

## RESEARCH ARTICLE

# Structure, Composition, and Environmental Conditions of Rehabilitated Mangrove Forests in Kupang Bay, Indonesia

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**ABSTRACT**

Mangrove rehabilitation is widely implemented to restore degraded coastal ecosystems; however, post-restoration stand development and its environmental controls remain insufficiently understood. This study assessed species composition, stand structure, diversity, and environmental drivers of growth in rehabilitated mangrove forests on the northern coast of Kupang Bay, Indonesia. Vegetation data were collected using systematic sampling across nine permanent plots, covering growth stages from seedlings to trees, and analyzed using the importance value index (IVI), Shannon-Wiener diversity index ( $H'$ ), and species richness index. Environmental variables, including salinity, mud thickness, pH, and slope, were measured to evaluate their influence on mangrove growth using multiple linear regression. A total of eight mangrove species were identified, with *Avicennia marina* dominating at the seedling stage (IVI 123.48%) and *Sonneratia alba* dominating at the sapling (IVI 93.86%), pole (IVI 146.83%), and tree stages (IVI 104.10%). Overall species diversity was moderate ( $H' = 1.16$ ), while species richness was low, indicating limited compositional complexity despite successful establishment. Environmental conditions were within suitable ranges for mangrove growth, with a mean salinity of 28.68 ppt, pH 7.19, mud thickness 71.97 cm, and slope 2.08%. Regression analysis showed that environmental variables explained 51% of the variation in growth ( $R^2 = 0.51$ ), with mud thickness and pH exerting significant positive effects, whereas salinity and slope were not significant predictors. These findings demonstrate that rehabilitated mangrove forests can achieve structurally stable communities under favorable environmental conditions; however, species diversity remains constrained. The results highlight the importance of substrate characteristics and soil chemistry in shaping restoration outcomes and provide critical insights for improving mangrove management and rehabilitation strategies in tropical coastal ecosystems.

## 1. Introduction

Globally, mangrove ecosystems have been degraded in quantity and quality due to human activities (Matatula, 2023; Putra et al., 2025). Several activities, such as land reclamation, coastal development, and pollution, have negative impacts on the mangrove ecosystem (Matatula et al., 2021). Mangrove forests play an important role in providing environmental services in coastal areas, such as acting as windbreaks, preventing coastal erosion, and reducing seawater intrusion (Matatula et al., 2019). Mangrove ecosystems also serve as habitats for economically valuable marine organisms, such as fish, shrimp, and crabs (Matatula et al., 2021). Furthermore, mangrove forests provide valuable non-timber forest products, including tannins, and support ecotourism activities (Simanjuntak et al., 2025; Singh, 2020; Widhyastini et al., 2025). In addition, mangrove forests play an important role in climate change mitigation by reducing atmospheric carbon emissions (Ilman et al., 2016). Therefore, sustainable management of mangrove ecosystems has become a critical challenge in various archipelagic countries, including Indonesia (Sadono et al., 2020; Salampessy et al., 2025).

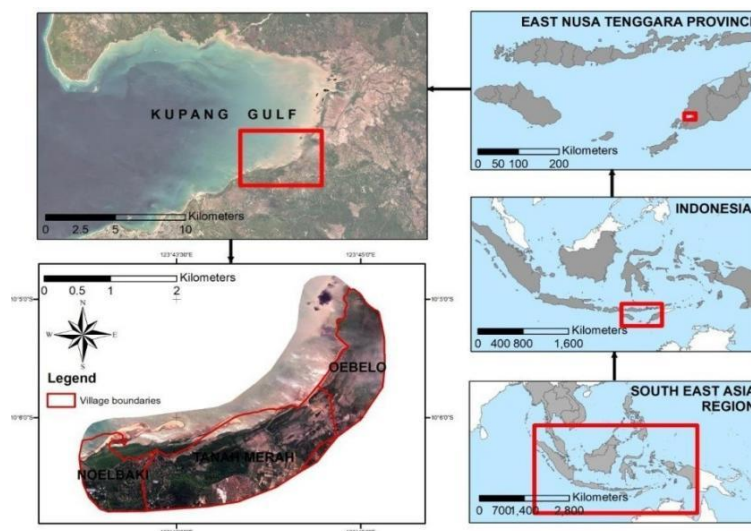
Indonesia has 3.31 million ha of mangrove forests, equivalent to 23% of the world's mangrove ecosystems, distributed proportionally across provinces (Ministry of Environment and Forestry, 2021). However, the causes of mangrove forest destruction are divided into two: anthropogenic factors, such as land conversion, illegal logging, waste pollution, and mining activities, and natural factors, such as coastal abrasion and erosion, excessive sedimentation carried by rivers, natural disasters, and climate. Damage caused by anthropogenic and natural pressures leads to ecosystem changes, causing the rate of mangrove loss to exceed the capacity for natural regeneration (Eddiwan, 2018; Goldberg et al., 2020). As a result, most mangrove forests cannot provide optimal environmental services in coastal areas. This also negatively affects coastal communities (Matutina et al., 2021; Pathibang et al., 2023). This situation encourages communities to reforest the mangrove ecosystem. However, mangrove reforestation is not easy because it requires high community participation as the key to ensuring the success of the reforestation program (Matatula et al., 2023).

Over the past few years, many coastal areas have carried out mangrove reforestation. Unfortunately, only a few areas have succeeded in achieving their goals, including the coastal area in the northern part of Kupang Bay, Kupang Regency, East Nusa Tenggara. Mangrove reforestation activities on the northern coast of Kupang Bay have been carried out since 2004 through cooperation between the local community and the local government. Since 2004, this effort has added more than 100 ha of mangrove forest cover in the area (Sadono et al., 2020). However, the results of mangrove reforestation, especially those related to the composition, structure and environmental conditions in this area, are rarely documented. Consequently, information is needed to determine the best strategy for sustainable management of the mangrove ecosystem and to characterize the composition, structure, and environmental conditions of mangrove forests, providing adequate baseline information on mangrove growth in this location.

## 2. Materials and Methods

### 2.1. Place and Time

The research was conducted in the coastal mangrove forest area of the northern part of Kupang Bay, located at coordinates  $10^{\circ}5'43''$ – $10^{\circ}7'48''$  S and  $123^{\circ}43'13''$ – $123^{\circ}44'48''$  E (Fig. 1). The total area of the mangrove forest is 120 ha. This site represents a rehabilitation area established in 2004, 2006, and 2008. The northern part of the Kupang Bay mangrove forest is in Kupang Regency.



**Fig. 1.** Location of mangrove forest in northern Kupang Bay (Sadono et al., 2020).

### 2.2. Tools and Materials

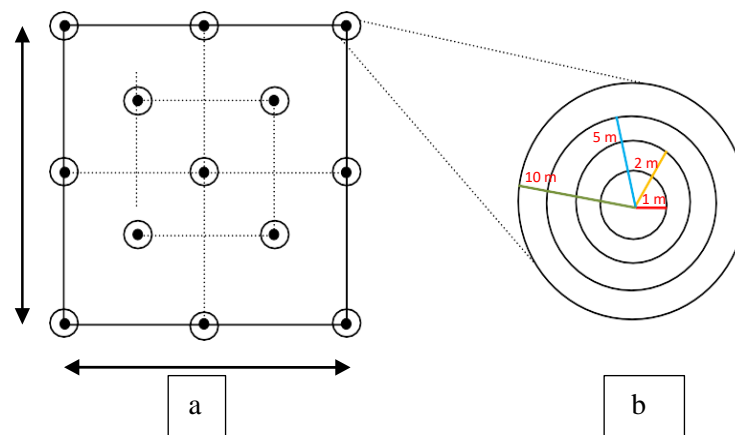
The research materials used were mangrove forests, boundary maps, and administrative maps. The equipment includes a roll meter, a salt refractometer (RHS-10ATC, China), litmus paper, a clinometer, a rope, a Haga hypsometer, a compass tape, a machete, a camera, and a GPS (Garmin 78s, Garmin Ltd, USA).

### 2.3. Methods

#### 2.3.1. Composition and growth structure of mangrove forests

The method used in this study was systematic sampling, which involves placing and distributing clusters to match the spatial distribution of previous research clusters (Poedjirahajoe et al., 2019). To identify the mangroves, we used the Indonesian Mangrove Guidebook (Noor et al., 1999) from Wetlands International - Indonesia Program. The northern part of the Kupang Bay Mangrove Forest covers 30 ha, and the sampling intensity used was 7.5%. Based on the sampling intensity, 9 clusters were used.

Sampling of mangrove vegetation structure and composition was conducted in nine permanent plots (50 m × 50 m) (Fig. 2). The distance between clusters was 100 m × 100 m. In each permanent sample cluster, 13 circular sub-plots were made in different positions (Fig. 2). The radius of the circular sub-plot is 10 m. In each sub-plot, several measurement plots were made with different radii to facilitate vegetation measurement, namely seedlings (1 m), saplings (2 m), poles (5 m) and trees (10 m) (Director General of Forest Planning and Environmental Management of Indonesia Number P.1/PKTL/IPSDH/PLA.1/1/2017). The parameters measured for seedlings, saplings, and poles were species, number of species, and height, while the parameters observed for poles and trees were species, diameter, and height.



**Fig. 2.** Design of permanent sample plots for vegetation analysis in mangrove areas: (a) Permanent sample plot shape with dimensions of 50 m × 50 m; (b) Circular sub-plot shape for vegetation measurement (Matatula et al., 2021).

#### 2.3.2. Environmental conditions

The environmental conditions or parameters measured are as follows: (a) salinity; (b) mud thickness; (c) slope; and (d) pH.

### 2.4. Data Analysis

The data analysis used to determine species composition and structure includes the important value index (IVI), diversity index, and species richness index.

#### 2.4.1. Importance value index

The important value index (IVI) is a quantitative parameter that measures the level of dominance (control) of a species in a growing community (Fachrul, 2007). To calculate the IVI, the following formulas are used: (a) density, (b) relative density, (c) frequency, (d) relative frequency, (e) dominance and (f) relative dominance.

#### 2.4.2. Shannon-Wiener diversity index ( $H'$ )

The diversity index used in this study is the Shannon–Wiener index (Strong, 2016), as shown in Equation 1.

$$H' = -\sum [p_i \times (\ln p_i)] \quad (1)$$

where  $H'$  is the Shannon–Wiener index,  $pi$  represents the relative abundance of a given species, calculated by dividing the number of individuals of that species ( $n$ ) by the total number of individuals across all species ( $N$ ), and  $\ln$  is the natural logarithm of this relative abundance.

#### 2.4.3. Margalef species richness index ( $d$ )

The species richness index used in this study is the Margalef index (Singh, 2020).

#### 2.4.4. Multiple linear regression analysis

The analysis used to determine the factors influencing mangrove growth is a multiple linear regression using SPSS version 26.0, as shown in Equation 2.

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + bnX_n \quad (2)$$

where  $a$  is the constant,  $b_1, b_2, b_3, b_4$  are the regression coefficients,  $Y$  is the mangrove growth,  $X_1$  is the salinity (ppt),  $X_2$  is the mud thickness (cm),  $X_3$  is the pH, and  $X_4$  is the slope (%). Statistical tests were conducted using the F-test and t-test.

### 3. Results and Discussion

#### 3.1. Species Composition and Structure of Mangrove Forests

##### 3.1.1. Species composition

The species composition of the mangrove area on the northern coast of Kupang Bay is shown in **Table 1**. The mangrove forest in the northern part of Kupang Bay has various species. The results of the study showed that 8 species make up the mangrove forest, namely *Lumnitzera racemosa*, *Rhizophora stylosa*, *Avicennia marina*, *Sonneratia alba*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia caseolaris*, and *Aegialitis annulata*. The total observed across nine clusters was 3,083 individuals, distributed across the tree, pole, sapling, and seedling categories. The most dominant mangrove species were *A. marina* and *S. alba*, while the least common species were *R. mucronata* and *S. caseolaris*.

**Table 1.** Species composition in rehabilitated mangrove forests on the northern coast of Kupang Bay

No.	Species	Amount
1	<i>Lumnitzera racemosa</i>	128
2	<i>Rhizophora stylosa</i>	201
3	<i>Avicennia marina</i>	1418
4	<i>Sonneratia alba</i>	1056
5	<i>Rhizophora apiculata</i>	60
6	<i>Rhizophora mucronata</i>	2
7	<i>Sonneratia caseolaris</i>	7
8	<i>Aegialitis annulata</i>	207
<b>Total</b>		<b>3083</b>

#### 3.2. Mangrove Forest Structure

##### 3.2.1. Seedlings

Seedlings are undergrowth or tree seedlings that are less than 1.5 m tall. The results of the seedling-level vegetation analysis for several mangrove species are shown in **Table 2**. Based on the observations, 6 vegetation types were identified at the seedling level. The results of the data analysis in **Table 2** show that the highest importance value index (IVI) is for the *A. marina*, at 123.48%. While the lowest is found in *L. racemosa* at 5.53% (Fachrul, 2007), the importance value index (IVI) describes the importance of a vegetation type in its ecosystem. A high importance value index indicates a greater contribution of species to the ecosystem (Yuliana et al., 2019). The dominance of *A. marina* indicates that the environmental conditions in the mangrove forest area on the northern coast of Kupang Bay are consistent with the habitat of *A. marina*, which can occupy and grow in various habitats, even in places with high salinity or in other words, the *A. marina* can adapt well so that the *A. marina* greatly affects the stability

of the ecosystem. The vegetation analysis results showed a density of 28,744.08 individuals/ha, with the highest density in *A. marina* at 20,741.47 individuals/ha. Based on the division of Environmental Quality Standard values (Minister of Environment Decree Number 02 of 1988), the density of all species at the seedling level is classified as very high because it is supported by habitat conditions that are in accordance with the types of mangroves and the adaptation of mangrove plants to environmental conditions that are typical in the northern mangrove forest of Kupang Bay.

**Table 2.** Results of vegetation analysis of the seedling stage in rehabilitated mangrove forests on the northern coast of Kupang Bay

No.	Species	Amount	D	RD (%)	F	RF (%)	IVI (%)
1	<i>Lumnitzera racemosa</i>	21	571.62	1.99	0.03	3.54	5.53
2	<i>Rhizophora stylosa</i>	28	762.15	2.65	0.09	9.73	12.39
3	<i>Aegialitis annulata</i>	175	4763.46	16.57	0.20	20.35	36.93
4	<i>Avicennia marina</i>	762	20741.47	72.16	0.50	51.33	123.48
5	<i>Sonneratia alba</i>	55	1497.09	5.21	0.09	9.73	14.94
6	<i>Rhizophora apiculata</i>	15	408.30	1.42	0.05	5.31	6.73
<b>Total</b>		<b>1056</b>	<b>28744.08</b>	<b>100</b>	<b>0.966</b>	<b>100</b>	<b>200</b>

Notes: D = Density; RD = Relative Density; F = Frequency; RF = Relative Frequency; IVI = Important Value Index.

### 3.2.2. Sapling

The results show that there are 296 vegetation species at the sapling level in the mangrove forest of the northern coast of Kupang Bay, comprising six species: *S. alba*, *R. stylosa*, *L. racemosa*, *R. apiculata*, *A. marina*, and *A. annulata*. **Table 3** shows that the highest important value index (IVI) is for the *S. alba*, at 93.86%. The lowest is found in *R. apiculata*, at 6.63%. This shows that *S. alba* is more adapted than the others. *S. alba* competes in the community to maintain its species by securing nutrients and habitat space, making it important for ecosystem stability because saplings become the next generation for future ecosystem sustainability. In terms of vegetation, it greatly affects ecosystem stability compared to other vegetation types in the northern mangrove forest of Kupang Bay. At the sapling level, it shows 2014.26 individuals/ha, with a range of 61.24–932.28 individuals/ha. At the sapling growth stage, *S. alba* has the highest density, namely 932.28 individuals/ha. This shows that this species can compete and grow under the environmental conditions in the northern mangrove forest of Kupang Bay.

**Table 3.** Results of vegetation analysis of sapling stage in rehabilitated mangrove forests on the northern coast of Kupang Bay

No.	Species	Amount	D	RD (%)	F	RF (%)	IVI (%)
1	<i>Lumnitzera racemosa</i>	9	61.24	3.04	0.04	4.85	7.89
2	<i>Rhizophora stylosa</i>	11	74.85	3.72	0.06	6.80	10.51
3	<i>Aegialitis annulata</i>	22	149.71	7.43	0.03	3.88	11.32
4	<i>Avicennia marina</i>	106	721.32	35.81	0.30	33.98	69.79
5	<i>Sonneratia alba</i>	137	932.28	46.28	0.42	47.57	93.86
6	<i>Rhizophora apiculata</i>	11	74.85	3.72	0.03	2.91	6.63
<b>Total</b>		<b>296</b>	<b>2014.26</b>	<b>100</b>	<b>0.88</b>	<b>100</b>	<b>200</b>

Notes: D = Density; RD = Relative Density; F = Frequency; RF = Relative Frequency; IVI = Important Value Index.

### 3.2.3. Pole

Based on **Table 4**, there are 813 individuals at the pole level in the northern mangrove forest area of Kupang Bay, comprising six species: *S. alba*, *R. stylosa*, *L. racemosa*, *R. apiculata*, *A. marina*, and *A. annulata*. The results of the data analysis showed that the highest important value index (IVI) was found in the *S. alba*, at 146.83%, indicating that this vegetation type played the greatest role in the community in influencing ecosystem stability. The lowest was found in the *A. annulata*, at 3.12%. The high IVI of *S. alba* in this study was inseparable from the carrying capacity of environmental conditions at the research location, where, in the study, the type of substrate, salinity, and pH were still within the normal range that allowed it to live (**Table 7**). Based on the calculation results, the density at the pole level was 885.19 individuals/ha, classified as very high. At the pole growth level, *S. alba* had the highest

density, at 448.58 individuals/ha. This shows that interactions among mangrove plants can also affect mangrove density. Mangrove plants protect from wind and waves, and compete with each other for nutrients and sunlight. This can affect competition between mangrove plants and affect the overall density of the mangrove population.

**Table 4.** Results of the analysis of vegetation at the pole stage in rehabilitated mangrove forests on the northern coast of Kupang Bay

No	Species	AoS	BA	D	RD (%)	F	RF (%)	Do	RDo (%)	IVI (%)
1	<i>Lumnitzera racemosa</i>	13	0.05	14.15	1.60	0.05	3.80	0.06	1.54	6.93
2	<i>Rhizophora stylosa</i>	72	0.33	78.39	8.86	0.12	8.86	0.36	9.30	27.01
3	<i>Aegialitis annulata</i>	10	0.04	10.89	1.23	0.01	0.63	0.05	1.25	3.12
4	<i>Avicennia marina</i>	300	1.28	326.64	36.90	0.54	39.87	1.40	35.92	112.69
5	<i>Sonneratia alba</i>	412	1.83	448.58	50.68	0.61	44.94	1.99	51.22	146.83
6	<i>Rhizophora apiculata</i>	6	0.03	6.53	0.74	0.03	1.90	0.03	0.78	3.42
<b>Total</b>		<b>813</b>	<b>3.57</b>	<b>885.19</b>	<b>100</b>	<b>1.35</b>	<b>100</b>	<b>3.89</b>	<b>100</b>	<b>300</b>

Notes: AoS = The amount of Species; BA = Base Area; D = Density; RD = Relative Density; F = Frequency; RF = Relative Frequency; Do = Dominance; RDo = Relative Dominance; IVI = Important Value Index.

### 3.2.4. Tree

There are 914 individual mangrove species of the seven species at the tree level that shape the mangrove forest area on the Tanah Merah coast, consisting of seven species, namely *S. alba*, *R. stylosa*, *L. racemosa*, *R. apiculata*, *A. marina*, *R. mucronata*, and *A. annulata* (Table 5).

**Table 5.** Results of the analysis of tree stage in rehabilitated mangrove forests on the northern coast of Kupang Bay

No	Species	Amount	BA	D	RD (%)	F	RF (%)	Do	RDo (%)	IVI (%)
1	<i>Lumnitzera racemosa</i>	85	2.60	23.14	9.30	0.10	6.59	0.71	12.88	28.77
2	<i>Rhizophora stylosa</i>	90	2.93	24.50	9.85	0.16	10.44	0.80	14.54	34.83
3	<i>Avicennia marina</i>	250	3.03	68.05	27.35	0.55	35.16	0.83	15.04	77.56
4	<i>Sonneratia alba</i>	452	2.93	123.03	49.45	0.62	40.11	0.80	14.54	104.10
5	<i>Rhizophora apiculata</i>	28	3.06	7.62	3.06	0.08	4.95	0.83	15.17	23.18
6	<i>Rhizophora mucronata</i>	2	2.81	0.54	0.22	0.02	1.10	0.77	13.94	15.26
7	<i>Sonneratia caseolaris</i>	7	2.80	1.91	0.77	0.03	1.65	0.76	13.88	16.30
<b>Total</b>		<b>914</b>	<b>17.57</b>	<b>248.79</b>	<b>100</b>	<b>1.56</b>	<b>100</b>	<b>5.49</b>	<b>100</b>	<b>300</b>

Notes: AoS = The amount of Species; BA = Base Area; D = Density; RD = Relative Density; F = Frequency; RF = Relative Frequency; Do = Dominance; RDo = Relative Dominance; IVI = Important Value Index.

Vegetation types at the tree level have different importance value indices. *S. alba* has the highest density, frequency and dominance levels or the highest IVI. This shows that this species plays a major role in the mangrove forest community, influencing ecosystem stability, compared to other species that shape the mangrove forest in the northern mangrove forest of Kupang Bay. The high IVI value of the *S. alba* indicates that the environmental conditions in the mangrove forest area in the northern mangrove forest of Kupang Bay are suitable for the *S. alba*, or in other words, this species can adapt well. Species with the smallest IVI is *R. mucronata*. This shows that the presence of this species has a very small influence compared to other species that shape the mangrove area, and that it does not significantly affect the stability of the rehabilitated mangrove forests on the northern coast of Kupang Bay.

### 3.3. Species Diversity

The species diversity index measures variation in species composition, and the species richness index measures the level of species richness influenced by the even distribution of species in an area (Hidayat and Hardiansyah, 2012). The diversity of mangrove species in the observation plot is calculated using the Shannon–Wiener index (*H'*), and the level of species richness is calculated using the Margalef index (*d*). Vegetation at the tree level exhibits the highest plant species diversity index in the Tanah Merah coastal mangrove forest. In other words, the types of vegetation at the tree level that make up the

mangrove forest area in the northern mangrove forest of Kupang Bay have more species and abundance of vegetation types compared to the species at the seedling, pole and sapling stages. Meanwhile, the lowest vegetation diversity index in the northern mangrove forest of Kupang Bay is at the seedling level, at 0.92 (**Table 6**).

**Table 6.** Species diversity index

Vegetation level	Diversity index (H')	Richness index (d)
Seedling	0.92	0.71
Saplings	1.31	1.05
Pole	1.08	0.75
Tree	1.32	1.03
<b>Average</b>	<b>1.16</b>	<b>0.89</b>

This study shows that the mangrove forest species diversity in the northern mangrove forest of Kupang Bay falls within the moderate category, with an average species diversity of 1.16. The results of this study are consistent with previous research in the mangrove forest area of Langge Village, Anggrek District, North Gorontalo Regency (Rahim 2019), which also reported a species diversity index value in the moderate category. According to Rahim (2019), the diversity index remains in good condition, indicating that the mangrove ecosystem has sufficient productivity, moderate ecological pressure and a fairly balanced ecosystem condition. Ecosystem components are available in sufficient quantities and function according to the characteristics of each ecosystem, both biotic and abiotic components. According to Soerianegara and Indrawan (2005), this moderate diversity results from repeated successional changes and the availability of nutrients, light, and water. Therefore, the shape and number of plant species are arranged according to where they grow. Furthermore, Azizah (2017) stated that the low level of plant species diversity is due to the area's vulnerability to various disturbances.

The richness index of mangrove forest species in the northern part of Kupang Bay is classified as low, with an average species richness of 0.89. The low species richness index in the northern mangrove forest in Kupang Bay is due to human activities, such as mangrove cutting for housing and boat building. Another factor affecting the low species richness index is pollution from household waste dumped in the mangrove forest of the northern mangrove forest in Kupang Bay, which can contaminate the mangrove habitat, disrupt the balance of the mangrove ecosystem, and kill mangrove plants. Competition will increase the fighting power needed to survive; the stronger species will win and suppress others, so that the losing species become less adaptive and exhibit low reproduction rates and low density (Kunarso and Aswar, 2017). This is consistent with Matatula (2021), who stated that mangroves will grow rapidly under environmental conditions that support their growth. When environmental conditions are unfavorable, these species will be outcompeted. Even if some survive, it is due to natural selection, so that when found, they will show low density, frequency, and dominance values. Environmental conditions that influence mangrove growth on the Tanah Merah coast include mud thickness and pH. The mud thickness value averages 71.97 cm, and a pH of 7.19 supports the growth of *Avicennia* and *Sonneratia* mangrove species (Matatula, 2010).

According to Wicaksono and Muhdin (2015), species diversity in an area is greatly influenced by biotic and abiotic factors. This species diversity can describe the level of succession or the stability of a community. The more species are observed in an area, the higher the diversity index. If stability is high, it will also affect the high level of complexity. This shows a high ability to handle disturbances in its components by creating interactions.

### 3.4. Environmental Conditions

Environmental conditions are an important factor for the sustainability of the mangrove ecosystem. In the mangrove ecosystem, there is an interaction between mangrove plants and their environment. The environmental conditions studied in the mangrove forest area are salinity, mud thickness, slope, and pH. Environmental conditions in the northern part of the Kupang Bay mangrove forest are shown in **Table 7**.

**Table 7.** Environmental conditions of the mangrove forest on the northern coast of Kupang Bay

Environmental conditions	Planting year			Average
	2004	2006	2008	
Salinity (ppt)	10–35	25–39	21–33	28.68
Mud thickness (cm)	76–130	60–80	40–69	71.97
pH	6–7	6–8	7–8	7.19
Slope (%)	1-3	1–3	1–3	2.08

### 3.4.1. Salinity

Salinity is an important factor in the growth, survival and zonation of mangrove species. The salinity range in the 2004 planting year was 10–35, with the lowest value in plot 7 at 10 ppt. This occurs because the plot is located at the back of the mangrove forest, where small streams of fresh water seep from the mainland into it. The highest salinity value is in Plot 35, which is located at the front. The salinity value in the plot increases during high tides due to inundation, and at low tide, the seawater does not completely recede because the higher slope of the front mangrove forest traps it. The salinity obtained in the 2006 planting year was in the range of 25–39 ppt. The value is higher than the salinity value in 2004. This is because the Tanah Merah mangrove forest has one condition that shows a change in the way of inundation, where the high tide coming from the front only reaches the front zone of the mangrove forest, then for inundation of the middle and back parts occurs by sea water going around the high pile of sand in the front so that the inundation system enters through the middle to the back. This happens because the front and middle parts of the mangrove forest are limited by sand piles, which are the main obstacles. The salinity value in the 2008 planting year ranged from 21 to 33 ppt. The diversity of salinity values in the 2008 planting year decreased more slowly than in the 2006 planting year. This happened because, in the 2008 planting year, the plot was in a river estuary. The salinity measured in the study averaged 28.68 ppt, which remains within the normal range. According to [Matatula et al. \(2021\)](#), mangroves generally live in saline or brackish areas with salinities ranging from 11–30 ppt. This is consistent with the research by [Matatula et al. \(2019\)](#) at the Kupang City mangrove tourism site, which found that coastal salinity averaged 24.4 ppt. This salinity data shows the salinity range that supports mangrove growth, as mangrove plants thrive in estuarine areas with salinities of 10 to 30 ppt, and some species can even grow at high salinity ([Matatula et al., 2021](#)).

### 3.4.2. Mud thickness

Mangroves have certain growth requirements, namely soil containing mud, tidal inundation by seawater and relatively small waves. Mud is used as an indicator of ecosystem stability, namely by examining its thickness and texture. If the mud is thicker, the area is stable; if the mud is thinner, the area is not yet stable ([Poedjirahajoe et al., 2014](#)). The thickness of the mud in the 2004 planting-year measurement plot ranges from 76–130 cm; the 2006 planting-year measurement plot ranges from 60–80 cm; and the 2008 planting-year measurement plot ranges from 40–69 cm. The large mud thickness values in the 2004 and 2006 measurement plots were due to longer inundation in several places. The conditions of large and small tides resulted in the mud thickness being concentrated in several observation plots. This inundation was caused by a buildup of sand in the front, so that when a large tide occurred, the middle and back were inundated. This occurs because, during low tide, water in the middle and back zones remains trapped. After all, the water at low tide cannot pass through the sand cushion at the front. The average mud thickness at the research location was 71.97 cm. This result is higher than that of the [Matatula et al. \(2019\)](#) study at the Mangrove Tourism location, which reported an average of 23.31 cm. The thickness of the mud plays an important role in determining the growth of mangrove plants. Mud thickness is predicted to be in line with nutrient content and organic matter ([Matatula et al., 2019](#)).

### 3.4.3. pH

The pH of water at the research location ranged from 6 to 7 in the 2004 planting year, from 6 to 8 in the 2006 planting year, and from 7 to 8 in the 2008 planting year. The average pH value obtained at the research location was 7.19. The average pH remains within the water quality standards for mangrove

biota (7–8.5) (Ministerial Decree of the Environment 2004). This means the pH is within the range for good mangrove growth. This shows that the research location is suitable for mangrove growth. In addition, according to Wibowo (Wiryanto et al., 2017), during litter decomposition, decomposing microorganisms function optimally at pH 6.0–8.0.

#### 3.4.4. Slope

The topography of the land at the research location shows a slope level with the same range, namely 1–3 degrees. This shows that the topography at the research location is still classified as sloping land. According to Alwidakdo et al. (2014), sloping areas will have higher diversity because the available land provides more space for growth, allowing species to be distributed more widely. On steep land, mangroves will have difficulty growing and developing, so the distribution, composition and area of the forest are shrinking. The coastal slope is an important factor influencing the characteristics of mangrove structure, especially the species composition and the size and area of mangroves. The flatter the beach and the greater the tides, the wider the mangrove forest will grow.

#### 3.5. The Influence of Environmental Conditions on Mangrove Growth

Multiple linear regression was used to determine the effects of environmental conditions on mangrove growth. Environmental conditions in this study were salinity (X1), mud thickness (X2), pH (X3) and slope (X4). The results of the F Test (Appendix 3) provide a significant value of 0.000, which is smaller than 0.05 and smaller than 0.01, meaning that salinity (X1), mud thickness (X2), pH (X3) and slope (X4) together have a very significant effect on mangrove growth (Y). The coefficient of determination ( $R^2$ ) shows the magnitude of the influence of environmental conditions (salinity, mud thickness, pH and slope) on mangrove growth. Based on the results of the analysis, the coefficient of determination ( $R^2$ ) of 0.510 indicates that mangrove growth can be explained by variations in salinity, mud thickness, pH and slope by 51%. The effects of salinity (X1), mud thickness (X2), pH (X3) and slope (X4) on mangrove growth (Y) are partially known from the T-test. The results of the T-test indicate that environmental conditions significantly affecting mangrove growth are mud thickness and pH, with a value of 0.000. At the same time, slope and salinity have no significant effect. Based on the T-test results, the relationship between environmental conditions and mangrove growth can be expressed as  $Y = 14.19 + 0.029 X1 + 0.064 X2 - 1.40 X3 - 0.054 X4$ .

## 4. Conclusion

The rehabilitated mangrove forests on the northern coast of Kupang Bay exhibit a structurally established community characterized by the dominance of *Avicennia marina* at early growth stages and *Sonneratia alba* at later stages, reflecting species-specific adaptation to site conditions. Despite successful stand development, species diversity remains moderate and species richness is low, indicating limited compositional complexity following rehabilitation. Environmental conditions, including salinity, mud thickness, pH, and slope, fall within ranges suitable for mangrove growth, with mud thickness and pH identified as significant factors influencing growth dynamics. In contrast, salinity and slope show no significant effects. These findings highlight the importance of substrate characteristics and soil chemical conditions in shaping post-restoration trajectories and emphasize the need to incorporate site-specific environmental considerations into mangrove rehabilitation planning to improve ecological outcomes and long-term ecosystem stability.

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