Media Konservasi, 30 (1) 84-95

RESEARCH ARTICLE

MEDIA KONSERVASI
SCIENTIFIC JOURNAL IN CONSERVATION OF NATURAL RESOURCES AND ENVIRONMENT

Check for updates

Article Info:
Received 23 May 2024
Revised 25 November 2024
Accepted 25 November 2024

Corresponding Author:
Luisa Febrina Amalo
Environmental Research Center, IPB University, Bogor 16680, Indonesia
E-mail:
luisafebrina@apps.ipb.ac.id

Assessment of Mangrove Restoration Feasibility Using Water Quality and Substrate Parameters on Sebaru Kecil Island, Indonesia

Luisa Febrina Amalo[a], Marfian Dwidima Putra[a], Luluk Dwi Wulan Handayani[a], Sumpeno[b], Ruben Luturmas[b] and Suryadi[b]

[a] Environmental Research Center, IPB University, Bogor 16680, Indonesia
[b] PT Artha Graha Peduli, Jakarta 14430, Indonesia

Abstract

Mangrove have a substantial impact on ecosystems, both ecologically and economically. Planting mangroves is currently considered as an effective way to overcome mangrove forest degradation, especially on Sebaru Kecil Island where research is still limited. Besides natural forces contributing to the success of mangrove plantations, ecological parameters are also crucial to assessing mangrove restoration areas. The parameters include physical-chemical water quality, plankton and benthos, and substrate quality. This measurement is carried out to evaluate the level of water fertility and soil conditions at the location that will be used for mangrove planting. This research aimed to determine the feasibility of the area for mangrove restoration based on physical, biological, and chemical water quality conditions, and to provide recommendations for planting mangroves suitable for Sebaru Kecil Island based on its substrate condition. The results showed that the physical-chemical parameters of the seawater at the mangrove planting locations met the quality standards, except for nitrate. The condition of plankton and benthos showed a high diversity index, with no dominant species. Based on the substrate results and physical condition of Sebaru Kecil Island, the location is suitable for mangrove planting, and we recommend planting Rhizophora stylosa in the mangrove restoration area. These findings can serve as a guide for mangrove restoration efforts in areas with similar characteristics.

Keywords: mangrove restoration, Sebaru Kecil, substrate, water quality

1. Introduction

Mangrove plants have significant ecological and economic effects on ecosystems. These plants serve as a protective barrier against sea waves and wind, providing a habitat for various forms of biota and as feeding grounds for aquatic biota [1]. Additionally, they act as nursery grounds for the growth and development of biota, and function as spawning grounds for aquatic biota [2,3]. Furthermore, mangroves contribute to the complexity of the habitat and diversity of marine fauna, such as fish, crustacea, and mollusks, which are the most dominant macrofauna in mangrove ecosystems [4]. Chemically, mangrove vegetation can process waste and reduce the risk of pollution while producing oxygen [5,6]. Moreover, these plants can regenerate through propagules embedded in the mangrove substrate and ultimately grow into mature trees.

Sebaru Kecil Island is one of the 110 islands in Kepulauan Seribu (Thousand Island, Jakarta, Indonesia). Sebaru Kecil Island is included in the national park tourism zone because of its diverse ecosystems, including mangroves. Efforts to increase biodiversity on Sebaru Kecil Island and protect the mangrove ecosystem can be facilitated by a mangrove restoration program in areas that are prone to erosion and possess low-density mangroves [7]. Mangroves can be restored by planting trees along the coast, especially in locations where mangrove forests have been damaged [8]. Planting mangroves is currently considered an effective method for overcoming the degradation of mangrove forests [9]. Therefore, it is essential to plant mangroves in the waters surrounding Sebaru Kecil Island, particularly in mud-flat coastal areas that are protected from wind, waves, and strong currents [10,11].

Besides the natural forces that contribute to the success of mangrove plantations, ecological parameters are also important for assessing mangrove restoration areas. These parameters consist of physical-chemical water quality, plankton and benthos, and substrate quality [12,13]. This measurement was carried out to determine the level of water fertility and substrate conditions at the location to determine the potential mangrove restoration areas. This research aimed to determine the feasibility of the area for mangrove restoration based on physical, biological, and chemical water quality conditions, and to provide recommendations for types of mangrove planting that are suitable for Sebaru Kecil Island.

2. Materials and Methods

2.1. Study Area

Sebaru Kecil Island is part of the Indonesian archipelago, particularly located within the Kepulauan Seribu (Thousand Islands) near Jakarta (Figure 1). Like many others in the region, this island faces challenges due to rising sea levels, threatening coastal areas and ecosystems [14]. The islands in this region, including Sebaru Kecil, are known for their strategic importance, both geographically and functionally [15]. Additionally, the aboveground carbon stocks of marine mangroves on islands such as Pari and Lancang Kecil have been studied, highlighting the ecological significance of these areas [16].

2.2. Data Collection and Analysis

2.2.1. Water quality

Evaluating the quality of water is a critical step in determining the most suitable site for mangrove restoration [17]. This assessment takes into account the impact of human activities or natural conditions on the mangrove environment [18]. Additionally, key chemical parameters, such as Nitrate, Orthophosphate, and Total Dissolved Solids (TDS), were analyzed (Table 2) [19]. Aquatic life, including plankton (phytoplankton and zooplankton) and benthos (Table 3), is also a crucial indicator of water quality.

The analysis of physical and chemical parameters was carried out by taking a two-liter water sample and then preserving it using H_2SO_4 with a pH of up to 2 [20]. The physical and chemical parameters of the waters analyzed include Dissolved Oxygen (DO), pH, temperature, turbidity, and salinity, which were measured using an in-situ method and tested in the laboratory for TDS, Orthophosphate, and Nitrate parameters.

Plankton samples were taken by taking 50 liters of water. The collected water was filtered through a Benthos sieve with 1-mm diameter holes, after which the macrozoobenthos were collected and placed in a sample bag or bottle. To preserve the samples, preservative such as 70% alcohol or 4–5% formalin were added [20]. The samples were then identified in the laboratory for diversity index, uniformity index, dominance index, and community structure analysis.

2.2.2. Substrate

Substrate sampling was performed in plots measuring 20 × 20 m. The required samples were taken at a minimum of 500–1,000 g at the observation point and then stored in a Ziplock plastic bag for further analysis in the laboratory [21]. The key parameters used for the substrate analysis are listed in Table 1.

Table 1. Substrate parameters

No.	Parameter	Unit	No.	Parameter	unit
1	pH (H_2O & KCL)	-	6	PO_4	mg Kg^{-1}
2	C-Organic	%	7	Pb	mg Kg^{-1}
3	N-Total	%	8	Ammonium	mg Kg^{-1}
4	3-Fractions Texture	%	9	Nitrate	mg Kg^{-1}
5	Pirit	mg Kg^{-1}	10	Nitrite	mg Kg^{-1}

2.2.3. Mangrove Species Determination

Mangrove trees typically thrive in intertidal regions and are subjected to periodic flooding daily or during full moon tides [10]. Plant species found in mangrove forests vary depending on factors such as soil type, depth of inundation, salinity, and resistance to waves and currents [22,23]. The substrate condition is crucial in determining the mangroves zoning. *Avicennia* sp. and *Sonneratia* sp. tend to thrive in sandy mud substrates, while *Rhizophora* sp. prefers organic matter-rich mud substrates. In contrast, *Bruguiera* sp. prefers clay substrates with a low organic material content. Furthermore, mangroves can also grow on sandy and rocky beaches or with coral fragments as substrates, as evidenced by *Rhizophora stylosa* and *Sonneratia alba* [23]. Therefore, the recommended mangrove species were determined based on the literature.

3. Results

3.1. Overview of the study area

Based on field observations, it was determined that the optimal location for planting mangroves is in the southern region of Sebaru Kecil Island, particularly at coordinates 5°30'56.74"S and 106°31'59.50"E. The sloping beach in this area is characterized by a substrate dominated by sand, coral fragments, and moderate tidal conditions under normal natural conditions (Figure 2). The beach in this region is protected by a natural coral reef belt, making the southern area of Sebaru Island an ideal location for mangrove restoration. The success of mangrove planting depends on various factors, such as the type of mangrove planted, soil conditions, salinity, duration of inundation, and tidal currents [24]. Mangroves are known for their ability to adapt to their environments. However, they face challenges in growing in steep coastal areas with large waves and strong tidal currents, because these conditions do not allow the deposition of mud, which is essential for mangrove growth [25]. The mangrove ecosystem is unique in terms of both its physical conditions and natural resources, as well as its function and role in the terrestrial and marine life ecosystem.

Figure 1. Beach location in the south of Sebaru Kecil Island.

The presence of mangrove trees in the eastern part of Sebaru Kecil Island indicates that mangroves have the potential to thrive on the southern part of the island due to the similar coastal characteristics of the eastern and southern regions. Larger mangrove trees produce propagules or seeds that grow naturally or artificially. When propagules fall near the parent tree and adhere to the substrate, they become natural candidates for a new mangrove tree, which is also known as regeneration [26].

3.2. Physical-chemical of Water Analysis

Water quality typically reflects the state of water and is influenced by activities in the surrounding area. It is determined by physical, chemical, and biological conditions, which are evaluated based on appropriate measurements. In Table 2, the majority of the physical-chemical parameters of the seawater at the mangrove planting locations met the quality standards, except nitrate.

Table 2. Results of physical and chemical parameters water quality measurements

No.	Parameter	Unit	Result	Quality standard*
	Physical			
1	Temperature	°C	31.9	28–32
2	Salinity	psu	31	< 34
3	Dissolved Oxygen (DO)	mg L^{-1}	7.20	> 5
4	pH	-	8.24	7–8.5
5	Turbidity	NTU	4.22	5
	Chemical			
1	TDS	mg L^{-1}	19,600	-
2	Orthophosphate	mg L^{-1}	<0.003	0.015
3	Nitrate	mg L^{-1}	1.9	0.008

*Quality standards based on Indonesian Government Regulation No. 22/2021 Appendix VIII (Sea Water/Mangrove Quality Standards)

The monitoring of physical parameters has indicated that the seawater temperature at the planting location is 31.90°C. The salinity of the seawater used to determine the location for planting mangroves was 31 psu. According to Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management, the quality standard for mangrove salinity parameters is currently 34 psu.

Dissolved Oxygen (DO) is the amount of oxygen dissolved in water. In most aquatic organisms, DO is required for respiration. The DO measurement results at the mangrove planting location were obtained at 7.20 mg L^{-1}. Based on Government Regulation Number 22 of 2021, Appendix VIII states that the dissolved oxygen quality standard for marine biota has a concentration higher than 5 mg L^{-1}.

The pH at the planting location was 8.24. This finding can be considered indicative of pH meeting the quality standards necessary for the survival of marine biota and mangroves. According to the measurement results, the turbidity level was found to be 4.22 NTU, which is considered to be within the acceptable range for the growth of mangroves (quality standard of 5 NTU). The total dissolved solids (TDS) value was 19,600 mg L^{-1}. This value is still within the water quality standard (0.015 mg L^{-1}). Nitrate measurements indicated a value of 1.9 mg L^{-1}.

3.3. Biological Analysis

Based on observations, plankton show a high diversity index, and no one dominates. Phytoplankton groups found at the planting location included Bacillariophyceae, Cyanophyceae, Dinophyceae, and Euglenophyceae (26 taxa). The Cyanophyceae group had the highest number of species and highest abundance. Oscillatoria sp. is a phytoplankton species from the Cyanophycea group with the highest density of 251,658 cells m^{-3}.

The zooplankton groups found at the planting location were Bivalves, Malacostraca, Nematoda, Ostracoda, Rhizopoda, and Rotifera (11 taxa). The Malacostraca group had the highest number of species and highest abundance. Nauplius (27,060 ind m^{-3}) had the highest density. The diversity, uniformity, and dominance indices of phytoplankton, zooplankton, and benthos from the planting location are presented in Figure 3.

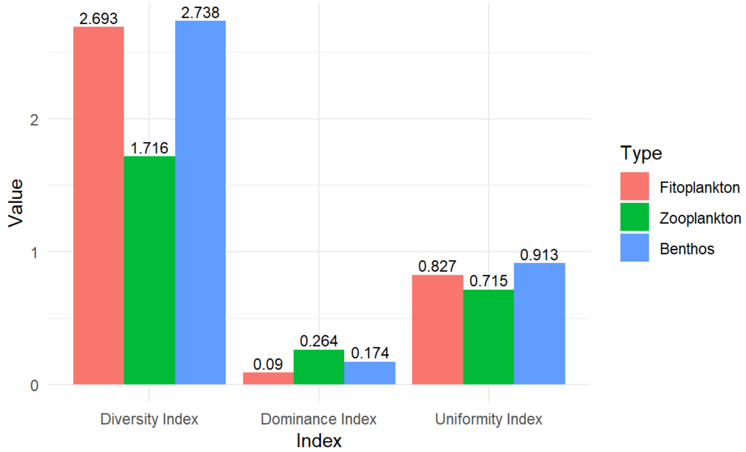

Figure 2. Diversity, uniformity, and dominance index of phytoplankton, zooplankton, and benthos at the planting location.

Table 3. Results of plankton and benthos analysis

Phytoplankton	Total	Zooplankton	Total	Benthos	Total
BACILLARIOPHYCEAE		**BIVALVIA**		**BIVALVIA**	
Amphiprora sp.	104,632	Larva	902	*Dosinia* sp.	58
Amphora sp.	28,864	**MALACOSTRACA**		*Mactra* sp.	87
Bacillaria sp.	220,088	*Acanthocyclops* sp.	2,706	**GASTROPODA**	
Bacteriastrum sp.	85,690	*Calanus* sp.	2,706	*Cerithium* sp.	174
Biddulphia sp.	7,216	*Canthocamptus* sp.	19,844	*Littoraria* sp.	58
Campylodiscus sp.	9,922	*Cyclops* sp.	2,706	*Nassarius* sp.	29
Chaetoceros sp.	9,020	*Diacyclops* sp.	1,804	*Planaxis* sp.	145
Cocconeis sp.	13,530	Nauplius	27,060	**POLYCHAETA**	
Coscinodiscus sp.	62,238	**NEMATODA**		*Lumbrineris* sp.	58
Diploneis sp.	41,492	Larva	3,608	*Nereis* sp.	29
Fragilaria sp.	60,434	**OSTRACODA**			
Licmophora sp.	10,824	Larva	1,804		
Mastogloia sp.	30,668	**RHIZOPODA**			
Navicula sp.	55,022	*Arcella* sp.	2,706		
Nitzschia sp.	234,520	**ROTIFERA**			
Pinnularia sp.	10,824	*Philodina* sp.	902		
Pleurosigma sp.	124,476				
Rhabdonema sp.	50,512				
Rhizosolenia sp.	6,314				
Striatella sp.	8,118				
Surirella sp.	17,138				
Synedra sp.	11,726				
CYANOPHYCEAE					
Merismopedia sp.	144,320				
Oscillatoria sp.	251,658				
DINOPHYCEAE					
Peridinium sp.	28,864				
EUGLENOPHYCEAE					
Euglena sp.	3,608				
Number of taxa	26	Number of taxa	11	Number of taxa	8
Abundance (Cells m^{-3})	1,631,718	Abundance (Cells m^{-3})	66,748	Abundance (Cells m^{-3})	638
Diversity Index	2.693	Diversity Index	1.716	Diversity Index	2.738

Phytoplankton	Total	Zooplankton	Total	Benthos	Total
Uniformity Index	0.827	Uniformity Index	0.715	Uniformity Index	0.913
Dominance Index	0.090	Dominance Index	0.264	Dominance Index	0.174

The diversity index value (H') allows for categorizing the community structure of phytoplankton, zooplankton, and benthos at the planting location into several groups, as detailed in Table 4. According to this table, the community structures of phytoplankton and benthos are remarkably stable, whereas zooplankton also exhibit a high level of stability.

Table 4. Condition of phytoplankton, zooplankton, and benthos community structure at the planting location

Diversity Index	Community structure conditions	Phytoplankton	Zooplankton	Benthos
> 2.41	Very stable	√	-	√
1.81–2.40	More stable	-	-	-
1.21–1.80	Stable	-	√	-
0.61–1.20	Quite stable	-	-	-
< 0.60	Less stable	-	-	-

3.4. Substrate Analysis

Mangrove habitats are typically found in intertidal zones, where the soil is composed of mud, clay, and sand and is periodically submerged in water, either daily or during full moon tides [12]. The substrate analysis showed that the water beneath the planting location primarily consisted of sand and dead coral fragments. Table 5 presents details of the substrate analyses at the planting locations.

Table 1. Substrate analysis results

No.	Parameter	Category	Unit	Value
1	pH	H_2O	-	9.0
		KCl	-	8.9
2	C-Organic		%	0.78
3	N-Total		%	
4	3-Fractions texture	Sand	%	100
		Dust	%	0
		Clay	%	0
5	Lead (Pb)		mg Kg^{-1}	27.12
6	$N\text{-}NO_3$		%	0.02
7	$N\text{-}NO_2$		%	0.01
8	$N\text{-}NH_4$		%	0.02

Figure 3. Substrate conditions of mangrove planting location on Sebaru Island in February 2024.

The pH of the substrate is a critical factor in determining the solubility and availability of nutrients for mangrove growth [23]. The pH was measured with values of 9.0 and 8.9, respectively. The pH of the substrate represents the balance between acids and bases, and the C-organic value of the substrate was 0.78%. This indicates the level of productivity and fertility of the mangrove ecosystem as a source of growth and development [16] The content of heavy metal lead (Pb) was found to be 27.12 mg Kg^{-1}. Mangroves have physiological mechanisms that reduce the absorption of heavy metals when the concentration in the sediment is high [27]. Planting mangroves at this location can improve the quality of aquatic environments.

4. Discussion

4.1. Water Quality and Substrate Assessment

Seawater temperature is largely influenced by sunlight penetration, as increased sunlight typically raises water temperature [19]. The temperature range suitable for aquatic biota is between -28 and 32°C. When water temperatures drop below 14°C, fish mortality may occur, while temperatures below 25°C can negatively impact fish digestion. Conversely, temperatures exceeding 32°C can induce stress in fish due to increased oxygen demand [28].

Salinity is crucial for the growth, survival, and distribution of mangrove species [24,29]. The findings suggest that mangroves can adapt and thrive in the chosen location, which is characterized by estuarine areas with salinity levels from 10 to 30 psu. Some mangrove species can even tolerate high salinity [24]. Each species adapts in unique ways, such as root and leaf modifications, as well as distinctive patterns in community association and zoning. Dissolved Oxygen (DO) is essential for respiration in most aquatic organisms. The DO levels measured at the mangrove planting site meet the minimum regulatory requirement of 5 mg L^{-1} (Government Regulation Number 22 of 2021, Appendix VIII), with the safe minimum for aquatic life being 2 mg L^{-1} to support normal conditions [17].

The pH levels at the planting location meet the quality standards essential for marine biota and mangrove survival. The acceptable pH range for these organisms is typically 7–9, with an optimal range of 7–8.5 [30]. Low pH values (below 6) can harm aquatic life and inhibit mangrove growth [19]. Likewise, excessively high pH levels (8.65–9.50) may hinder mangrove growth, while pH values above 10 can lead to fish mortality [31]. Turbidity levels at the site fall within the acceptable range for mangrove growth (5 NTU). Elevated turbidity can negatively impact mangroves, especially at the seedling stage, as young plants struggle to access the necessary oxygen without a developed root system [2]. Mature mangroves, however, can better withstand high turbidity, using their roots to filter and trap organic materials in the water [18].

Total Dissolved Solids (TDS) concentration is positively correlated with salinity; higher salinity leads to increased TDS [32]. Freshwater typically has a TDS value between 0–1 mg L^{-1}, brackish water 1,001–10,000 mg L^{-1}, saline water 10,001–100,000 mg L^{-1}, and brine over 100,000 mg L^{-1}. High TDS levels are attributed to the abundance of dissolved organic and inorganic compounds, minerals, and salts in seawater, which also results in elevated salinity and electrical conductivity [32]. Phosphate levels at the site fall within the water quality standard (0.015 mg L^{-1}), while nitrate levels were measured at 1.9 mg L^{-1}. Phosphate and nitrate are essential nutrients for phytoplankton growth and reproduction, playing a vital role in aquatic ecosystems [17].

Overall, water quality and substrate parameters monitoring at the mangrove planting site indicate that conditions are within the acceptable ranges specified by environmental regulations. The seawater temperature, salinity, dissolved oxygen, pH, turbidity, TDS, phosphate, and nitrate levels align with prescribed quality standards, suggesting that the site is suitable for mangrove development. These findings demonstrate that the environmental conditions at this location support mangrove health, resilience, and growth in alignment with ecological and regulatory requirements.

4.2. Biological Condition (Plankton and Benthos)

Plankton and benthos inhabit various parts of the water, including the surface area, the water column, and the bottom [33]. These communities consist of phytoplankton, zooplankton, and nektons in the water column, and benthos, which inhabit the water's bottom. Plankton are generally categorized into two primary classifications: phytoplankton and zooplankton. Phytoplankton are microscopic plant life present in large numbers, with thousands to millions of cells per liter of seawater [20].

In contrast, zooplankton, such as jellyfish, are larger than phytoplankton and can reach sizes greater than one meter. The existence of plankton is crucial in aquatic ecosystems as they serve as a food source for various species of animals. The abundance and diversity of plankton are influenced by environmental factors including sedimentation, water level fluctuations, nutrients, heavy metals, temperature, pH, and oxygen content [34]. Macrozoobenthos are known to crawl, cling, burrow, and move at the bottom and on the surface of water. Mangrove habitats typically inhabit hard substrates, such as mud. Table 3 shows the outcomes of plankton and benthos measurements.

The diversity index (H') values of phytoplankton, zooplankton, and benthos provide insights into the health and stability of aquatic ecosystems, especially in mangrove environments [35]. Higher diversity index values typically indicate a more stable and resilient ecosystem with a balanced distribution of species, which is beneficial for supporting a range of life forms [36]. Figure 3 shows that phytoplankton has a diversity index of approximately 2.693, zooplankton 1.716, and benthos 2.738, suggesting a healthy level of species richness, particularly for phytoplankton and benthos. Phytoplankton, being primary producers, are crucial for supporting food webs, whereas benthos, as bottom-dwelling organisms, play an essential role in nutrient cycling and sediment stability, both of which are critical for mangrove health [37].

In mangrove ecosystems, a high diversity index in these groups supports the overall ecological balance and resilience [35]. For instance, a diverse benthic community can help stabilize sediment, which protects mangrove roots from erosion and enhances nutrient retention [36]. A healthy population of phytoplankton and zooplankton contributes to ecosystem productivity, serving as food for higher trophic levels, including fish that utilize mangrove areas as nursery habitats. Moreover, a diverse community of benthic organisms is associated with good water quality and low pollution levels, which further supports the growth of mangroves by providing suitable conditions for young plants and reducing competition with algae for resources [38].

4.3. Substrate Analysis

The substrate characteristics at the mangrove planting site, with a composition of sand and dead coral fragments, provide a suitable foundation for mangrove establishment [39,40]. High pH levels (9.0 and 8.9) indicate an alkaline environment, which can influence nutrient availability essential for mangrove growth and resilience. The moderate C-organic content (0.78%) suggests a low-to-moderate level of productivity, which supports the early stages of mangrove development [41]. These substrate conditions were good for mangrove planting, with considerations for soil fertility and contamination levels to optimize long-term growth and health.

According to the laboratory analysis, substrates that are dominated by sand are suitable for planting the mangrove species *Avicennia alba*, *Aegiceras corniculatum*, *Rhizophora apiculata*, *Rhizophora stylosa*, *Rhizophora mucronata*, *Sonneratia alba*, *Bruguiera gymnorrhiza*, *Bruguiera parviflora*, and *Ceriops tagal* [42].

4.4. Recommendation Mangrove Species for Restoration

Sebaru Kecil Island boasts a shoreline with sandy substrate and fragmented coral reefs. The mangroves that are well suited to these conditions are *Rhizophora stylosa*, *Rhizophora mucronata, Rhizophora apiculata*, *Bruguiera gymnorrhiza*, and *Ceriops tagal* [43]. *Rhizophora* sp. is particularly adept at thriving under these conditions, as it can flourish in land-based areas as long as it receives a sufficient supply of saltwater [44,45].

On Sebaru Kecil Island, the tides are ideal for *Rhizophora stylosa*, a mangrove species that can thrive on coastal areas that are inundated by normal tides. In addition to *Rhizophora stylosa*, other mangrove species that can survive in average tidal conditions are *Rhizophora apiculata, Rhizophora mucronata, Ceriops tagal,* and *Bruguiera parviflora*. The adaptability of each type of mangrove to water is influenced not only by substrate type but also by salinity. If salinity exceeds the mangroves' adaptation capacity. It can cause plants to dry, experience nutritional imbalances, encounter specific ion toxicity, or a combination of these factors. *Rhizophora stylosa* has a relatively high salinity tolerance (30%).

Rhizophora stylosa is a mangrove species found on coastal edges or lower tidal reaches [46]. Sometimes extend upstream along brackish tidal waterways. One typical niche that can be occupied is the mangrove edges on islands with coral sand substrates [46]. In the wet intertidal zone, the mean sea level and the highest tide and variable rainfall are separated by a height of 0–6 m (0–20 feet). *Rhizophora stylosa* thrives in open coastal areas. This recommendation is particularly relevant for coastal area management, as it supports biodiversity and provides a natural barrier against coastal degradation.

5. Conclusions

The results showed that the physical-chemical parameters of the seawater at the mangrove planting locations met the quality standards, except for nitrate. The condition of plankton and benthos showed a high diversity index, and no one dominated. Based on the substrate result and the physical condition of Sebaru Kecil Island, the location is suitable for mangrove planting, and we recommend *Rhizophora stylosa* be planted in the mangrove restoration area.

Author Contributions

LFA: Conceptualization, Investigation, Writing - Review & Editing; **MDP**: Methodology, Investigation, Writing; **LDW**: Supervision, Writing – Review; **SP**: Data acquisition; **RL**: Data acquisition; **SY**: Data acquisition.

Conflicts of Interest

There are no conflicts to declare.

Acknowledgements

The authors thank Bursa Berjangka Jakarta and Artha Graha Peduli for funding this research.

References

1. Boynauw, M.Y.; Lasabuda, R.; Rembet, U.N.W.J. Study on Ecological Economic Benefits of Mangrove in Sauk Village, Lolak Sub-District, Bolaang Mongondow District. *J. Ilm. Platax* **2017**, *5*, 170–176, doi:10.35800/jip.5.2.2017.15911.
2. Nagelkerken, I.; Blaber, S.J.M.; Bouillon, S.; Green, P.; Haywood, M.; Kirton, L.G.; Meynecke, J.O.; Pawlik, J.; Penrose, H.M.; Sasekumar, A.; et al. The Habitat Function of Mangroves for Terrestrial and Marine Fauna: A Review. *Aquat. Bot.* **2008**, *89*, 155–185, doi:10.1016/j.aquabot.2007.12.007.
3. Abu El-Regal, M.A.; Ibrahim, N.K. Role of Mangroves as a Nursery Ground for Juvenile Reef Fishes in the Southern Egyptian Red Sea. *Egypt. J. Aquat. Res.* **2014**, *40*, 71–78, doi:10.1016/j.ejar.2014.01.001.
4. Baderan, D.W.K.; Hamidun, M.S.; Utina, R.; Rahim, S.; Dali, R. The Abundance and Diversity of Mollusks in Mangrove Ecosystem at Coastal Area of North Sulawesi, Indonesia. *Biodiversitas* **2019**, *20*, 987–993, doi:10.13057/biodiv/d200408.
5. Rahadian, A.; Prasetyo, L.B.; Setiawan, Y.; Wikantika, K. A Historical Review of Data and Information of Indonesian Mangroves Area. *Media Konservasi* **2019**, *24*, 163–178, doi:10.29244/medkon.24.2.163-178.

6. Rahman; Effendi, H.; Rusmana, I.; Yulianda, F.; Wardiatno, Y. Green Open Spaces Management Based on Mangrove Ecosystem as a Mitigation of Greenhouse Gases in Tallo River Area of Makassar City. *J. Pengelolaan Sumberd. Alam dan Lingkung.* **2020**, *10*, 320–328, doi:10.29244/jpsl.10.2.320-328.
7. Nordhaus, I.; Toben, M.; Fauziyah, A. Impact of Deforestation on Mangrove Tree Diversity, Biomass and Community Dynamics in the Segara Anakan Lagoon, Java, Indonesia: A Ten-Year Perspective. *Estuar. Coast. Shelf Sci.* **2019**, *227*, 1–12, doi:10.1016/j.ecss.2019.106300.
8. Arifanti, V.B.; Kauffman, J.B.; Subarno, J.B.; Ilman, M.; Tosiani, A.; Novita, N. Contributions of Mangrove Conservation and Restoration to Climate Change Mitigation in Indonesia. *Glob. Chang. Biol.* **2022**, *28*, 4523–4538, doi:10.1111/gcb.16216.
9. Kusmana, C. Lesson Learned From Mangrove Rehabilitation Program in Indonesia. *J. Pengelolaan Sumberd. Alam dan Lingkung.* **2017**, *7*, 89–97, doi:10.29244/jpsl.7.1.89-97.
10. Shedage, S.; Shrivastava, P. Mangroves for Protection of Coastal Areas from High Tides, Cyclone and Tsunami. *Int. J. Plant Soil Sci.* **2018**, *23*, 1–11, doi:10.9734/ijpss/2018/42151.
11. Mancheño, A.G.; Vuik, V.; van Wesenbeeck, B.K.; Jonkman, S.N.; van Hespen, R.; Moll, J.R.; Kazi, S.; Urrutia, I.; van Ledden, M. Integrating Mangrove Growth and Failure in Coastal Flood Protection Designs. *Sci. Rep.* **2024**, *14*, 1–19, doi:10.1038/s41598-024-58705-4.
12. Harefa, M.S.; Rohim, N.; Pramuja, I.; Harahap, P.R.; Agustin, S.; Siregar, K.; Sitanggang, J.P. Bio-Ecological Study on Aceh Coast to Determine Mangrove Ecosystem Restoration Areas Suitability. *Depik* **2023**, *12*, 361–372, doi:10.13170/depik.12.3.32211.
13. Kusmana, C.; Chaniago, Z.A. Land Suitability Mangrove Trees Species in Bulaksetra, Pangandaran West Java. *J. Trop. Silvic.* **2017**, *8*, 48–54, doi:10.29244/j-siltrop.8.1.48-54.
14. Pasaribu, R.A.; Ratna Suhita, N.P.A.; Gumilar, G.; Choiriyah, N.; Siregar, R.R.; Yonatika, N.O. Sea Level Rise Implication on Small Islands in Kepulauan Seribu, Jakarta. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1251*, 1–13, doi:10.1088/1755-1315/1251/1/012059.
15. Trisnaputra, A.; Barus, B.; Trisasongko, B.H. Modeling Land Use/Land Cover Change in Berau Pantai Forests, Berau Regency, East Kalimantan Province. *J. Pengelolaan Sumberd. Alam dan Lingkung.* **2023**, *13*, 386–397, doi:10.29244/jpsl.13.3.386-397.
16. Kusumaningtyas, M.A.; Kepel, T.L.; Ati, R.N.A.; Salim, H.L.; Rustam, A.; Suryono, D.D.; Daulat, A.; Sudirman, N.; Rahayu, Y.P.; Hutahaean, A.A. Aboveground Carbon Stock of Marine Mangroves in Kepulauan Seribu Islands. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1251*, doi:10.1088/1755-1315/1251/1/012003.
17. Retnaningdyah, C.; Ridlo, I.A.; Febriansyah, S.C.; Nusantara, O.B. Water Quality Evaluation of Some Mangrove Ecosystems with Variations of Time Restoration in South Malang, East Java, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *743*, doi:10.1088/1755-1315/743/1/012011.
18. Sari, N.; Patria, M.P.; Soesilo, T.E.B.; Tejakusuma, I.G. The Structure of Mangrove Communities in Response to Water Quality in Jakarta Bay, Indonesia. *Biodiversitas* **2019**, *20*, 1873–1879, doi:10.13057/biodiv/d200712.
19. Wailisa, R.; Putuhena, J.D.; Soselisa, F. Analisis Kualitas Air Di Hutan Mangrove Pesisir Negeri Amahai Kabupaten Maluku Tengah. *J. Hutan Pulau-Pulau Kecil* **2022**, *6*, 57–71, doi:10.30598/10.30598.jhppk.2022.6.1.57.
20. Heriyanto, N.M. Keragaman Plankton Dan Kualitas Perairan Di Hutan Mangrove. *Bul. Plasma Nutfah* **2016**, *18*, 38–44, doi:10.21082/blpn.v18n1.2012.p38-44.
21. Cui, B.; Wang, X.; Su, Y.; Gong, C.; Zhang, D.; Ouyang, Z.; Wang, X. Responses of Tree Growth, Leaf Area and Physiology to Pavement in *Ginkgo biloba* and *Platanus orientalis*. *Front. Plant Sci.* **2022**, *13*, 1–18, doi:10.3389/fpls.2022.1003266.
22. Daris, L.; Jaya; Wahyuti; Arianto, I.F. Kajian Ekosistem Mangrove Berdasarkan Jenis Dan Karakteristik Substrat Di Desa Tompotana Kecamatan Kepulauan Tanakeke Kabupaten Takalar. *Lutjanus* **2023**, *28*, 16–27.
23. Windusari, Y.; Sarno, S.; Saleh, E.; Hanum, L. Substrate Characteristics and Its Impact on Distribution of Mangrove Species : A Case Study in Sungai Barong Kecil in The Sembillang National Park at Banyuasin, South Sumatra. *Berk. Penelit. Hayati* **2014**, *20*, 82–86, doi:10.23869/bphjbr.20.1.20141.
24. Poedjirahajoe, E.; Matatula, J. The Physiochemical Condition of Mangrove Ecosystems in the Coastal District of Sulamo, Kupang, East Nusa Tenggara, Indonesia. *J. Manaj. Hutan Trop.* **2019**, *23*, 173–184, doi:10.7226/jtfm.25.3.173.

25. Kusumaningrum, P.B.; Haryono, E. The Potential of Delta Ecosystem in North Coast of Java in Reducing CO2 Emissions. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *451*, 1–9, doi:10.1088/1755-1315/451/1/012071.
26. Yona, D.; Hidayati, N.; Sari, S.H.J.; Amar, I.N.; Sesanty, K.W. Teknik Pembibitan Dan Penanaman Mangrove Di Banyuurip Mangrove Center, Desa Banyuurip, Kecamatan Ujungpangkah, Kabupaten Gresik. *J-Dinamika J. Pengabdi. Masy.* **2018**, *3*, 1–4, doi:10.25047/j-dinamika.v3i1.744.
27. Rahman, F.A.; Hadi, A.P. Kandungan C-Organik Substrat Ekosistem Mangrove Di Danau Air Asin Gili Meno Kabupaten Lombok Utara. *Biosci. J. Ilm. Biol.* **2021**, *9*, 516–526, doi:10.33394/bioscientist.v9i2.4276.
28. Sihombing, K.; Harahap, R.H.; Mulya, M.B. Analysis of Coastal Water Quality At Marine Tourism Sites in the City of Sibolga. *Asian J. Aquat. Sci.* **2023**, *6*, 447–455, doi:10.31258/ajoas.6.3.447-455.
29. Matatula, J.- Keragaman Kondisi Salinitas Pada Lingkungan Tempat Tumbuh Mangrove Di Teluk Kupang, NTT. *J. Ilmu Lingkung.* **2019**, *17*, 425–434, doi:10.14710/jil.17.3.425-434.
30. Wantasen, A.S. Kondisi Kualitas Perairan dan Substrat Dasar sebagai Faktor Pendukung Aktivitas Pertumbuhan Mangrove Di Pantai Pesisir Desa Basaan I, Kabupaten Minahasa Tenggara. *J. Ilm. Platax* **2013**, *1*, 204–209.
31. Indawan, E.; Indri Hapsari, R.; Ahmadi, K.; Khaerudin, D.N. Quality Assessment of Mangrove Growing Environment in Pasuruan of East Java. *J. Degrad. Min. Lands Manag.* **2017**, *04*, 815–819, doi:10.15243/jdmlm. 2017.043.815.
32. Effendi, H. *Telaah Kualitas Air Bagi Pengelolaan Sumber Daya dan Lingkungan Perairan*; Kanisius: Yogyakarta, Indonesia, 2003.
33. Fitriyah, A.; Syafrudin, S.; Sudarno, S. Identifikasi Karakteristik Fisik Mikroplastik Di Sungai Kalimas, Surabaya, Jawa Timur. *J. Kesehat. Lingkung. Indones.* **2022**, *21*, 350–357, doi:10.14710/jkli.21.3.350-357.
34. Liu, H.; Cheng, W.; Xiong, P.; Li, H.; Liu, Z.; Ai, J.; Yuan, D.; Wan, F.; Wan, Y.; Zou, H.; et al. Temporal Variation of Plankton and Zoobenthos Communities in a Freshwater Reservoir: Structure Feature, Construction Mechanism, Associated Symbiosis and Environmental Response. *Ecol. Indic.* **2023**, *154*, 1–13, doi:10.1016/j.ecolind. 2023.110774.
35. Rahman, M.M.; Zimmer, M.; Ahmed, I.; Donato, D.; Kanzaki, M.; Xu, M. Co-Benefits of Protecting Mangroves for Biodiversity Conservation and Carbon Storage. *Nat. Commun.* **2021**, *12*, 1–9, doi:10.1038/s41467-021-24207-4.
36. Choosak, S.; Thongjoo, C.; Chaichana, R. Ecological Roles of Commercial Mangrove Plantation Forests for Benthic Macroinvertebrate Communities in Thailand. *Appl. Ecol. Environ. Res.* **2016**, *14*, 421–432, doi:10.15666/aeer/ 1402_421432.
37. Khatun, B.; Jewel, M.A.S.; Haque, M.A.; Akter, S.; Hossain, M.B.; Albeshr, M.F.; Arai, T. Seasonal Pattern of Taxonomic Diversity and Functional Groups of Macro-Benthos from a Sub-Tropical Mangrove Estuary. *J. Mar. Sci. Eng.* **2023**, *11*, 1–18, doi:10.3390/jmse11071453.
38. De Oliveira, A.B.; Rizzo, A.E.; Conceição, E. Da; Couto, G. Benthic Macrofauna Associated with Decomposition of Leaves in a Mangrove Forest in Ilhéus, State of Bahia, Brazil. *J. Mar. Biol. Assoc. United Kingdom* **2012**, *92*, 1479–1487, doi:10.1017/S0025315411001482.
39. De Souza Silva-Camacho, D.; Gomes, R.D.S.; Santos, J.N.S.; Araújo, F.G. Distribution of Benthic Fauna in Sediment Grains and Prop Roots of a Mangrove Channel in South-Eastern Brazil. *J. Mar. Biol. Assoc. United Kingdom* **2017**, *97*, 377–385, doi:10.1017/S0025315416000485.
40. Li, W.; Cui, L.; Zhang, M.; Wang, Y.; Zhang, Y.; Lei, Y.; Zhao, X. Effect of Mangrove Restoration on Crab Burrow Density in Luoyangjiang Estuary, China. *For. Ecosyst.* **2015**, *2*, 1–9, doi:10.1186/s40663-015-0046-3.
41. Romero-Mujalli, G.; Melendez, W. Nutrients and Trace Elements of Semi-Arid Dwarf and Fully Developed Mangrove Soils, Northwestern Venezuela. *Environ. Earth Sci.* **2023**, *82*, 1–14, doi:10.1007/s12665-022-10701-5.
42. Lewerissa, Y.A.; Sangaji, M.; Latumahina, M.B. Pengelolaan Mangrove Berdasarkan Tipe Substrat Di Perairan Negeri Ihamahu Pulau Saparua. *J. Trit.* **2018**, *14*, 1–9.
43. Royna, M.; Murdiyarso, D.; Sasmito, S.D.; Arriyadi, D.; Rahajoe, J.S.; Zahro, M.G.; Ardhani, T.S.P. Carbon Stocks and Effluxes in Mangroves Converted into Aquaculture: A Case Study from Banten Province, Indonesia. *Front. Ecol. Evol.* **2024**, *12*, 1–12, doi:10.3389/fevo.2024.1340531.
44. Haneda, N.F.; Kusmana, C.; Fitria, D.; Kusuma, D. Keanekaragaman Serangga Di Ekosistem Mangrove Diversity of Insects in Mangrove Ecosystem. *J. Silvikultur Trop.* **2013**, *4*, 42–47.
45. Syahrial, S.; Sastriawan, Y. Pola Sebaran, Indikator Kualitas Lingkungan dan Ekologi Komunitas Mangrove Pulau Tunda. *SAINTEK Perikan. Indones. J. Fish. Sci. Technol.* **2018**, *14*, 43–51, doi:10.14710/ijfst.14.1.43-51.

46. Azzahra, F. Estimasi Serapan Karbon Pada Hutan Mangrove Desa Bedono, Demak, Jawa Tengah. *JFMR-Journal Fish. Mar. Res.* **2020**, *4*, 308–315, doi:10.21776/ub.jfmr.2020.004.02.15.