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Blue Carbon Potential of Mangrove Ecosystems in Jakarta Bay for Climate Change Mitigation

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Abstract

Mangrove ecosystems are crucial for sustaining tropical coastal environments and play a vital role in climate change mitigation through their capacity to sequester and store blue carbon in both vegetation and sediment. Despite their ecological value, mangroves in Jakarta Bay are under increasing pressure from coastal development, land conversion, pollution, and unsustainable exploitation. These anthropogenic threats reduce mangrove cover and diminish their ability to function as carbon sinks. This study examined mangrove carbon stocks at four locations Muara Village, Kapuk Muara, Marunda, and Muara Jaya Village through vegetation surveys, biomass measurement, and the calculation of the Important Value Index (IVI) to analyze species composition and dominance. The results demonstrated considerable variation in biomass and carbon reserves across sites. Muara Village recorded the highest biomass (558.72 tons ha $^{-1}$) and carbon stock (262.59 tons ha $^{-1}$), followed by Kapuk Muara (411.18 tons ha $^{-1}$), Muara Jaya (365.39 tons ha $^{-1}$), and Marunda, which had the lowest values (208.9 tons ha $^{-1}$). Dominant species included Rhizophora mucronata and Avicennia marina, reflecting their ecological adaptability and contribution to blue carbon storage. The findings emphasize that mangrove areas with higher biomass and carbon reserves are critical for maintaining ecosystem resilience in Jakarta Bay. Conservation and restoration should therefore prioritize sites with strong carbon storage potential, while degraded areas require rehabilitation to enhance ecological services. Strengthening mangrove management will not only support biodiversity and coastal protection but also contribute significantly to regional climate change mitigation strategies through the preservation of blue carbon.

Keywords: *Mangrove, blue carbon, biomass, carbon storage, coastal ecosystem*

Introduction

Mangrove forests play a crucial role in mitigating global climate change by absorbing and storing significant amounts of carbon dioxide (CO_2) (Melaku Canu *et al.*, 2015). With an average absorption rate of 8 tons CO_2e.ha^{-1}.y^{-1}, mangroves outperform tropical forests in carbon sequestration (Murray *et al.*, 2011). Indonesia, home to approximately 3.7 million hectares of mangroves (Sirait *et al.,* 2021), faces significant degradation due to population growth, land conversion, and industrial activities, particularly in Jakarta Bay (BAKOSURTANAL, 2009).

The mangrove area in Muara Angke, Jakarta Bay, has decreased from 1,154 ha in 1970 to 327.7 ha in 2014 (DLHK DKI Jakarta, 2018), while Muara Gembong now retains only 9.81% of its original coverage (Hanan *et al.,* 2020). Despite these challenges, mangrove ecosystems in the area still hold significant potential for climate change mitigation and community-based ecotourism (Bouillon *et al.*, 2008; Alongi, 2012).

Efforts to conserve mangroves through rehabilitation and the establishment of protected areas have been undertaken (Purnobasuki, 2005). However, sustainability studies on Jakarta Bay's mangrove ecosystems remain limited, highlighting the need for collaborative research involving the government, communities, and scientists to ensure long-term conservation. Studies from other regions demonstrate that mangroves have high carbon sequestration potential, such as 5.4 tons CO_2 ha^{-1} y^{-1} in Central Kalimantan (Kauffman *et al.*, 2011) and 10 tons CO_2 ha^{-1} y^{-1} in Sumatra (Murdiyarso *et al.*, 2015).

Mangrove species like *Rhizophora apiculata* and *Avicennia marina* are essential for carbon absorption and storage, making them vital components of blue carbon ecosystems (Marzuki, Nurdin *et al.*, 2023). Despite prior studies, the blue carbon potential of Jakarta Bay remains underexplored. This study aims to assess the role of mangroves in climate change mitigation, examine sustainable conservation practices, and promote ecotourism. Expected results include carbon storage

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quantification, conservation recommendations, and support for mangrove-based ecotourism.

Materials and Methods

The study was conducted in the mangrove ecosystem of Jakarta Bay's coastal area from December 2024 to January 2025. Four observation stations were selected (Figure 1) using purposive sampling, a method that strategically chooses study sites based on specific environmental conditions (Fachrul, 2007).

Data collection techniques

Data collection was conducted using observation and survey methods (direct measurements in the field) following SNI 7724:2011 on biomass and carbon estimation. The data to be obtained include both primary and secondary data. The variables and data sources used are shown in Table 1.

Observation procedure

Given the ecological variability of Jakarta Bay's mangroves, sample selection used a purposive sampling method considered factors such as accessibility, tidal exposure, and land use variations (Yanuar *et al.,* 2023). The study included four stations: Station 1 (Muara Village), Station 2 (Kapuk Muara), Station 3 (Marunda Cilincing), and Station 4 (Muara Jaya) (Figure 1).

Mangrove sampling followed the transect quadrat method (English *et al.,* 1998). Sample plots included 10 × 10 m^2 for trees, 5 × 5 m^2 for samplings (nested within tree plots), and 2 × 2 m^2 for seedlings (nested within both tree and sapling plots). Diameter at breast height (DBH) was measured for trees taller than 1.3 m (Kauffman and Donato, 2012; NOAA, 2017). Biomass estimation utilized allometric equations, following the Forestry Research and Development Agency Regulation No. P.01/VIII-P3KR/2012.

Data analysis

The data analysis involved several calculations, including species composition, mangrove biomass, and biomass carbon content. The ecological indices used to analyze species in a given area are based on the methods outlined by English *et al.* (1998). Species density (K_i) is calculated by dividing the number of individuals of a species (n_i) by the plot area (A), expressed as $K_i = n_i.K_i^{-1}$, where the density is measured in individuals per square meter ($ind.m^{-2}$). Relative density (KR) represents the percentage of a species density relative to the total density of all species and is calculated using the formula $KR = (K.\ \Sigma K^{-1}) \times 100$, where (K) is the species density of all species in the plot. Species coverage (C_i) is determined by dividing the total basal area (ΣBA) of the species by the plot area (A), and is calculated as $C_i = \Sigma BA.A^{-1}$. Relative coverage (CR) represents the percentage of a species coverage relative to the total coverage of all species, calculated as $CR = (C_i.\Sigma C_i^{-1}) \times 100$, where ($C_i$) is the coverage of a specific species and (ΣC) is the total coverage value for all species. Species frequency (F_i) is the proportion of plots where a species was found, calculated as $F_i = p_i.\Sigma p_i^{-1}$, where ($p_i$) is the number of plots in which the species appeared and (Σp_i) is the total number of plots. Relative frequency (FR) is the percentage of a species frequency relative to the total frequency of all species,

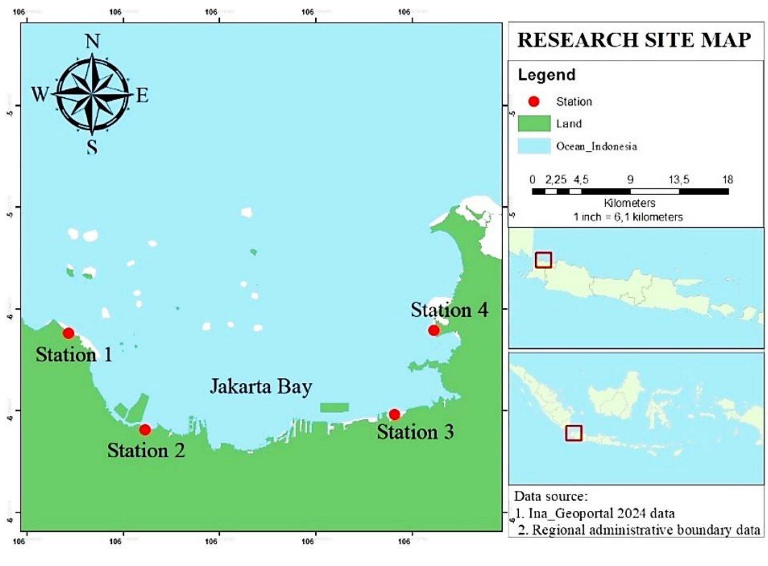

Figure 1. Map of the Research Location at Four Observation Points (Indicated by Red Circles) Facing the Jakarta Bay Area

Table 1. Variables and Data Sources

No	Objective	Variables	Data Type
1	Analyze and identify the ecological condition of the mangrove ecosystem	Vegetation Type, Vegetation Structure	Primary and Secondary
2	Calculate the potential carbon stock	Mangrove Biomass, Carbon Stock	Primary and Secondary

Table 2. Quality Standard Criteria for Mangrove Forests

Criteria	Coverage (%)	Density (ind.ha^{-1})
Good/Dense	≥75	≥1500
Moderate	50 – 75	1000 – 1500
Damaged/ Sparse	<50	<1000

Source: (KLH, 2004)

Table 3. Allometric Equations for Mangrove Species Stands

Types of Plants	AGB equations	ρ	References
Rhizophora mucronata	Wag= 0,128*DBH^{2,60}	-	Komiyama *et al* (2005)
Rhizophora apiculata	Wag= 0,235*DBH^{2,42}	-	Ong *et al* (2004)
Avicennia marina	Wag= 0,308*DBH^{2,11}	-	Komiyama *et al* (2005)
*Sonneratia alba**	Wag= 0.251ρDBH$^{2.46}$	0.78	Komiyama *et al* (2005)

Note: The equation for Sonneratia alba is general.

Explanation: Wag = Above-ground biomass (kg) (total biomass above the soil surface); D= Stem diameter (cm); DBH= Diameter at breast height (cm)*(diameter of the stem at 1.3 meters from the ground);* ρ= Wood density (kg.cm^3); H= Height (m) (calculated as $\frac{D}{0.025D+0.583}$)

expressed as *FR= (F$_i$.ΣF^{-1})×100*, where (F$_i$) is the frequency of the species and (ΣF) is the total frequency. Lastly, the Importance Value Index (IVI) is a composite measure that combines relative density, relative coverage, and relative frequency, calculated as *IVI= RD+RC+RF*, where (RD), (RC), and (RF) are the relative values of density, coverage, and frequency, respectively. These indices provide a comprehensive understanding of the ecological significance of species within an ecosystem, highlighting their distribution and contribution to community structure.

The importance value index of a mangrove species ranges from 0% to 300%, reflecting its ecological role within the community. The analysis results provide tree density (individuals per hectare) and canopy cover percentage, assessed against the quality standard criteria for mangrove forests outlined in the Ministry of Environment Decree No. 201 of 2004 (Table 2).

The carbon content is determined through several methods, such as calculating biomass, carbon from biomass, and carbon from sediments.Carbon storage in mangrove vegetation is estimated based on biomass, with approximately 46–50% of biomass consisting of carbon (Kauffman and Donato, 2012). Organic carbon stock is determined from biomass weight, calculated using DBH measurements and allometric equations specific to mangroves. Biomass estimation follows SNI 7724-2011, as outlined in Table 3.

Carbon from biomass

Carbon stock or carbon stocks are estimated from the biomass. According to Kauffman and Donato (2012), 46-50% of the biomass is carbon. The carbon mass is calculated using the following equation:

$$Cag= B \times \%\ C\text{-organik}$$

Note: Cag= Carbon mass/carbon content from biomass (kg or ton), B= Biomass (kg or ton), % C$_{organic}$= Percentage of organic carbon content, which is 0.47, or the percentage of carbon obtained from laboratory analysis.

Results and Discussion

Mangrove species diversity

Mangrove ecosystems are productive coastal habitats that provide essential services like coastal protection and carbon sequestration. However, they have significantly declined, losing around 35% of global cover in the 1980s and 1990s, mainly due to human activities (Friess *et al.*, 2019). The main factors contributing to this widespread deforestation were the conversion of mangrove habitats into aquaculture ponds, agricultural land, urban infrastructure, and the overexploitation of natural resources.

Mangroves, as blue carbon ecosystems (BCEs), play a vital role in mitigating climate change by sequestering atmospheric carbon dioxide (CO_2). Along with tidal marshes and seagrasses, they efficiently capture and store large amounts of carbon in their biomass and sediment (Kelleway *et al.*, 2020). This carbon storage potential renders mangroves vital in global climate change mitigation efforts. However, the effectiveness of mangrove ecosystems in sequestering carbon is often constrained by the limited availability of revegetation areas, which poses a challenge for restoration and conservation initiatives (Gao *et al.*, 2022; Adame *et al.*, 2024).

In the past two decades, the global rate of mangrove loss has decreased, thanks to national and international conservation policies. However, mangroves remain threatened by extreme climate events like sea-level rise, coastal erosion, and stronger storms. Additionally, reduced fluvial sediment supply from river damming and altered hydrology poses risks to their long-term stability and resilience. (Friess *et al.*, 2019; Zhang *et al.*, 2023).

The mangrove species in Jakarta Bay exhibit diversity influenced by local environmental conditions, such as pollution levels, salinity, and human activities. Based on the observations, several mangrove species were identified at the observation stations (Figure 2). The mangrove vegetation at Station I (Muara Village) identified within the observation plots included *Rhizophora mucronata*, *Rhizophora apiculata*, and *Avicennia marina*. Additionally (Table 4), there was a species not included in the plots, *Avicennia alba*. Several species were identified at Station II (Kapuk Muara), such as *Rhizophora mucronata*, *Avicennia marina*, and *Sonneratia alba*. The mangrove species found at Station III (Marunda) were similar to those at Station II. At Station IV (Muara Jaya), the identified species included *Rhizophora mucronata* and *Avicennia marina*.

According to Minister of Environment Decree No. 201 of 2004, the mangrove condition at Station I and Station III is classified as good, while Station II is categorized as poor and Station IV as moderate. The highest total density was observed at Station III (3940 individuals ha^{-1}). The species distribution pattern in Jakarta Bay appears to be influenced by frequent mangrove rehabilitation efforts (Jusoff, 2013). Mangrove rehabilitation contributes to climate change mitigation by enhancing blue carbon storage and coastal protection (Debrot *et al.*, 2022). The use of blue carbon accounting models such as BlueCAM enables standardized carbon stock estimation, facilitating financing opportunities in voluntary carbon markets (Lovelock *et al.*, 2023).

A high IVI indicates strong ecological dominance and adaptive capacity. *Avicennia marina* had the highest IVI at three stations, reflecting its high tolerance to environmental conditions. This species is frequently found in rehabilitated areas, as observed in Paradiso Beach, Kupang (Seran, 2019). In contrast, *Rhizophora apiculata* was reported as the dominant species in Kuala Idi, demonstrating its adaptability to muddy-sandy substrates (Parmadi *et al.*, 2016).

As a pioneer species, *Avicennia marina* is well-suited for rehabilitation efforts due to its ability to grow in diverse tidal (Noor *et al.*, 2006; Ariga and Malonga, 2024). Its high IVI signifies its dominance and strong adaptive capacity (Parmadi *et al.*, 2016; Purnama *et al.*, 2019; Ariga and Malonga, 2024). *Rhizophora mucronata* dominated Stations I and III, which frequently undergo rehabilitation. Both *Rhizophora mucronata* and *Avicennia marina* are commonly dominant in Indonesian mangrove ecosystems due to their broad environmental tolerance (Kusumahadi, 2008).

Avicennia marina exhibits high tolerance to elevated salinity, low rainfall, and high temperatures. Its physiological adaptations include small leaf size, trichomes on leaves, salt crystal excretion from leaf surfaces, and cryptopore stomata to reduce physiological stress (Atia *et al*., 2022; Su *et al*., 2022). The muddy substrate common in Indonesia also supports the growth of *Rhizophora mucronata* and *Avicennia marina*, making them key species for mangrove conservation and rehabilitation.

Mangrove biomass and carbon stock

Substrate characteristics serve as key limiting factors for mangrove growth, influencing species composition and vegetation density (Baderan *et al*., 2018; Akram *et al.*, 2023; Lakhnarayan and Phillip, 2024). Observations across four study stations in Jakarta Bay revealed variations in mangrove density. Stations I and III exhibited high vegetation density, whereas Stations II and IV had sparse to low densities based on the Ministry of Environment criteria (KLH, 2004). The dominance of *Rhizophora mucronata* and *Avicennia marina* in high-density areas indicates strong adaptation to environmental conditions, underscoring the need for conservation and rehabilitation efforts.

Mangrove ecosystems act as effective carbon sinks due to their high biomass and rapid

Station III

sequestration rates, making them a cost-effective nature-based solution for mitigating CO_2 emissions (Rovai *et al*., 2022; Cooray *et al*., 2024). Biomass, referring to the dry weight of vegetation, is primarily concentrated in above-ground structures.

At Station I, *Rhizophora mucronata* had the highest density (197 individuals.ha^{-1}), contributing 268.62 tons.ha^{-1} of biomass and 126.25 tons.ha^{-1} of carbon stock. *Avicennia marina* (63 individuals.ha^{-1}) added 84.32 tons.ha^{-1} of biomass and 39.63 tons..ha^{-1} of carbon stock. *Rhizophora apiculata* (52 individuals.ha^{-1}) contributed significantly with 205.78 tons.ha^{-1} of biomass and 96.71 tons.ha^{-1} of carbon stock. Total biomass at Station I was 558.72 tons.ha^{-1}, with carbon stock of 262.59 tons.ha^{-1}. (Table 5).

At Station II, *Rhizophora mucronata* (27 individuals.ha^{-1}) exhibited lower biomass (111.20 tons.ha^{-1}) and carbon stock (52.26 tons.ha^{-1}). *Avicennia marina* (41 individuals.ha^{-1}) contributed 107.52 tons.ha^{-1} of biomass and 50.53 tons.ha^{-1} of carbon stock. *Sonneratia alba* demonstrated high biomass (192.46 tons.ha^{-1}) and carbon stock (90.46 tons.ha^{-1}) despite low density. The total biomass was 411.18 tons.ha^{-1}, with carbon stock of 193.25 tons.ha^{-1}.

At Station III, *Rhizophora mucronata* (97 individuals.ha^{-1}) had significantly lower biomass (17.16 tons.ha^{-1}) and carbon stock (8.06 tons.ha^{-1}). *Avicennia marina* (96 individuals.ha^{-1}) exhibited biomass of 61.20 tons.ha^{-1} and carbon stock of 26.76 tons.ha^{-1}. *Sonneratia alba* (4 individuals.ha^{-1}) had relatively high biomass (13.22 tons.ha^{-1}) and substantial carbon stock (130.54 tons.ha^{-1}). The total biomass was 208.9 tons.ha^{-1}, with carbon stock of 96.17 tons.ha^{-1}.

At Station IV, *Rhizophora mucronata* (25 individuals.ha^{-1}) had a high biomass of 236 tons.ha^{-1} and carbon stock of 110.92 tons.ha^{-1}. *Avicennia marina* (41 individuals.ha^{-1}) showed higher biomass (129.39 tons.ha^{-1}) and carbon stock (60.81 tons.ha^{-1}). The total biomass at Station IV was 365.39 tons.ha^{-1}, with carbon stock of 171.73 tons.ha^{-1}.

The highest total biomass was observed in *Rhizophora mucronata*, likely due to its high density and growth characteristics. Tree density significantly influences biomass potential (Rachmawati *et al*., 2014), while trunk diameter plays a crucial role in carbon storage (Hairiah and Rahayu, 2007; Köhl *et al*., 2017). Larger tree diameters correlate with greater carbon stock, as supported by allometric models that link DBH and total height to biomass estimates (Mahmood *et al*., 2021).

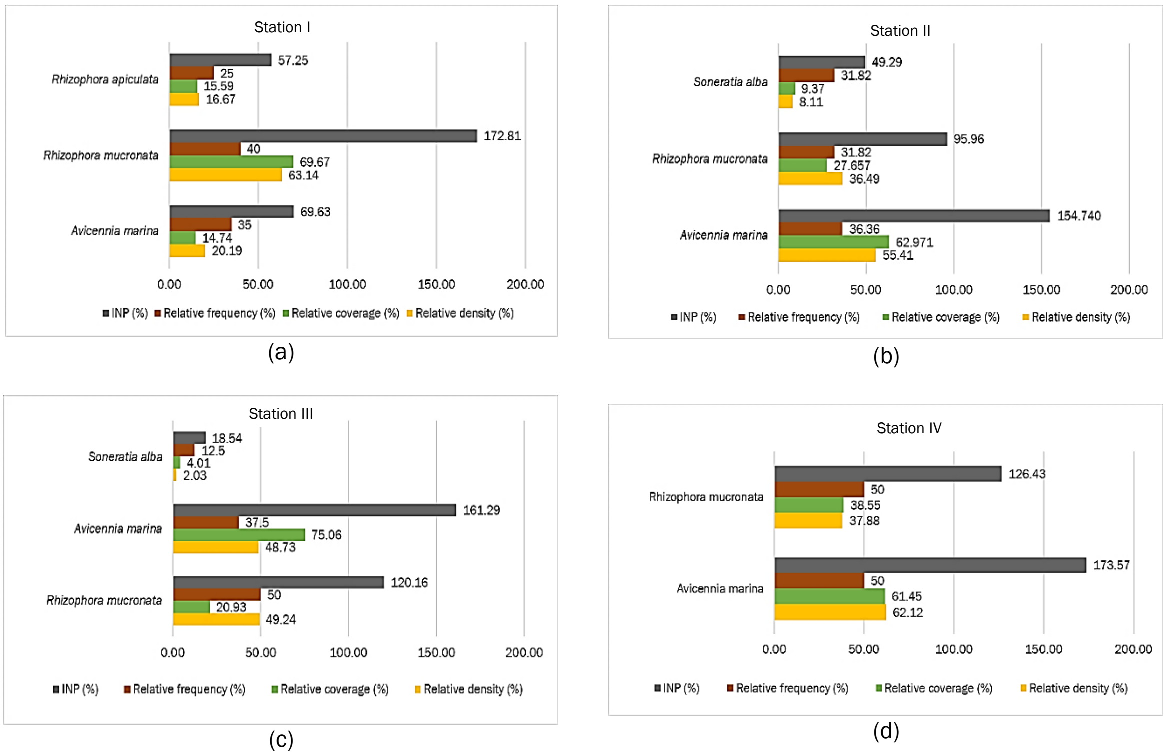

Figure 2. Diversity, Species Density, and Importance Value Index (IVI) of Mangroves in Jakarta Bay. (a) Muara Village, (b) Kapuk

The total carbon stock across all study sites was 723.74 tons ha^{-1}, slightly lower than the 790.91 tons ha^{-1} reported by Yaqin *et al.* (2022) in Tugurejo Village, Semarang. This variation may be attributed to differences in tree diameter, a major determinant of carbon storage (Kauffman *et al.*, 2020; Rifandi, 2021; Yanuar *et al.*, 2023). Effective mangrove management and conservation practices enhance carbon sequestration capacity (Fitria and Dwiyanoto, 2021).

Mangroves offer critical ecological services, including coastal protection from erosion and storm surges, habitat provision for marine biodiversity, and long-term carbon sequestration (Bouillon *et al.*, 2008; Alongi, 2012). Additionally, they provide economic benefits through fisheries, ecotourism, and raw materials for local communities. However, ongoing threats, such as land conversion for aquaculture, urban expansion, and industrial development, jeopardize mangrove sustainability, underscoring the need for effective conservation initiatives.

Educational efforts are crucial in promoting community awareness of mangrove conservation. Restoring degraded mangrove ecosystems and implementing sustainable management strategies will enhance their resilience and maximize their role in mitigating global climate change.

Table 4. Composition of Mangrove Vegetation at Observation Sites

Location	Mangrove Species	K_i (ind.ha^{-1})	Mean (ind.ha^{-1})	SD (ind.ha^{-1})	SE (ind.ha^{-1})	C_i	F_i
Station I	*Avicennia marina*	700	1156	732.37	422.84	10.83	0.78
	Rhizophora mucronata	2189				51.2	0.89
	Rhizophora apiculata	578				11.46	0.56
Station II	*Avicennia Marina*	455.56	274	159.82	92.27	8.94	0.89
	Rhizophora mucronata	300				3.93	0.78
	Sonneratia alba	66.67				1.33	0.33
Station III	*Rhizophora mucronata*	1940	1313	872.14	503.53	6.26	0.8
	Avicennia marina	1920				22.47	0.6
	Sonneratia alba	80				1.2	0.2
Station IV	*Avicennia marina*	683.33	550	133.33	94.28	16.12	1
	Rhizophora mucronata	416.67				10.2	1

Note: K_i=Species density; SD= Standar deviation; SE= Standar error; C_i=Species coverage; F_i=Species frequency

Table 5. Biomass and Carbon Stock of Mangrove Biomass Analysis

Station	Mangrove Species	N_i (ind.ha^{-1})	Biomass (ton.ha^{-1})	Mean (ton.ha^{-1})	SD (ton.ha^{-1})	SE (ton.ha^{-1})	Carbon Stock (ton.ha^{-1})
I	*Rhizophora mucronata*	197	268.62				126.25
	Avicennia marina	63	84.32	186.24	76.5	44.17	39.63
	Rhizophora apiculata	52	205.78				96.71
II	*Rhizophora Mucronata*	27	111.2				52.26
	Avicennia Marina	41	107.52	137.06	39.2	22.63	50.53
	Sonneratia alba	6	192.46				90.46
III	*Rhizophora Mucronata*	97	17.16				8.06
	Avicennia Marina	96	61.2	69.63	46.67	26.94	26.76
	Sonneratia alba	4	130.54				61.35
IV	*Rhizophora Mucronata*	25	236	182.695	53.31	30.78	110.92
	Avicennia Marina	41	129.39				60.81

Note: N_i= Number of individuals; SD= Standar deviasi; SE= Standar error

Climate change mitigation

The findings of this study demonstrate that mangrove stands in Jakarta Bay hold considerable biomass carbon stocks, with values ranging from 96.17 ton C.ha^{-1} in Station III to 290.25 ton C.ha^{-1} in Station II. On average, the mangroves stored approximately 205.2 ton C.ha^{-1}, which is comparable to values reported in other tropical mangrove regions. For example, Kauffman and Donato (2012) reported an average of 102–499 ton C.ha^{-1} in mangroves across the Indo-Pacific, while Alongi 2012 highlighted that mangrove ecosystems typically store two to four times more carbon than upland tropical forests. These comparisons emphasize that Jakarta Bay mangroves, despite pressures from urbanization and coastal development, still provide a substantial contribution to regional carbon storage.

The relatively high carbon stock observed in Station II is strongly influenced by species composition and stand density, particularly the dominance of *Rhizophora spp*., which are characterized by large aboveground biomass. In contrast, the lower carbon stock in Station III may reflect degraded conditions and reduced mangrove density, consistent with findings by Murdiyarso *et al.* (2015) who reported that disturbed or fragmented mangroves exhibit significantly reduced carbon storage potential. This spatial variability suggests that site-specific management and restoration are crucial for maximizing the carbon sequestration capacity of mangroves in Jakarta Bay.

From a climate change mitigation perspective, the measured carbon stocks indicate that Jakarta Bay mangroves play a critical role as long-term carbon sinks. Mangroves not only sequester carbon in above- and belowground biomass but also in sediments, where organic matter can be preserved for centuries to millennia due to anoxic conditions (Alongi *et al.* 2015). Protecting and rehabilitating mangrove ecosystems in Jakarta Bay could therefore strengthen Indonesia's commitments to reducing greenhouse gas emissions, particularly in the context of the Nationally Determined Contributions (NDCs) under the Paris Agreement. Moreover, mangrove conservation aligns with the national target to rehabilitate 600,000 ha of mangroves by 2024, underscoring their importance in blue carbon strategies.

Beyond carbon storage, mangroves provide multiple co-benefits including shoreline stabilization, biodiversity support, and fisheries productivity. Therefore, conservation and sustainable management of mangroves should be recognized not only as a biodiversity priority but also as a nature-based climate solution. This integrated role highlights that the protection of Jakarta Bay mangroves can simultaneously address local ecological resilience and global climate change mitigation.

Conclusion

The mangrove ecosystem in the Jakarta Bay region exhibits a relatively similar species diversity across all observed locations. The dominant mangrove species identified include *Rhizophora mucronata*, *Avicennia marina*, and *Sonneratia alba*. Station I (Muara Village) and Station III (Marunda Cilincing) exhibit high mangrove density, indicating a well-established ecosystem. In contrast, Station II (Kapuk Muara) has poor mangrove conditions with low density, and Station IV (Muara Jaya) shows a relatively sparse distribution. In terms of biomass and carbon storage, Station I recorded the highest values, with a total biomass of 558.72 tons.ha^{-1} and a carbon stock of 262.59 tons.ha^{-1}. Conversely, Station III exhibited the lowest values, with a biomass of 208.9 tons.ha^{-1} and a carbon stock of 96.17 tons.ha^{-1}. These findings indicate that the mangrove ecosystem in Jakarta Bay holds significant potential for carbon sequestration, particularly in areas with high mangrove density. Therefore, it is crucial to preserve existing mangrove forests and implement rehabilitation efforts in degraded areas to maximize the ecological benefits of this ecosystem.

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