ecosystem in Menipo Nature Tourism Park.

e. Tree-Level Vegetation Analysis Results

The results of the tree-level vegetation analysis of the mangrove forest ecosystem in Menipo Nature Tourism Park are presented in Table 6.

Table 6. Results of Tree-Level Vegetation Analysis

No.	Species Name	Number	K	KR	FR	DR
1	*Avicennia alba*	167	16.9	2.96	7.68	4.08
2	*Bruguiera gymnorrhiza*	168	17	2.98	3.92	0.91
3	*Bruguiera parviflora*	663	67.11	11.75	26.63	6.8
4	*Ceriops tagal*	43	4.35	0.76	1.96	0.21
5	*Excoecaria agallocha*	12	1.21	0.21	0.65	0.1
6	*Lumnitzera racemosa*	18	1.82	0.32	0.82	0.1
7	*Rhizophora apiculata*	26	2.63	0.46	0.49	0.52
8	*Rhizophora mucronata*	3693	373.79	65.46	35.29	61.26
9	*Rhizophora stylosa*	735	74.39	13.03	18.63	14.85
10	*Scyphora hydrophylacea*	11	1.11	0.19	1.14	0.07
11	*Sonneratia alba*	39	3.95	0.69	0.98	0.44
12	*Sonneratia caseolaris*	67	6.78	1.19	1.8	10.67
	Total	**5642**	**571.05**	**100**	**100**	**100**

The study also revealed a distinctive ecological phenomenon in Menipo Nature Tourism Park, where tree-level mangrove vegetation exhibited very high stand density, while seedling and sapling strata beneath the canopy were still able to establish and persist at relatively high densities. This condition was particularly evident among species of the family *Rhizophoraceae*. Such a pattern is possible because mangrove canopies are not permanently closed; instead, they naturally contain canopy gaps that allow sufficient sunlight to penetrate to the forest floor. These openings create favorable microhabitat conditions for seedling establishment and sapling growth, thereby supporting continuous natural regeneration despite the dense overstory vegetation. This finding suggests that the mangrove ecosystem in Menipo Nature Tourism Park maintains a healthy regeneration process and demonstrates strong ecological resilience, which is essential for sustaining long-term forest structure and ecosystem functions.

f. Potential CO_2 Emission Sequestration by Mangrove Vegetation

The carbon stock and CO_2 sequestration potential of mangrove stands in Menipo Nature Tourism Park are presented in Table 7.

Table 7. Biomass Potential, Carbon Stock, and CO_2 Sequestration of Mangrove Stands

Vegetation Density	Biomass (Ton/Ha)	Carbon Stock (Ton/Ha)	CO_2 Sequestration (Ton/Ha)
Dense	1,409.45	662.44	2,428.95
Moderate	466.85	219.42	804.54
Sparse	82.97	39.00	142.98
Average	**653.09**	**306.95**	**1,125.49**
Total	**1,959.27**	**920.86**	**3,376.48**

The findings demonstrate a positive relationship between mangrove stand density and carbon storage potential. Higher vegetation density contributes to greater biomass accumulation, which in turn enhances carbon stocks and increases the capacity of mangrove ecosystems to sequester atmospheric CO_2. These results underscore the importance of maintaining dense mangrove stands to maximize their function as blue carbon ecosystems and their contribution to climate change mitigation.

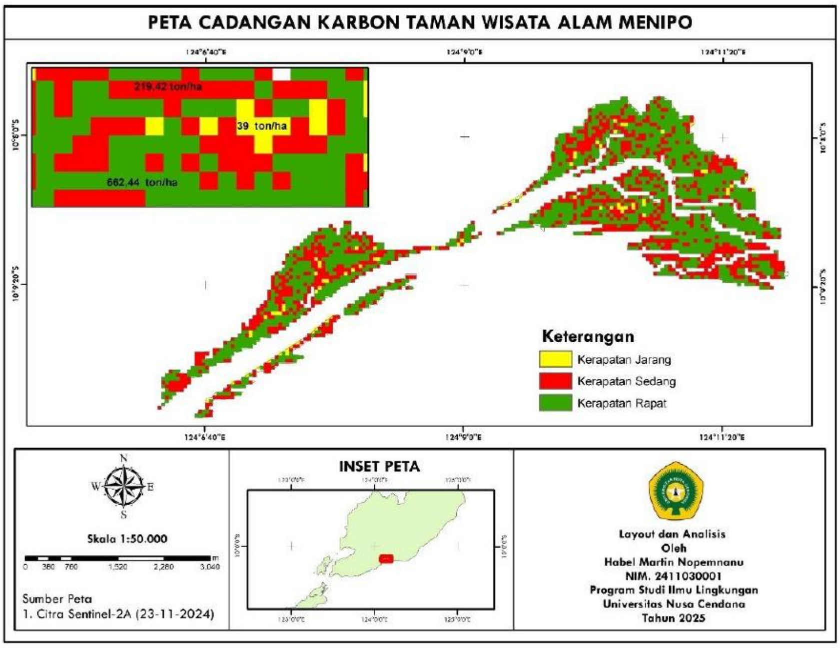

Figure 3. Map of Mangrove Carbon Potential in Menipo Nature Tourism Park

The estimated CO_2 sequestration capacity of the mangrove ecosystem in Menipo Nature Tourism Park (TWA Menipo) reached 3,376.48 t CO_2 ha^{-1}, supported by a substantial carbon stock of 920.86 t C ha^{-1}. These findings highlight the strategic role of the Menipo mangrove ecosystem in biodiversity conservation and climate change mitigation at both regional and national scales. The considerable carbon storage and sequestration potential underscore its significance as a natural carbon sink capable of contributing to greenhouse gas emission reduction efforts. Consequently, the mangrove ecosystem of TWA Menipo represents a strong candidate for inclusion in Indonesia's Blue Carbon initiatives and the implementation of the country's Nationally Determined Contribution (NDC) targets, particularly within the forestry and land-use sectors aimed at reducing national greenhouse gas emissions (Fenetiruma & Priyanto, 2025).

g. Mapping of Key Factors in Mangrove Ecosystem Management at Menipo Nature Tourism Park (TWA Menipo)

The relationships among the principal factors influencing mangrove ecosystem management were examined using the Matrix of Cross Impact Multiplications Applied to Classification (MICMAC) method. The analysis was undertaken to assess the influence and dependence levels of seven strategic factors that play a significant role in shaping mangrove management outcomes in Menipo Nature Tourism Park (TWA Menipo).

Based on the MICMAC analysis, the sustainability of mangrove rehabilitation and the level of mangrove degradation emerged as the most influential driving variables shaping the future direction of mangrove ecosystem management in Menipo Nature Tourism Park (TWA Menipo). The positive outcomes of rehabilitation initiatives, particularly mangrove planting programs, highlight the critical role of ecosystem restoration in enhancing vegetation cover, increasing carbon stocks, and strengthening the ecological functions of the coastal landscape. Conversely, anthropogenic pressures and natural disturbances remain the primary drivers of mangrove degradation, emphasizing the need for management approaches that are grounded in ecological suitability while supported by effective regulations and community empowerment strategies. Ecosystem resilience and research development were identified as linkage variables, indicating their strong reciprocal interactions with other components of the management system. Mangrove ecosystem resilience is particularly important for climate change adaptation and mitigation, given the dominance of species capable of attenuating wave energy, trapping sediments, and sequestering substantial amounts of carbon. In contrast, customary regulations and the availability of environmental monitoring instruments were classified as dependent variables, reflecting their reliance on institutional support and management policies. Although customary rules have the potential to strengthen conservation efforts, their implementation remains suboptimal due to limited integration into the formal governance framework. Meanwhile, early mangrove education was categorized as an autonomous variable with relatively low influence within the current system. Nevertheless, it possesses significant long-term potential to foster environmental awareness and pro-conservation behavior, particularly when integrated with educational programs, local institutions, and socio-cultural values.

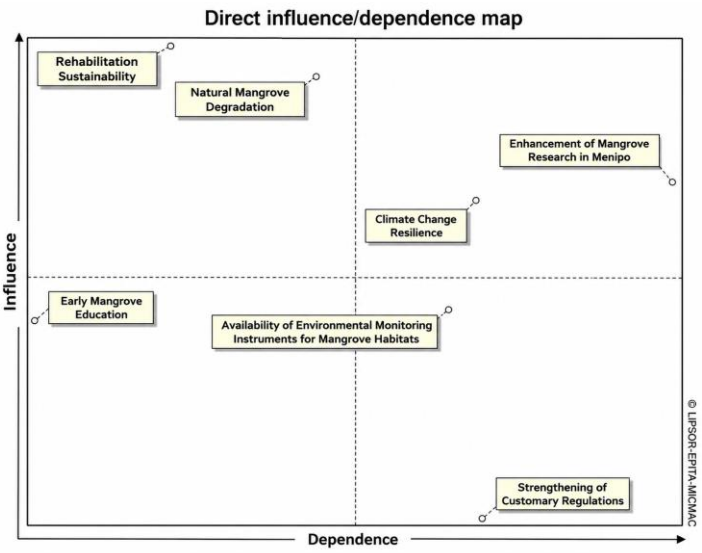

Figure 4. Mapping of Key Mangrove Management Factors Based on Their Levels of Influence and Dependence

h. Mapping of Key Stakeholders in Mangrove Ecosystem Management at Menipo Nature Tourism Park

The results of the stakeholder influence–dependence mapping related to mangrove ecosystem management in Menipo Nature Tourism Park are presented in Figure 5.

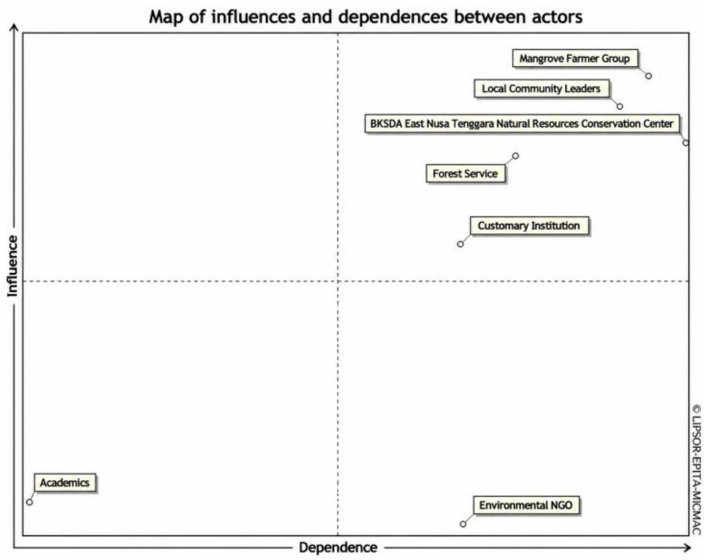

Figure 5. Stakeholder Mapping of Mangrove Management Based on Influence and Dependency Levels among Actors in Menipo Nature Tourism Park

The MACTOR analysis revealed the absence of a dominant driver actor in the management of the mangrove ecosystem within Menipo Nature Tourism Park, indicating that management effectiveness is highly dependent on collaboration and mutual support among stakeholders. Strategic positions are occupied by the Mangrove Farmer Group, non-governmental organizations (NGOs), the East Nusa Tenggara Natural Resources Conservation Agency (BBKSDA NTT), village government authorities, and customary leaders. These stakeholders function as linkage actors, characterized by both strong influence and high interdependence in rehabilitation activities, policy formulation, community facilitation, and the provision of social legitimacy for conservation initiatives. Meanwhile, PT PLN is classified as a dependent actor, contributing primarily through financial support for mangrove rehabilitation programs under its Corporate Social Responsibility (CSR) scheme. However, its capacity to influence management decisions remains limited and largely contingent upon the actions of other key stakeholders. In contrast, academics are categorized as autonomous actors because their involvement is mainly confined to research and scientific publication activities, while the integration of research findings into rehabilitation planning and implementation remains relatively weak. These findings highlight the importance of strengthening multi-stakeholder collaboration and enhancing the incorporation of scientific knowledge into management processes to improve the long-term effectiveness and sustainability of mangrove ecosystem governance.

i. Policy and Governance Strategy Directions for Mangrove Ecosystems in Menipo Nature Tourism Park

Based on the analysis of ecological conditions, key driving factors, and stakeholder roles, mangrove ecosystem management in Menipo Nature Tourism Park should adopt an integrated approach that balances ecological, social, and institutional dimensions. Mangrove rehabilitation initiatives should be preceded by comprehensive biophysical assessments, including substrate characteristics, tidal dynamics, and salinity regimes, to ensure that selected species are ecologically compatible with local habitat conditions. Such an approach is essential for improving rehabilitation success and enhancing ecosystem resilience. Strengthening customary institutions is equally important and should be achieved through the enforcement of local regulations that discourage destructive activities within mangrove areas by both local communities and external actors. This effort should be complemented by the development of alternative livelihood opportunities through social forestry schemes in protected forest areas, thereby reducing community dependence on mangrove resources while maintaining socioeconomic welfare. Sustainable utilization of aquatic resources should also be promoted by allowing local communities to harvest fisheries resources in ways that do not compromise ecosystem integrity. In addition, operational measures aimed at minimizing environmental pollution, such as conducting boat maintenance outside mangrove habitats and establishing designated mooring areas, should be implemented. Furthermore, the development of a rehabilitation zoning map represents a critical management instrument for guiding restoration planning and implementation. Such zoning can support the identification of priority restoration sites, determine rehabilitation extents, and facilitate more effective, efficient, and sustainable mangrove management practices.

CONCLUSION

The results revealed that the mangrove ecosystem in Menipo Nature Tourism Park (Menipo NTP) comprises 15 mangrove species, with *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, *Rhizophora stylosa*, and *Bruguiera parviflora* identified as the dominant species. The mangrove community exhibited a moderate level of species diversity, while species evenness and richness were relatively low. The estimated total biomass reached 1,959.27 t ha^{-1}, with a carbon stock of 920.86 t ha^{-1} and a CO_2 sequestration capacity of 3,376.48 t ha^{-1}, highlighting the significant contribution of this ecosystem to climate change mitigation. The analysis further identified the sustainability of rehabilitation efforts and the extent of mangrove degradation as the primary factors influencing mangrove management in the area. Key stakeholders with strategic roles in ecosystem governance include mangrove farmer groups, non-governmental organizations (NGOs), the East Nusa Tenggara Natural Resources Conservation Agency (BBKSDA NTT), village governments, and customary leaders. Accordingly, effective mangrove governance should be supported by comprehensive biophysical assessments prior to rehabilitation activities, strengthened customary regulations, community empowerment through social forestry programs, sustainable utilization of coastal resources, the provision of designated boat parking facilities, and the development of rehabilitation priority zoning to ensure the long-term conservation and resilience of the mangrove ecosystem.

RECOMMENDATION

It is recommended that customary regulations be formally established and enforced to bind both local community members and external stakeholders. In addition, the active involvement of traditional leaders in the planning, implementation, and monitoring of mangrove management programs is essential to strengthen community ownership, enhance social legitimacy, and improve compliance with conservation measures.

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