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ESTIMATION OF CARBON STORAGE AND ECONOMIC VALUE OF CARBON IN THE MANGROVE FOREST ECOSYSTEM OF BENGKALIS DISTRICT, BENGKALIS REGENCY, INDONESIA

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ABSTRACT

Mangrove ecosystems play a crucial role in climate change mitigation by absorbing and storing carbon in biomass and sediments. This study aimed to estimate biomass carbon stocks, sediment carbon, CO_2 sequestration, and the economic value of mangrove carbon. The research was conducted in May 2025 in Bengkalis District, Bengkalis Regency. A survey method was employed, utilizing data on mangrove species composition, tree density, and diameter at breast height (DBH). The results identified six mangrove species: *Rhizophora apiculata*, *R. mucronata*, *Avicennia alba*, *Sonneratia alba*, *Xylocarpus granatum*, and *Excoecaria agallocha*. The mangrove ecosystem in Bengkalis District exhibited an average aboveground tree carbon stock of 87.75 t ha^{-1}, root carbon stock of 36.77 t ha^{-1}, sediment carbon stock of 54.03 t ha^{-1}, and CO_2 sequestration of 456.97 t ha^{-1}. The estimated economic value of carbon was IDR 388,342,353 ha^{-1}. These findings indicate that the mangrove ecosystem in Bengkalis District has substantial potential as a carbon sink and storage system, highlighting the importance of sustainable management strategies to support climate change mitigation efforts.

Keywords: Mangrove Ecosystem, Carbon Storage, Economic Value, Bengkalis Regency

1. INTRODUCTION

Mangrove ecosystems are among the most important coastal ecosystems, playing a crucial role in maintaining environmental balance and supporting marine biodiversity. In addition to functioning as natural barriers against coastal erosion, mangroves contribute significantly to climate regulation by absorbing carbon dioxide (CO_2) from the atmosphere and storing it in biomass and sediments. Mangroves have a greater capacity to store carbon than most terrestrial ecosystems, making them vital components in global efforts to mitigate climate change. Indonesia, with the world's largest mangrove extent, has substantial potential for carbon storage.

Bengkalis Regency is one of the regions with relatively extensive mangrove ecosystems. However, land-use changes and increasing anthropogenic activities have led to a decline in mangrove coverage, thereby reducing the ecosystem's capacity to sequester carbon. Carbon stocks in mangrove ecosystems are primarily stored in three main components: aboveground biomass, belowground biomass, and sediments. Therefore, estimating carbon stocks in the mangrove ecosystems of Bengkalis District is essential to assess their carbon storage potential and to support sustainable mangrove management strategies in the region.

2. RESEARCH METHOD

Time and Place

This study was conducted in May 2025. Sampling was carried out in the mangrove forest ecosystem of Bengkalis District, Bengkalis Regency. Sediment

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analysis was performed at the Marine Chemistry Laboratory, Department of Marine Science, Faculty of Fisheries and Marine Science, Universitas Riau.

Method

This study employed a survey method. Mangrove biomass was estimated using allometric equations, while sediment carbon was determined using the loss on ignition (LOI) method.

Procedures

Determination of the Research Station

The research stations were selected using a purposive sampling method, in which locations were deliberately selected to reflect site-specific conditions and ensure representativeness based on mangrove density, species composition, and average stem diameter at each station. A total of five sampling stations were established within Bengkalis District, Bengkalis Regency.

Station I was located in Meskom Village, situated near a river estuary. Station II was established in Sebauk Village, a community-managed mangrove ecotourism area. Station III was located in Penampi Village and featured a homogeneous mangrove stand resulting from reforestation activities with regular planting spacing. Station IV was situated in Kelemantan Village, adjacent to the Sungai Dua crossing toward Pedang Island. Station V was located on the northern coast of Sekodi Village, directly facing the open sea.

Placement of Transect and Plots

Transects and plots were established following the method developed by Bengen[1]. Transect lines were laid perpendicular to the shoreline, extending from the seaward edge toward the landward area. Each transect consisted of three 10 × 10 m (100 m²) square plots, with a 20 m spacing between adjacent plots. Three transects were established at each station as replicates.

Mangrove Species Identification

Mangrove species were identified by matching morphological characteristics, including leaves, stems, flowers, fruits, and root structures. To ensure accurate identification, the observed morphological features were cross-referenced with the mangrove identification guide developed by Noor et al.[2]. In accordance with the criteria established by Komiyama et al.[3], all mangrove individuals within the plots with a stem diameter ≥ 5 cm were identified and recorded by species.

Sediment Sampling

Sediment sampling in this study followed the method developed by English et al.[4]. Samples were collected at a depth of 10 cm in mangrove areas characterized by clay, sandy, and silty substrates. Sediment sampling was conducted in flat areas that were not inundated at the time of collection using a PVC corer with a diameter of 5 cm. The PVC pipe was inserted vertically into the soil to a depth of 10 cm. The collected sediment samples were placed into plastic containers, properly labelled, and transported to the laboratory for further analysis.

Sediment Carbon Analysis

The calculation of mangrove sediment carbon followed the standard method issued by the SNI[5]. Initially, sediment samples were homogenized using a mortar to obtain a uniform particle size. The homogenized samples were weighed at 30 g and placed into aluminium foil containers. Subsequently, the samples were oven-dried at 105°C for 48 hours to obtain a constant dry weight. After drying, the samples were combusted in a furnace at 550°C for 4 hours. After combustion, the samples were reweighed to determine the final weight.

Data Analysis

Mangrove Stand Density Analysis

The density of mangrove stands was calculated using the formula proposed by Cahyani & Hardjana[6], as follows:

$$K = \frac{I}{L\ Plot}$$

Descriptions:

K	=	Density of a species (individuals m^{-2})
I	=	Number of individuals (trees)
L_{plot}	=	Total plot area (ha)

Mangrove Biomass Analysis

Mangrove biomass was measured using allometric equations. Data collection in this study was conducted using a non-destructive method to prevent damage to the vegetation. The estimation of mangrove biomass was calculated using the formula proposed by Komiyama et al.[3], as follows:

$$AGB = 0{,}251 \times \rho \times (DBH)^{2{,}46}$$

$$BGB = 0{,}199 \times \rho^{0{,}90} \times (DBH)^{2{,}22}$$

Descriptions:

AGB	=	Aboveground biomass (kg/m^2)
BGB	=	Below ground biomassa (kg/m^2)
ρ	=	Wood density (g/cm^3)
DBH	=	Diameter at breast height (cm)

Biomass Carbon Stock Analysis

The calculation of carbon storage from mangrove biomass was carried out using the formula established by the SNI[5], as follows:

$$Cb = B \times \%C\ Organic$$

Descriptions:

Cb	=	Carbon content (kg/m^2)
B	=	Biomass (kg/m^2)
%C Organik	=	Organic carbon fraction 0,47

Sediment Carbon Stock Analysis

Mangrove sediment carbon stock was estimated based on several parameters, including sediment sampling depth, bulk density, and the percentage of organic carbon. The calculation followed the formula proposed by Howard et al.[7], with the detailed computation as follows:

The bulk density of the soil for each sample was calculated using the following formula:

$$Bulk\ Density = \frac{Dry\ Weight\ of\ Sample}{Sample\ Volume}$$

Subsequently, the percentage of organic matter lost during the dry combustion process (Loss on Ignition, LOI) was calculated using the following formula:

$$\%BO = \left(\frac{wo - wt}{wo} \times 100\right)$$

Descriptions:

%BO	=	Percentage of organic matter lost during combustion (%)
Wo	=	Dry weight of the sample (g)
Wt	=	Final weight of the sample (g)

Subsequently, the percentage of organic matter was converted into the percentage of sediment organic carbon using the following formula:

$$\%C = \frac{1}{1{,}724} \times \%BO$$

Descriptions:

%C	=	Percentage of organic carbon in sediment (%)
1,174	=	The constant used to convert the percentage of organic matter into the percentage of organic carbon

Subsequently, carbon density in mangrove sediments was calculated using the following formula:

$$Carbon\ density = \%C \times BD$$

Subsequently, the mangrove sediment carbon stock was estimated using the following formula:

$$Carbon\ Stock = BD \times \%C \times D$$

BD	=	Bulk density of the sediment (g cm^{-3} or kg m^{-3})
%C	=	Percentage of organic carbon
D	=	Sediment depth interval (cm)

CO_2 Sequestration Capacity Analysis

The calculation of CO_2 sequestration was performed using the formula proposed by Bismark et al.[8], as follows:

$$S\ CO_2 = \frac{Mr.CO_2}{Ar\ C} \times Kc$$

descriptions:

S CO_2	=	CO_2 sequestration (kg/m^2)
Mr. CO_2	=	44
Ar C	=	12
Kc	=	Carbon content (kg/m^2)

Economic Valuation of Carbon

Carbon economic valuation was conducted to estimate the monetary value of carbon using the Social Cost of Carbon

(SCC), set at USD 51 per ton of carbon. The estimated value was subsequently converted to Indonesian Rupiah (IDR) using the Bank Indonesia mid-rate of 1 USD = IDR 16,670.

Based on environmental economics principles, carbon economic valuation can be formulated as follows:

Carbon Economic Value = (SCC×TCS)×ER

Descriptions:

SCC = 51 USD/ton

TCS = Total carbon stock (tons)

ER = Exchange rate (IDR per USD)

3. RESULT AND DISCUSSION

Vegetation Composition and Mangrove Stand Density

The mangrove species identified at the research stations included *Rhizophora apiculata*, *R. mucronata*, *Avicennia alba*, *Sonneratia alba*, *Xylocarpus granatum*, and *Excoecaria agallocha*. The species composition, number of individuals recorded, and mangrove stand density at each station are presented in Table 1.

Table 1. Vegetation composition and mangrove stand density

Station	Number of mangroves stands (individuals)						Total	Density
	R.apiculata	*R.mucronata*	*A.alba*	*S.alba*	*X.granatum*	*E.agalloca*		(ind/ha)
I	79	-	-	-	-	47	126	1400
II	284	-	-	16	-	-	300	3.333,33
III	249	-	2	-	-	-	251	2.788,89
IV	69	13	32	13	20	-	147	1.633,33
V	14	-	9	14	-	-	37	411,11

Rhizophora apiculata was the most frequently encountered species and was present at all sampling stations. This dominance is likely associated with *R. apiculata's* strong adaptive capacity. The species is known for its tolerance to environmental variations, including fluctuations in temperature, salinity, and pH, which contributes to its higher adaptability compared to other mangrove species.

The highest mangrove stand density was recorded at Station II, reaching 3,333.33 ind ha^{-1}, whereas the lowest density was observed at Station V, with 411.11 ind.ha^{-1}. The mangrove stands densities at Stations I, III, and IV were 1,400, 2,788.89, and 1,633.33 ind.ha^{-1}, respectively. The analysis of mangrove stand density revealed considerable variation among the sampling stations.

Aboveground Carbon (Stem Biomass)

Based on the research conducted in Bengkalis District, the average carbon stock of mangrove stands at each station is presented in Figure 1.

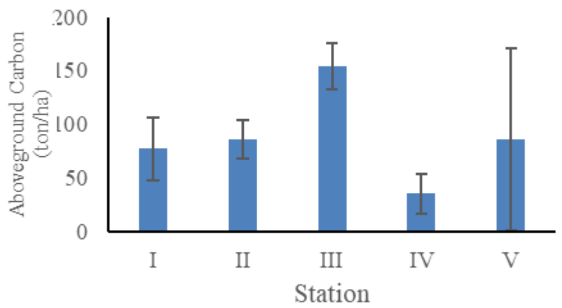

Figure 1. Aboveground carbon stock at each sampling station

Based on Figure 1, the comparison of aboveground carbon across the five sampling stations in Bengkalis District shows that the highest average carbon stock was recorded at Station III, with 153.86 t.ha^{-1}. In contrast, the lowest average aboveground carbon was observed at Station IV, with 35.31 t.ha^{-1}. The average aboveground carbon stocks at Stations I, II, and V were also relatively high, measuring 77.17, 86.42, and 85.97 t ha^{-1}, respectively.

The analysis of aboveground carbon storage showed the highest values at Station III, where aboveground biomass (AGB) reached 327.35 tons/ha. The large average tree diameter and the high stand density influence this. Station III is dominated by the species *R.apiculata*, accounting for 99.2% of the trees, with an average tree diameter of 12.36 cm, resulting in high average biomass and carbon storage. This species has the capacity to accumulate substantial biomass due to its classification as a hardwood species. This finding aligns with Howard et al.[7], who reported that mangrove species with hardwood can store more carbon than those with softwood.

Belowground Carbon (Roots)

The results of the belowground carbon storage analysis for each station are presented in Figure 2.

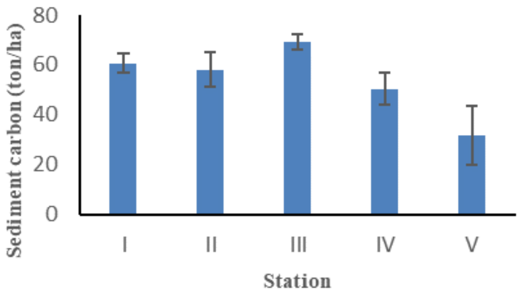

Figure 2. Belowground carbon storage at each observation station

Based on Figure 2, the comparison of belowground carbon across the five research stations in the Bengkalis District shows that the highest mean belowground carbon storage was at Station III, at 65.85 tons/ha. In contrast, the lowest mean belowground carbon storage was observed at Station IV, at 16.06 tons/ha. The mean belowground carbon storage at Stations I, II, and V also showed relatively similar values of 32.27, 38.86, and 30.83 tons/ha, respectively.

The highest belowground carbon storage at Station III is attributed to its highest belowground biomass (BGB), reaching 140.1 tons/ha. Station III exhibits a high capacity for carbon accumulation in both above- and belowground components. This occurs because aboveground and belowground carbon accumulation are positively correlated. This finding aligns with Meng et al.[9], who reported that AGB and BGB exhibit a significant linear correlation, enabling BGB to be estimated from AGB. This condition is also associated with the maturity of the mangrove stand, characterized by a relatively large average tree diameter of 12.4 cm and a complex, deep root structure, which plays an important role in carbon absorption and storage within the mangrove ecosystem.

Mangrove Sediment Carbon

The average mangrove sediment carbon storage at each station is shown in Figure 3.

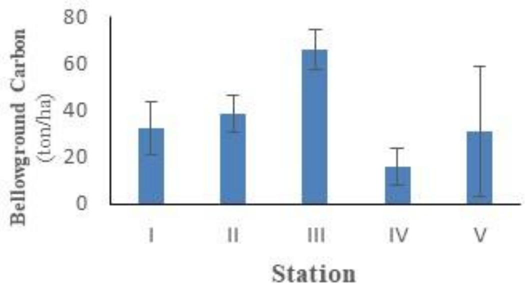

Figure 3. Mean sediment carbon (tons/ha) at each observation station

Based on Figure 3, the comparison of mangrove sediment carbon across the five research stations in the Bengkalis District shows that the highest average sediment carbon storage was at Station III (69.35 tons/ha), while the lowest was at Station V (31.58 tons/ha). The average sediment carbon storage at Stations I, II, and IV was 60.71, 58.13, and 50.4 tons/ha, respectively.

Station III, which had the highest soil organic carbon content, also exhibited the highest aboveground carbon, at 153.86 tons/ha. This indicates that denser and healthier mangrove ecosystems tend to contribute more organic material to the soil through leaf litter, dead roots, and other decomposition processes. Station III has a high stand density, so litter falling in this station is more likely to settle and accumulate, becoming a source of sediment organic matter. This observation aligns with Alongi[10], who reported that soil organic carbon content in mangrove ecosystems is strongly influenced by primary productivity, litter accumulation, and slow decomposition rates under anaerobic conditions in the mangrove substrate. The substrate at Station

III is dominated by black mud rich in organic matter, resulting in higher sediment carbon storage at this station compared to the others.

Estimated CO_2 Sequestration Potential

The results of CO_2 gas sequestration at each station are presented in Figure 4.

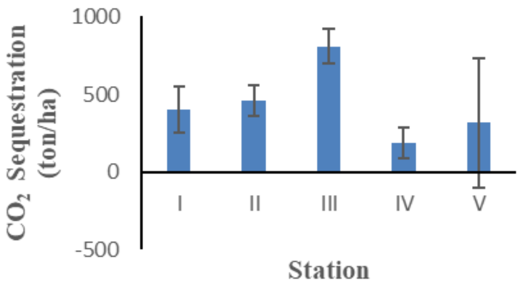

Figure 4. CO_2 sequestration at each observation station.

The highest CO_2 sequestration was observed at Station III, as the mangrove stand at this location has a high total stem carbon storage of 153.86 tons/ha and substantial root carbon of 65.85 tons/ha. This occurs because the mangrove ecosystem at Station III has a good stand density of 2,788.89 individuals/ha and relatively large tree diameters averaging 12.4 cm. This is supported by Ibrahim & Muhsoni[11], who stated that higher carbon content is directly correlated with the ability to sequester CO_2 from the atmosphere, up to 3.67 times the total carbon.

Economic Value Estimation of Carbon Sequestration

The economic value of mangrove carbon in this study was estimated using the social cost of carbon (SCC). The estimated economic value of CO_2 sequestration in the mangrove forests of Bengkalis District is presented in Table 2.

Based on Table 2, the estimated economic value of mangrove stem carbon is 273,606,810 IDR/ha, while the economic value of mangrove root carbon is 114,735,543 IDR/ha. The total economic value of carbon storage in the mangrove forests of Bengkalis District is 388,342,353 IDR/ha. The economic value of carbon storage was calculated by multiplying the CO_2 sequestration by the Social Cost of Carbon (SCC). The SCC value is 51 USD. The USD value was then converted to Indonesian Rupiah at a rate of 16,670 IDR/USD (as of November 2025).

Table 2. Estimated value of carbon sequestration

Carbon pool	CO_2 Sequestration (ton/ha)	USD	Rupiah (IDR)
Aboveground biomass	321,83	16.413,13	273.606.810
Bellowground biomass	134,96	6.882,76	114.735.543
Total	456,79	23.295,88	388.342.353

The United States established the SCC value during President Biden's administration at 51 USD/ton of carbon. Developed countries are required to reduce emissions to at least 5% below 1990 levels. Indonesia, which has extensive forests, can help reduce atmospheric emissions by protecting and conserving its forests, thereby limiting the amount of carbon released into the atmosphere. As a benefit, Indonesia receives financial compensation for preserving its forests, which helps mitigate global carbon emissions.

4. CONCLUSION

The mangrove ecosystem in Bengkalis District shows considerable potential for carbon storage and CO_2 sequestration. Six mangrove species were identified, with *R. apiculata* dominating across all sampling stations. The mangrove ecosystem stored an average of 87.75 $ton.ha^{-1}$ of aboveground carbon, 36.77 $ton.ha^{-1}$ of belowground carbon, and 54.03 $ton.ha^{-1}$ of sediment carbon. Station III, located in Penampi Village, exhibited the highest carbon stock and CO_2 sequestration capacity, driven by higher stand density, larger tree diameters, and organic-rich substrates. The total CO_2

sequestration reached 456.97 ton.ha^{-1} with an estimated economic value of IDR 388,342,353 ha^{-1}. These findings highlight the important role of mangrove ecosystems in Bengkalis District as significant carbon sinks and support the need for sustainable mangrove management to enhance climate change mitigation efforts.

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