Journal of Coastal and Ocean Sciences *e-issn: 2746-4512*
Volume 6 No. 2, May 2025: 94-101 *p-issn: 2745-4355*

Organic Carbon Stock in Sediment of the Rehabilitated Mangrove Ecosystem in Kedabu Rapat Village, Meranti Islands Regency

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Received: 4 April 2025; Accepted: 5 May 2025

ABSTRACT

Global climate change caused by increasing atmospheric CO_2 emissions threatens coastal ecosystems, including mangrove forests that function as carbon sinks. Kedabu Rapat Village in Meranti Islands Regency has implemented a mangrove rehabilitation program since 2017 to overcome coastal abrasion and restore the ecosystem. This study examines mangrove density, organic carbon stock in sediment, the relationship between density and carbon stock, and variations in carbon stock between sediment depths. The study was conducted at three stations according to the year of rehabilitation using a survey method with sediment sampling as deep as 30 cm, Organic carbon was analyzed using the LOI method. The study's results identified one mangrove species, *Avicennia alba*, from the Acanthaceae family, which dominated all observation stations. Vegetation density is classified as very dense, averaging 7,911 ind/ha, with the highest density at Station 1 (8,935 ind/ha). All stations' average sediment carbon stock reached 117.23 tons/ha, with the highest value at Station 3 (135.19 tons/ha) and the lowest at Station 1 (96.97 tons/ha). Statistical analysis revealed a weak correlation ($r = 0.218$; $p > 0.05$) between mangrove density and sediment carbon stock, indicating that other environmental factors, such as sedimentation and sediment input, play a more significant role. The distribution of carbon stock by depth was relatively uniform, ranging from 38.25 to 40.58 tons/ha. These results indicate that external factors are also determinants of carbon absorption rates.

Keywords: Organic Carbon, Rehabilitation, Sediment Depth, Mangrove Density, Meranti Islands

1. INTRODUCTION

Climate change is one of the significant environmental issues of concern to the world. The increase in the average temperature of the atmosphere, sea, and land is caused by the increasing concentration of greenhouse gases in the atmosphere, especially carbon dioxide (CO_2), which is primarily produced by human activities such as burning fossil fuels, deforestation, and industrial activities. The accumulation of this gas causes global warming with wide-ranging impacts, such as the melting of polar ice and rising sea levels. The rise in sea levels poses a real threat to coastal areas, such as abrasion, tidal flooding, and loss of land. Human activities such as land clearing for settlements and industry also accelerate the degradation of coastal ecosystems, including mangrove forests, which have an essential function as natural fortresses. Mangroves not only withstand abrasion but also serve as a habitat for marine biota, filter pollutants, and play a role in the carbon cycle.

Mangrove conservation efforts are carried out through various strategies, one of which is through a rehabilitation program in the form of replanting in damaged areas. This rehabilitation maintains the sustainability of the mangrove ecosystem and contributes to improving the quality of the coastal Environment. Mangrove rehabilitation activities can maintain the sustainability of the mangrove forest ecosystem based on ecological, economic, and social aspects. Mangrove forest rehabilitation is one of the conservation efforts to restore the mangrove ecosystem to its original condition (Fikriyan, 2013). One of the areas that has implemented a rehabilitation program is Kedabu Rapat Village, Meranti Islands Regency, Riau Province. This village has a semi-open coastline susceptible to abrasion due to currents, waves, and sea tides. Mangrove rehabilitation is also a conservative effort to restore the function of degraded mangrove forests (Farhana et al., 2016). Since 2017, the local community and government have rehabilitated mangroves and strengthened the coastline with gabion stones. The dominant type planted is *Avicennia alba*, which is known to resist dynamic environmental conditions.

Mangrove rehabilitation in Kedabu Rapat Village aims to protect the coast and opens up opportunities for developing ecosystem functions as carbon absorbers. Mangroves are included in the blue carbon category, namely coastal ecosystems that can store large amounts of carbon, especially in sediment layers. Murdiyarso et al. (2015) stated that most of the carbon stores in the mangrove ecosystem are in sediment, even higher than in mainland tropical forests (Kauffman et al., 2012). Mangrove sediments can store carbon for a very long time, even up to thousands of years. Although mangrove growth in Kedabu Rapat has been studied previously (Efriyeldi et al., 2021), no study has examined the potential for organic carbon stocks in rehabilitated sediments. This study aims to explore the organic carbon reserves of sediment in the mangrove area resulting from the rehabilitation of Kedabu Rapat Village and to provide scientific contributions to sustainable conservation and climate change mitigation efforts.

2. RESEARCH METHOD

Time and Place

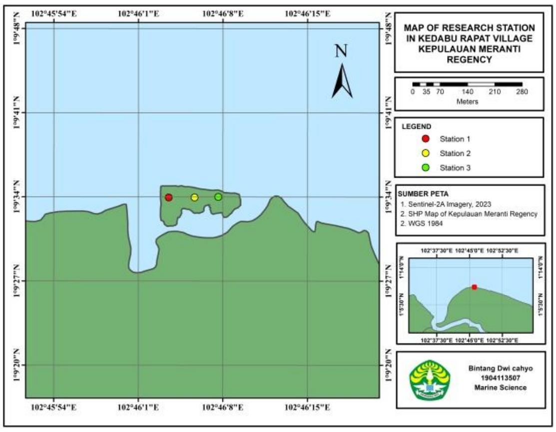

Figure 1. Map of research location

This research was conducted in January 2025 in the mangrove ecosystem rehabilitation area of Kedabu Rapat Village, Meranti Islands Regency (Figure 1). Data analysis was performed at the Marine Chemistry Laboratory, Department of Marine Sciences, Faculty of Fisheries and Marine Sciences, Universitas Riau.

Method

The method used in this study is the survey method, where the data collected is primary data, including mangrove density, carbon stock for each station, carbon stock data based on depth, and water quality parameters. All measurements were conducted on the same day at each station to minimize environmental variability and avoid data bias. The collected data were then presented descriptively in tables and figures.

Procedures

Determination of Research Locations

A purposeful sampling method was used to determine the research station, which represents the entire research area. The research location was divided into three stations based on the year of mangrove rehabilitation: station 1 in 2017, station 2 in 2018, and station 3 in 2019.

Transect Placement

The method used in making transects in this study is the line transect method. There is one transect line at each station. One transects consists of three plots measuring 10 m x 10 m. An illustration of the transect placement can be seen in Figure 2.

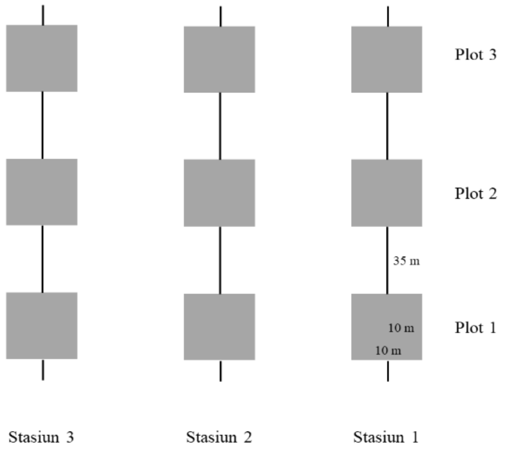

Figure 2. Illustration of a transect and plot position

The method used in making transects in this study is the line transect method. There is one transect line at each station. One transects consists of three plots measuring 10 m x 10 m (Figure 2).

Mangrove Density

Mangrove density data were obtained from three predetermined transects at the station, consisting of 3 transects; each transect has three plots measuring 10 m x 10 m for a total of 9 plots. Mangrove density data was obtained by calculating the total number of mangrove trees in each plot with the criteria of tree trunk diameter ≥ 4 cm. Furthermore, the density can be calculated using the following formula:

$$D = \frac{ni}{A} \times 10.000$$

Description:
D : Mangrove species density (ind/ha)
ni : Number of individuals
A : Total plot area

Mangrove vegetation density refers to the Decree of the Minister of Environment No. 201 of 2004 on Standard Criteria and Guidelines for Determination of Damage (Table 1).

Table 1. Criteria for vegetation density

Criteria		Coverage (%)	Density (Ind/ha)
Good	Tight	≥ 75	≥ 1.500
	Medium	≥ 50 – < 75	≥ 1.000 – < 1.500
Damaged	Rare	< 50	< 1.000

Sediment Sample Handling

Sediment sampling was carried out at the research location using a systematic method to obtain carbon stock data. Before sampling, the soil surface was cleaned of organic waste and living leaves that might still be attached to avoid contaminating the sediment sample. Sampling was carried out using a core sampler with a diameter of 3 cm, which was inserted vertically into the ground at a predetermined point until it reached a depth of 30 cm. The core tool was then rotated slowly to cut fine roots in the soil and keep the sediment structure intact when lifted. After the core was pulled, the sediment samples obtained were split horizontally and divided into three parts based on depth: layers 0–10 cm, 10–20 cm, and 20–30 cm. Each sample part was placed in a plastic bag labeled according to depth to facilitate the identification process and laboratory analysis. To maintain sample quality, all bags were stored in an ice box to keep them stable until analyzed in the laboratory.

Data Analysis

Carbon in Sediment Samples

Analysis of organic matter content in sediment was carried out using the Loss on Ignition (LOI) method, which refers to the procedure used by Mucha et al. (2003). This process begins by preparing an aluminum foil cup, which is then heated in an oven for 2 minutes to remove the initial moisture. The cup is then weighed for its empty weight. The sediment sample that has been naturally dried (aired) is then placed in the cup. Furthermore, the sample is heated in an oven at a temperature of 105°C for 12 to 24 hours to evaporate the water content. After heating, the sample is cooled in a desiccator and then reweighed to obtain its dry weight, and its volume is calculated.

After that, the sample is dried and ground using a mortar until homogeneous with a uniform particle size. The homogenized sample is put into a furnace and incinerated at a temperature of 550°C for approximately three hours to burn all the organic matter in the sediment. After the incandescence, the sample is cooled again in a desiccator and weighed. The difference between the weight before and after combustion is used to calculate the percentage of organic matter in the sediment. This method is a practical approach to estimating organic carbon content indirectly through mass loss due to combustion.

Data Processing

Before looking for the estimated value of carbon absorption, the percentage value of organic material is needed, which refers to the Loss on Ignition (LOI) method of Mucha et al. (2003). The formula used is as follows:

$$\%\ BO = \frac{w_0 - w_t}{w_0} \times 100\%$$

Description:
%BO : Percentage value of organic matter
w_0 : Initial weight of the sample before combustion
w_t : Weight of the sample after combustion
w_a : Initial weight of sediment

The percentage value of organic carbon in mangrove sediment was obtained using Loss on Ignition (LOI) method Mucha et al. (2003); the formula used is as follows:

$$\%\ C = 0.58 \times \%\ BO$$

Description:
% C : Percentage value of organic carbon
% BO : Percentage value of organic matter
0.58 : Conversion constant of organic carbon

The estimated carbon stock value in mangrove sediments was obtained using a formula referring to the SNI (2011). The formula used is as follows:

$$Ct = Kd \times p \times \% C$$

Description:

Ct	:	Soil organic carbon stock (sediment) expressed in g/cm^2.
Kd	:	Soil extraction depth expressed in cm.
P	:	Bulk density, which is the ratio of dry soil mass to its volume, is expressed in g/cm^3.
%C	:	Percentage value of organic carbon

Calculate carbon stock in sediment per hectare using a formula referring to the SNI (2011). The formula used is as follows:

$$Cth = Ct \times 100$$

Description:

Cth	:	Carbon stock per hectare in sediment is expressed in tons/ha.
Ct	:	Soil organic carbon stock (sediment) is expressed in g/cm^2.
100	:	Conversion factor g/cm^2 to tons/ha.

Data Analysis

The data obtained from the field measurements and laboratory analysis results were then processed using Microsoft Excel to get the results of carbon stock estimates in sediments between stations. A simple linear regression test was carried out to determine the relationship between mangrove density and carbon stock estimates, and an ANOVA test was carried out to determine the difference in carbon stock (C) between stations and the difference in carbon stock (C) between depths.

3. RESULT AND DISCUSSION

General Conditions of Research Locations

Kedabu Rapat Village, located in Rangsang Pesisir District, Meranti Islands Regency, Riau Province, is a coastal area directly adjacent to the Malacca Strait. This geographical location causes the area to experience strong water dynamics, such as high tides and large waves, resulting in high abrasion along the coastline. To overcome this problem, from 2017 to 2019, efforts have been made to gradually rehabilitate the mangrove ecosystem by replanting mangrove trees and installing gabion stones along the coastline. Gabion stones function to reduce wave energy while accelerating the formation of sediment deposits needed as a medium for growing mangroves.

This study was conducted at three stations representing the rehabilitation zone based on the year of planting, namely Station 1 (planting in 2017), Station 2 (2018), and Station 3 (2019). Differences in position and rehabilitation time between stations affect the characteristics of each land. Station 3, which is in a lower position and closer to the sea, is more susceptible to tidal influences and shows the presence of faults in the surface layer of the soil. Similar conditions were also observed at Station 2, but with lower intensity. In contrast, Station 1, which had been planted earlier, showed more stable conditions and had experienced the formation of new sediment layers faster than the other two stations.

The substrate throughout the rehabilitation area was sandy mud suitable for the growth of *A. alba*, a dominant mangrove species at the research site. *A. alba* has a high tolerance to salinity, tides, and coastal water dynamics. It can grow and develop well even in challenging environmental conditions like Kedabu Rapat Village.

Water quality is a factor that significantly affects the condition of the mangrove ecosystem. The results of water quality measurements show the condition of the waters around the mangrove rehabilitation area of Kedabu Rapat. The parameters measured in this study include salinity, pH, and temperature. The results of water quality parameters measurements can be seen in Table 2

Table 2. Water quality parameters

No.	Parameters	Unit	Station (year of rehabilitation)		
			1 (2017)	2 (2018)	3 (2019)
1.	Salinity	‰	25	27	28
2.	pH	-	7.5	7.6	7.9
3.	Temperature	°C	28	29	30

The average value of the water quality parameter measurements in the mangrove rehabilitation of Kedabu Rapat Village is salinity 26.7‰, pH 7.7, and temperature 29°C. The highest salinity was recorded at station 3 with a value of 28 ‰, while the lowest salinity was recorded at station 1 with 25 ‰. The highest acidity (pH) value was at station 3, with a value of 7.9, while the lowest was at station 1, with a value of 7.5. The highest temperature was recorded at station 3, with a temperature of 30°C, while the lowest was at station 1, with a temperature of 28°C.

Mangrove Density

Mangrove vegetation density is one of the crucial parameters in assessing the success of a rehabilitation program and the ecological conditions of a coastal area. In this study, mangrove density was measured at three stations representing different planting years, namely 2017 (Station 1), 2018 (Station 2), and 2019 (Station 3). The measurement results showed that mangrove density at all stations was very high, with the average value of each station as follows: Station 1 at 8,033 ind/ha, Station 2 at 7,900 ind/ha, and Station 3 at 7,800 ind/ha. The overall average value was 7,911 ind/ha. The measurement results can be seen in Table 3.

Table 3. Mangrove density at each station

Station	Plot	Mangrove density (ind/ha)	Average (ind/ha)
1	1	7,100	8,033 ±1,209.68
	2	9,400	
	3	7,600	
2	1	8,400	7,900 ±624.5
	2	8,100	
	3	7,200	
3	1	7,400	7,800 ± 360.56
	2	7,900	
	3	8,100	
Average (ind/ha)			7,911

Referring to the Decree of the Minister of State for the Environment Number 201 of 2004 concerning Criteria and Guidelines for Determining Mangrove Damage, mangrove areas with a density of more than 1.500 individuals per hectare are categorized as very dense and undamaged. Thus, the rehabilitation mangrove area in Kedabu Rapat Village can be classified as an ecologically healthy and productive ecosystem. The high density of vegetation reflects the success of the rehabilitation program implemented in 2017. This success cannot be separated from several supporting factors. First, the selection of the *A. alba* mangrove species, which has a high tolerance to salinity, tides, and coastal environmental dynamics. Second, gabion stones should be installed along the coastline, which dampens wave energy and prevents abrasion while also helping maintain the substrate's stability where the mangroves grow. This physical protection provides a relatively stable environment for root development and vegetation growth.

Spatially, the highest density was recorded at Station 1, the oldest rehabilitation location and most protected from the direct influence of ocean waves. In contrast, Station 3, the youngest rehabilitation location and more open to ocean dynamics, showed a slightly lower density value. This difference indicates that the age of rehabilitation and geographical position influence the density level, where areas that have been planted longer and have better physical protection tend to have denser vegetation. This finding is consistent with the research of Isnaini et al. (2020), which states that the success of mangrove rehabilitation is influenced by factors such as planting age, location, and protection from physical disturbances such as waves. Interestingly, the density value in Kedabu Rapat Village is much higher than in other areas, such as Pangkalan Jambi Village, which only has a density of 3,086 ind/ha, indicating the effectiveness of the implemented rehabilitation program. According to Wantasen (2013), the existence of mangroves is greatly influenced by environmental quality, especially pH and salinity. Mangroves grow optimally at salinity between 10–30‰ and water pH between 6.0–9.0. The results of water quality measurements in Kedabu Rapat Village show salinity and pH values within the optimal range, supporting the success of mangrove growth.

Mangrove rehabilitation strategies cannot be generalized, but local environmental conditions such as topography, sedimentation, currents, and tidal dynamics must be considered. Considering these factors, rehabilitation interventions can be tailored to produce optimal results. Overall, it can be concluded that the mangrove rehabilitation program in Kedabu Rapat Village has positively impacted the increase in vegetation density. This success has significant implications for restoring the ecological function of coastal areas, including the ability to store carbon, protect the coast from abrasion, and increase local biodiversity.

Carbon Stock Based on Station

Based on the results of the analysis, it is known that the average sediment carbon stock at station 1 has a lower value than that of other stations, with an average value of 96.97 tons/ha. The station with the highest average sediment carbon stock value is station 3, with an average value of 135.19 Tons/Ha. The results of the calculation of the average value of sediment carbon stock at each station in the mangrove rehabilitation of Kedabu Rapat Village can be seen in Table 4.

Table 4. Carbon stock value at each station.

Station	Plot	Carbon stock (Ton/ha)	Average (Ton/ha)
1	1	99.27	96.97 ±3.026
	2	98.09	
	3	93.54	
2	1	110.76	119.53 ±7.841
	2	121.97	
	3	125.86	
3	1	135.07	135.19 ±2.448
	2	137.68	
	3	132.79	
Average (Ton/ha)			117.23

The total average of the three stations was 117.23 tons/ha. The results of the ANOVA test showed that the difference in carbon stocks between these stations was significant ($p < 0.05$), indicating that specific factors at each location influenced the value of carbon stored. The difference in carbon stock values between rehabilitation stations did not fully reflect the order of planting years. Locations with younger rehabilitation ages had higher carbon content, indicating that environmental factors significantly influenced them. One of the main factors is the topographic position and openness of the location to sea dynamics. Lower and more open stations tend to receive more organic material from outside the area, such as wood chips or "session," which are carried by the tides and accumulate around mangrove roots and gabion stones. This trapped organic material then undergoes a decomposition process and contributes to increasing carbon content in the sediment.

This process is reinforced by the physical structure of gabion stones, which help retain and trap organic material and encourage faster sedimentation processes around the mangrove roots. This condition proves that the carbon stock value in mangrove sediments is influenced by vegetation density and other ecological processes such as sedimentation, tidal currents, and micro-geographical positions. The results in Kedabu Rapat Village even showed higher values than several previous studies, as reported by Hickmah et al. (2021). Thus, mangrove rehabilitation planning and evaluation should consider local hydrodynamic aspects and physical structure placement strategies rather than relying solely on vegetative parameters such as plant age or density.

Relationship between Mangrove Density and Carbon Stock

Analysis of the relationship between mangrove density and sediment carbon stock showed a weak correlation, with a correlation coefficient (r) of 0.218 and a determination coefficient (R^2) of only 0.0476. This means vegetation density only explains about 4.76% of the variation in sediment carbon stock, while other factors influence the rest. This result is not statistically significant ($p>0.05$), indicating that an increase does not always follow increasing density in sediment carbon content. The results of the linear regression analysis are presented in Figure 3.

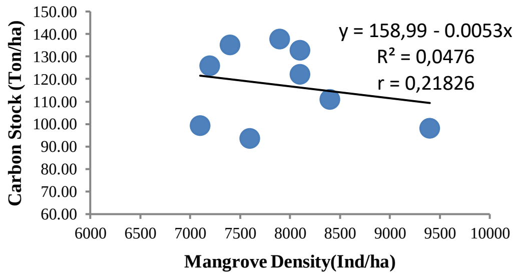

Figure 3. Linear regression analysis

This finding aligns with the study of Hendrayana et al. (2023), which states that although vegetation density is essential, carbon stock is more determined by ecological processes such as decomposition, organic matter transport, and sedimentation. This condition is also supported by the opinion of Murdiyarso et al. (2015), who explain that most of the mangrove ecosystem's carbon is stored in the sediment layer, not only in the upper biomass. So, even though mangrove vegetation is dense, the carbon stock value is not automatically high if there is no organic matter accumulation in the substrate. In this context, external factors such as tidal dynamics and the role of physical structures such as mangrove roots and gabion stones can trap external organic matter such as litter or session. Heriyanto & Subiandono (2016) also added that the type of substrate and sedimentation rate significantly affect the amount of carbon accumulated in mangrove soil.

In addition, Hickman et al. (2021) stated that the organic carbon content of sediment is also influenced by particle size, soil texture, and sediment pH. Locations that often experience seawater intrusion will bring more fine particles and organics that are easily accumulating. This process has a greater effect on carbon stocks than density factors alone. Therefore, although mangrove density remains an indicator of the success of structural rehabilitation, assessing the potential for sediment carbon storage must consider abiotic factors comprehensively, including water hydrodynamics and soil-vegetation interactions.

Comparison of Carbon Stock Values Based on Sediment Depth

The results of the analysis using the ANOVA test on three layers of depth, namely 0–10 cm, 10–20 cm, and 20–30 cm, showed that the average carbon stock at the three depths was 38.25 tons/ha, 40.58 tons/ha, and 38.40 tons/ha, respectively. The p-value from the ANOVA test results of 0.0002, which is less than 0.05, indicates that the difference in carbon stock between depths is statistically significantly different. The results of the Average Carbon Stock between Depths

However, the ecological value difference between depths does not look too striking. Similar average values indicate that organic carbon distribution in the upper sediment layer tends to be homogeneous. This condition is most likely caused by the influence of tides and the activity of benthic organisms (bioturbation), which continuously stir the sediment so that the composition of organic matter between layers is almost the same (Donato et al., 2011).

This phenomenon is also in line with the research results of Sakmiana et al. (2023); Pratiwi et al. (2023), which found that at a depth of 0–30 cm in the mangrove ecosystem, organic carbon stocks did not show significant variations between layers. The sampling interval of only 10 cm is thought to be another factor that causes the variation in carbon stocks between layers to be less visible (Murdiyarso et al., 2015).

Thus, although statistical tests show significant ecological differences, the distribution of carbon stocks between depths in the 0–30 cm range can still be categorized as even. Sampling up to a depth of 1 meter with a wider interval is highly recommended to describe carbon accumulation patterns more comprehensively, especially in long-term climate change mitigation

Table 5. Average carbon stock between depths

Station	Stock Carbon (Ton/ha)		
	1-10 cm	10-20 cm	20-30 cm
1	32.33	33.56	31.07
2	36.86	40.96	41.71
3	45.54	47.22	42.41
Average	38.25	40.58	38.4

4. CONCLUSION

This study shows that the mangrove rehabilitation program in Kedabu Rapat Village has been ecologically effective, as indicated by the achievement of a very dense vegetation structure with an average of 7,911 individuals/ha. The relatively high sediment organic carbon stock, which is an average of 117.23 tons/ha, especially at Station 3 (135.19 tons/ha), reflects the ability of the rehabilitated mangroves to function as carbon sinks. The high carbon content at this station is likely supported by the accumulation of organic matter, such as sesame, and the physical protection provided by the gabion structure, which increases root stability and organic matter retention.

Despite the high mangrove density, the weak correlation (r = 0.218) between vegetation density and sediment carbon stock indicates that carbon storage does not depend only on tree abundance. Instead, abiotic factors such as sedimentation rate, soil structure, tidal dynamics, and organic inputs play a more substantial role in determining carbon accumulation. This highlights the importance of integrating hydrodynamic and soil assessments in future rehabilitation strategies.

The results of this study indicate the need for a site-specific mangrove rehabilitation approach that not only focuses on planting density but also considers substrate conditions and shoreline stabilization efforts. Ensuring long-term carbon sequestration requires attention to biological recovery and the environmental context that supports below-ground carbon storage. Therefore, ongoing monitoring and adaptive management are recommended to optimize rehabilitated mangrove ecosystems' ecological functions and climate mitigation benefits.

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