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The Relationship of Tree Stand Structure Parameters with Aboveground Carbon as an Estimation Carbon Storage in Pancer Cengkrong Mangrove, Trenggalek, East Java

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ABSTRACT

Mangrove ecosystems play a vital role in mitigating climate change by sequestering atmospheric carbon. This study investigates the relationship between tree stand structure and aboveground carbon storage in the Pancer Cengkrong Mangrove, Trenggalek, East Java. The research aimed to analyze stand characteristics, estimate carbon biomass, and evaluate the influence of structural parameters on carbon sequestration capacity. A purposive sampling method was employed, focusing on tree stands with a diameter at breast height (DBH) ≥ 10cm. The results indicated that DBH had the strongest influence on carbon storage, showing a positive correlation with biomass accumulation. Tree height had a lesser impact, while tree density affected carbon storage depending on species composition and stand maturity. Station 1, dominated by *Rhizophora apiculata*, showed higher carbon biomass (268.45 tons/ha) and storage (126.17 tons/ha) compared to Station 2, where *Avicennia marina* was dominant, with lower biomass (86.33 tons/ha) and carbon storage (40.58 tons/ha). Regression analysis confirmed that DBH significantly explained the variation in carbon storage, with coefficients of determination (R^2) of 96.63% at Station 1 and 64.57% at Station 2. These findings highlight the importance of species selection in mangrove restoration efforts to maximize carbon sequestration. Future research should focus on belowground carbon storage and the long-term stability of rehabilitated mangrove forests. This study enhances our understanding of mangrove carbon dynamics and offers insights for optimizing climate change mitigation strategies.

INTRODUCTION

Global warming is a critical global phenomenon caused by the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere. These gases regulate the Earth's temperature by absorbing and emitting infrared radiation from sunlight **(Van Wijngaarden & Happer, 2020)**. Without them, the planet's temperature would be too low to sustain life. However, excessive greenhouse gas accumulation has led to rising global temperatures, disrupting ecosystems and causing severe environmental and socio-economic issues **(Syihabuddin & Ruhaeni, 2022)**. The main GHGs include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) **(EIA, 2023)**. Since the Industrial Revolution in 1992, emissions have increased by approximately 30% **(Melati, 2021)**. Among these gases, CO_2 is the most significant contributor, accounting for 75% of total emissions. Therefore, reducing CO_2 levels is a key focus of climate change mitigation efforts **(Sucipto *et al*., 2023)**.

A viable approach to mitigating climate change is reducing atmospheric CO_2 through plant-based carbon sequestration techniques **(Kepel *et al.*, 2019)**. Vegetation, particularly forests and mangroves, plays a crucial role in absorbing and storing atmospheric carbon, functioning as a natural CO_2 sink. Mangroves, which thrive in coastal and estuarine areas, have been identified as an essential component in climate change mitigation due to their high carbon sequestration capacity **(Mardliyah *et al.*, 2019)**. These ecosystems contribute significantly to environmental conservation and climate change mitigation efforts. Mangroves, found in tidal regions with muddy substrates, absorb CO_2 from the atmosphere and store it as biomass **(Ulqodry *et al.*, 2020)**. Through this process, mangroves effectively reduce net CO_2 levels in the atmosphere **(Nyanga, 2020)**.

Mangrove ecosystems consist of both aboveground biomass (tree diameter and height) and belowground biomass (roots and sediment) **(Lamont, 2020)**. Their total biomass directly influences their carbon storage capacity. Variations in biomass carbon stocks depend on structural characteristics such as tree density, diameter, canopy cover, and height **(Lumbu & Rumengan, 2022)**. The role of mangroves in carbon sequestration has gained significant attention due to their effectiveness in mitigating climate change. However, sequestration efficiency varies based on stand composition, environmental conditions, and human impact **(Prasanna *et al.*, 2023)**. Previous studies have examined mangrove carbon sequestration potential by assessing biomass and structural parameters. However, knowledge gaps persist regarding the influence of stand structure on carbon sequestration in rehabilitated versus natural mangroves.

Trenggalek Regency, Indonesia, is home to the Pancer Cengkrong Mangrove (PCM), a significant ecosystem undergoing rehabilitation. In 2003, approximately 50% of PCM's mangrove area was degraded, primarily due to activities such as land conversion for aquaculture, illegal logging, and coastal development **(Kiruba-Sankar & Barman,**

2024). The local community group, Kejung Samudra, initiated rehabilitation efforts to restore the ecosystem. Although these efforts have promoted mangrove regrowth, structural differences remain between rehabilitated and natural mangroves, potentially affecting carbon storage capacities. Understanding how tree stand structures influence carbon storage in rehabilitated and natural mangroves is crucial for optimizing future conservation and restoration strategies.

This study aimed to analyze the structural parameters of mangrove tree stands in PCM, estimate carbon biomass and aboveground carbon storage potential, and examine the relationship between tree stand structures and carbon storage in rehabilitated and natural mangroves. By addressing these objectives, this research contributes to a better understanding of how mangrove stand structures influence carbon sequestration. The findings offer valuable insights for mangrove rehabilitation and conservation strategies, ensuring that these ecosystems remain effective carbon sinks in the fight against global warming.

MATERIALS AND METHODS

1. Research methods

The research was conducted in the Pancer Cengkrong Mangrove (PCM) ecosystem, located in Karanggandu Village, Watulimo District, Trenggalek Regency, East Java Province. Data collection was carried out from March to April 2023. The research site was selected due to its significant ecological role and ongoing mangrove rehabilitation efforts. The research location map can be seen in Fig. (1).

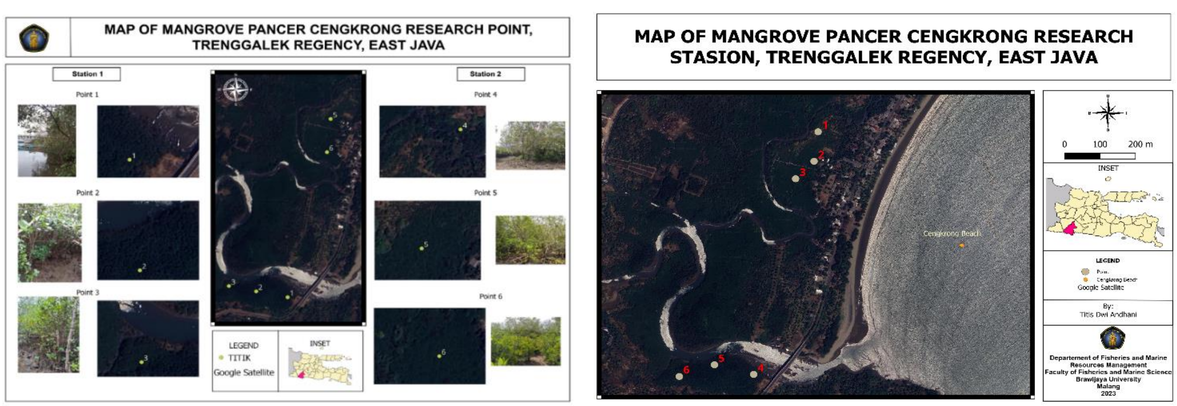

Fig. 1. Research location

This study employed a survey method, using a non-destructive approach for data collection. The structural characteristics of mangrove stands were measured, including tree height and diameter. The observation locations were determined using a purposive sampling method **(El-Masry, 2024)**, considering tree stand conditions, the distinction between natural and rehabilitated mangroves, and accessibility for data collection. The required tools and materials included a meter roll, GPS device, raffia, mobile phone, mangrove identification book, stationery, and research data sheets. Only trees with a diameter of ≥ 10 cm were included in the analysis.

2. Mangroves vegetation structure

Two observation stations were established, each containing three plots measuring 20x20m. The quadratic transect method was used for vegetation data collection.

2.1 Density

The density was calculated using the formula of **Noviatri *et al*. (2020)**:

$$\text{Di} = \frac{\text{Ni}}{\text{A}} \qquad\qquad \text{RDi} = \frac{\text{Ni}}{\sum n}\ x\ 100\%$$

Description:

Di : Density

Ni : Number of individuals of type I

A : Area of sampling area

RDi : Relative density (%)

Ni : Number of individuals of the Ith species (ind)

$\sum$: Number of all individuals (ind)

2.2 Frequency

Tree frequency was determined using the formula by **Salampessy *et al.* (2024)**:

$$\text{F} = \frac{\text{The number of plots occupied by a species}}{\text{Total number of plots}}$$

$$\text{Dat FR} = \frac{\text{Frequency of species}}{\text{Total frequency of all species}}\ \text{x } 100\%$$

2.3 Dominance

Dominance describes the relative influence of a species within a plot **(Sol *et al*., 2020)**. The dominance of each species was calculated using:

$$\text{D} = \frac{\text{Total Area of Base Field}}{\text{Total area throughout}}$$

$$DR = \frac{\text{Dominance of a species}}{\text{Dominance of all species}} \times 100\%$$

$$\text{Base Field Area(LBD)} = \frac{1}{4}\pi d^2$$

2.4 Index of importance (INP)

The following is the formula used for calculating the INP of the tree category **(Nizam *et al.*, 2022)**:

$$INP = KR + FR + DR$$

Description:
INP : Important Value Index
KR : Relative Density
FR : Relative Frequency
DR : Relative Dominance

3. Tree stand structure

3.1 Tree height

Tree height was measured using the observer's eye height, the distance between the observer and the tree, and the tilt angle from the observer’s eyes to the treetop. The tilt angle was measured using a protractor application **(Andrito *et al.*, 2020)**. The calculation formula is:

$$H = h_0 + h_1$$

Description:
H : stand height
h0 : observer's eye height
h1 : distance x tan θ

3.2 Tree diameter

Tree diameter was measured at 1.5m above ground level for mature trees. For species with supporting roots, measurements were taken 30cm above the highest root **(Rahmattin & Hidayah, 2020)**. The diameter was calculated using:

$$\text{Tree diameter} = \frac{\text{tree circumference}}{\pi}$$

4. Mangrove biomass calculation

Mangrove biomass was estimated using allometric equations based on tree diameter at breast height (DBH). Species-specific allometric equations were applied (Table 1).

Table 1. Mangrove biomass allometric equation

No	Species	Allometric Equation	Reference
1.	*R. mucronata*	0.143*D^2.519	Analuddin *et al.* (2018)
2.	*R. apiculate*	0.268*D^2.345	Analuddin *et al.* (2018)
3.	*S. alba*	0.251*0.7316*D^2.46	Komiyama *et al.* (2005)
4.	*S. caseolaris*	0.251*0.567* D^2.46	Komiyama *et al.* (2005)
5.	*A. alba*	0.079211(D)^2.470895	Poedjirahajoe *et al.* (2017)
6.	*B. gymnorhiza*	0.251*0.69 *D^2.46	Komiyama *et al.* (2005)

5. Estimation aboveground carbon storage

Aboveground carbon storage was estimated based on biomass values using a conversion factor of 0.47 **(Rifandi, 2021)**:

$$C_{abg} = W_{top} \times 0.47$$

Description:
$Cabg$: aboveground carbon stock (tons/ha)
$Wtop$: aboveground biomass
0.47 : conversion factor

6. Data analysis

Data analysis involved simple linear regression using Microsoft Excel. Descriptive analysis was conducted on mangrove stand parameters, including density, diameter, height, and carbon storage. To determine the relationship between structural parameters and carbon storage, classical assumption tests, hypothesis testing, and multiple regression model testing were conducted using Minitab 20 software:

$$Y = a + bx + e$$

Description:

Y : dependent variable or the one that is influenced
a : intercept
b : regression coefficient
x : independent variable
e : error term

7. Coefficient of determination (R-Square)

The coefficient of determination (R^2) was used to evaluate the predictive power of independent variables on the dependent variable. Higher R^2 values indicate a stronger influence of tree stand structure on aboveground carbon storage, whereas lower R^2 values suggest weaker predictive ability **(Puteri & Silvanie, 2020)**. The adjusted R^2 value was also calculated to determine the best-fit model for explaining the relationship between tree stand structure and carbon storage.

RESULTS AND DISCUSSION

1. Mangrove vegetation structure

The analysis of mangrove vegetation structure in Pancer Cengkrong identified eight mangrove species: *Avicennia alba*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia alba*, *Sonneratia caseolaris*, and *Aegiceras floridum*. Species distribution varied across stations, with six species recorded at Station 1 and five species at Station 2. The total number of mangrove individuals recorded was 264 at Station 1 and 165 at Station 2. *Rhizophora apiculata* dominated Station 1 with 108 individuals, while *Avicennia marina* was the most prevalent species at Station 2, with 113 individuals. The least abundant species were *Avicennia alba* (16 individuals at Station 1) and *Rhizophora mucronata* (5 individuals at Station 2). These findings suggest spatial variations in species composition and dominance, likely influenced by environmental conditions and ecological interactions (Table 2).

Table 2. Mangrove vegetation structure result

St.	Species	Total Species
1	*A. alba*	16
	B. gymnorrhiza	28
	R. apiculata	108
	R. mucronata	21
	S. alba	65

	S.caseolaris	26
	Total	**264**
	A. floridum	19
	A. marina	113
2	*R. apiculata*	18
	R.mucronata	5
	S.alba	10
	Total	**165**

Note: St = Station

1.1 Density

Mangrove species density values can be seen in Table (3).

Table 3. Mangrove species density values

St.	Species	Di (Ind/Ha)	Rdi (%)
	A. alba	133	6,1
	B. gymnorrhiza	233	10,6
	R. apiculata	900	40,9
1	*R. mucronata*	175	8
	S. alba	542	24,6
	S.caseolaris	217	9,8
	Total	**2200**	**100**
	A. floridum	158	11,5
	A. marina	942	68,5
2	*R. apiculata*	150	10,9
	R.mucronata	42	3
	S.alba	83	6,1
	Total	**1375**	**100**

Note: St = Station, Di = Density, Rdi = Relative density

Mangrove density varied significantly across stations (Table 3). At Station 1, the overall density was 2200 individuals per hectare (ind/ha), classifying it as very dense (>1500 ind/ha) per the Decree of the Minister of Environment No. 201 of 2004. In contrast, Station 2 exhibited moderate density (1375 ind/ha). The highest relative density was observed in *Avicennia marina* at Station 2 (68.5%), while *Rhizophora apiculata* exhibited the highest density at Station 1 (40.9%). The lowest density was recorded for *Rhizophora mucronata* at Station 2 (3%). The results suggest that high mangrove density at Station 1 indicates minimal disturbance, supporting healthy ecosystem conditions **(Xu *et al*., 2022)**.

1.2 *Frequency*

Species frequency and relative frequency varied among species (Table 4). The total frequency at Station 1 was 4.80, with *Bruguiera gymnorrhiza*, *Rhizophora apiculata*, and *Sonneratia alba* showing the highest values (20.83%). The lowest frequency values were recorded for *Avicennia alba* and *Rhizophora mucronata* (12.50%). At Station 2, the highest frequency was found in *Avicennia marina* (32.3%), while the lowest was in *Aegiceras floridum* (9.7%). Lower frequency values indicate species with lower tolerance and limited distribution within the study area **(Tariq *et al.*, 2024)**.

Table 4. Values of species frequency and relative frequency of mangroves

St.	Species	F	Fr (%)
1	*A. alba*	0.6	12.50
	B. gymnorrhiza	1	20.83
	R. apiculata	1	20.83
	R. mucronata	0.6	12.50
	S. alba	1	20.83
	S.caseolaris	0.6	2.56
	Total	**4.80**	**100**
2	*A. floridum*	0.3	9.7
	A. marina	1	32.3
	R. apiculata	0.6	19.4
	R.mucronata	0.6	19.4
	S.alba	0.6	19.4
	Total	**3.10**	**100**

Note: St = Station, F = Frequency, Fr = Relative Frequency

1.3 Dominance

Table 5. Values dominance species and relative dominance of mangroves

St.	Species	D	Dr (%)
1	*A. alba*	1.20	3.67
	B. gymnorrhiza	2.73	8,36
	R. apiculata	16.30	50.11
	R. mucronata	1.67	5.13
	S. alba	8.09	24.87
	S.caseolaris	2.56	7.85
	Total	**32.54**	**100**
2	*A. floridum*	1.46	10.1
	A. marina	10.33	70.95
	R. apiculata	1.36	9.35

R.mucronata	0.48	3.28
S.alba	0.93	6.41
Total	**14.56**	**100**

Note: St = Station, D = Density , Dr = Relative Density

The highest relative dominance at Station 1 was recorded for *Rhizophora apiculata* (50.11%), while the lowest was for *Avicennia alba* (3.67%) (Table 5). At Station 2, *Avicennia marina* dominated (70.95%), whereas *Rhizophora mucronata* showed the lowest dominance (3.28%). The dominance of *Avicennia marina* suggests high adaptability and competitive advantage in the study area **(Wijaya *et al*., 2021)**.

1.4 Important value index (INP)

The highest importance value index (INP) was recorded for *Avicennia marina* (171.69%) at Station 2, while *Avicennia alba* had the lowest (22.23%) at Station 1 (Table 6). The high INP value of *Avicennia marina* suggests that this species has a strong ecological presence in the rehabilitated mangrove areas, indicating its ability to thrive in disturbed environments and effectively recolonize degraded habitats. This dominance is likely due to *Avicennia marina*'s physiological adaptations, such as high salinity tolerance, rapid seedling establishment, and efficient nutrient uptake, which provide it with a competitive advantage over other species **(Nizam *et al.*, 2022)**.

Table 6. Mangrove INP result

St.	Species	INP (%)
1	*A. alba*	22.23
	B. gymnorrhiza	70.33
	R. apiculate	111.85
	R. mucronate	25.58
	S. alba	70.33
	S.caseolaris	30.20
	Total	**300**
2	*A. floridum*	31.20
	A. marina	171.69
	R. apiculate	39.61
	R.mucronata	25.66
	S.alba	31.83
	Total	**300**

Note: St = Station, INP = Important Index Value

2. Tree stand structure

Tree height at Station 1 averaged 9.06m, while Station 2 exhibited slightly lower tree heights (8.41m) (Table 7). The average tree diameter was 13.4cm at Station 1 and 11.5cm at Station 2. Mangrove stand density was higher at Station 1 (2200 ind/ha) than that recorded at Station 2 (1375 ind/ha). These structural attributes are influenced by photosynthesis efficiency and environmental conditions **(Rahmat *et al*., 2022; Suriani *et al*., 2023)**.

Table 7. Tree stand structure parameters

No	Parameter	St		Average
		1	2	
1	Height (m)	9.06	8.41	8.81
2	DBH (cm)	13.4	11.5	12.67
3	Density (ind/Ha)	2200	1375	325

Note: St = Station, DBH = Diameter at Breast Height

3. Aboveground carbon biomass

The estimation of aboveground biomass using the allometric method revealed significantly higher biomass at Station 1 (268.45 tons/ha) compared to Station 2 (86.33 tons/ha) (Fig. 2). This variation is primarily attributed to differences in tree diameter, as larger trees accumulate more biomass due to higher wood density and greater carbon sequestration potential **(Lekatompessy & Maitindom, 2022; Wirasatriya *et al*., 2022)**. The dominance of *Rhizophora apiculata* at Station 1, a species known for its dense wood and extensive root system, further explains the higher biomass **(Xu *et al*., 2020)**. In contrast, *Avicennia marina*, which dominated Station 2, has a lower wood density and a more opportunistic growth strategy, leading to lower biomass accumulation **(Rahman *et al*., 2020)**. Additionally, Station 1 may provide more stable hydrological and sedimentation conditions, allowing for enhanced growth, whereas Station 2, being a rehabilitated area, may still experience environmental fluctuations that limit biomass accumulation **(Tariq *et al*., 2024)**.

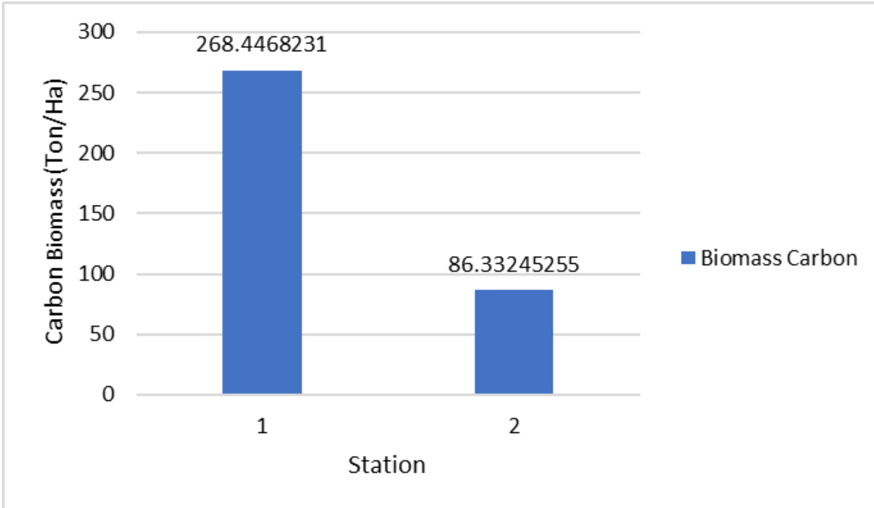

Fig. 2. Carbon biomass result

3. Aboveground carbon storage

Carbon storage was significantly higher at Station 1 (126.17 tons/ha) than at Station 2 (40.58 tons/ha) (Fig. 3). This disparity is consistent with the positive correlation between biomass and carbon storage, as greater biomass accumulation leads to increased carbon sequestration **(Karyati *et al*., 2021; Risfany *et al.*, 2022)**. The higher carbon storage at Station 1 can be attributed to the dominance of *Rhizophora apiculata*, a species with a high capacity for carbon retention due to its dense wood structure and extensive root system **(Tariq *et al*., 2024)**. Conversely, the lower carbon storage at Station 2 reflects the prevalence of *Avicennia marina*, which has a lower biomass accumulation potential and wood density, thereby reducing its ability to store carbon effectively **(Zhou *et al*., 2025)**.

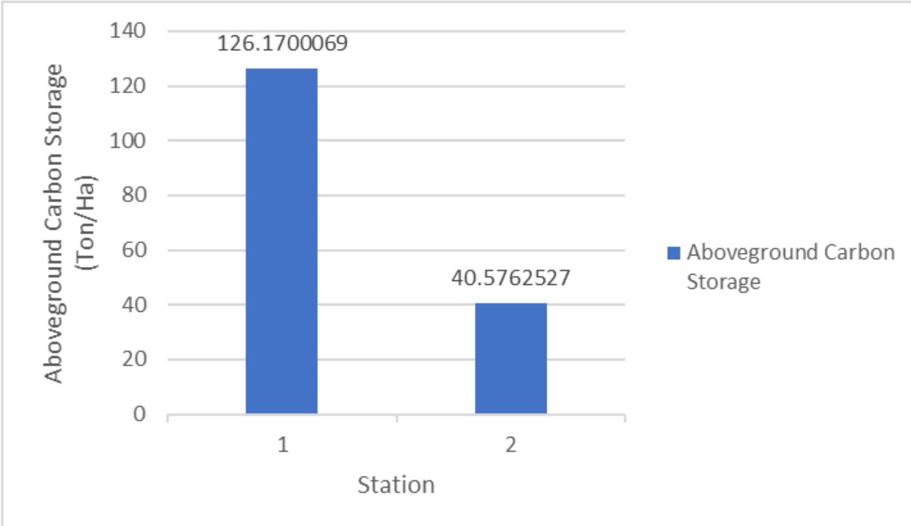

Fig. 3. Carbon storage result

5. Relationship between tree stand structure parameters and estimated aboveground carbon storage

The influence of tree stand parameters on aboveground carbon storage was assessed using regression analysis, with the coefficient of determination (R^2) used to evaluate the degree of correlation. A higher R^2 value indicates a stronger influence of tree stand parameters on carbon storage. If a parameter exhibited a negative coefficient, it was inferred that the parameter had no significant effect on carbon storage**.**

5.1 Tree height parameters

The regression analysis at Station 1 demonstrated a positive relationship between tree height and carbon storage, with a regression coefficient of 0.1954. This indicates that for every 1-meter increase in tree height, carbon storage increased by 0.1954 tons/ha. The coefficient of determination (R^2) was 57.41%, suggesting that tree height accounted for 57.41% of the variation in carbon storage, while the remaining 42.59% was influenced by other environmental and biological factors (Fig. 4a). At Station 2, the regression coefficient was lower (0.0294), with an R^2 value of 23.8%, indicating a weaker relationship (Fig. 4b). This discrepancy may be attributed to differences in species composition and environmental conditions. Previous studies suggest that tree height plays a role in carbon sequestration, although vertical growth often prioritizes the development of leaves, twigs, and reproductive structures rather than biomass accumulation **(Akbar *et al*., 2019)**.

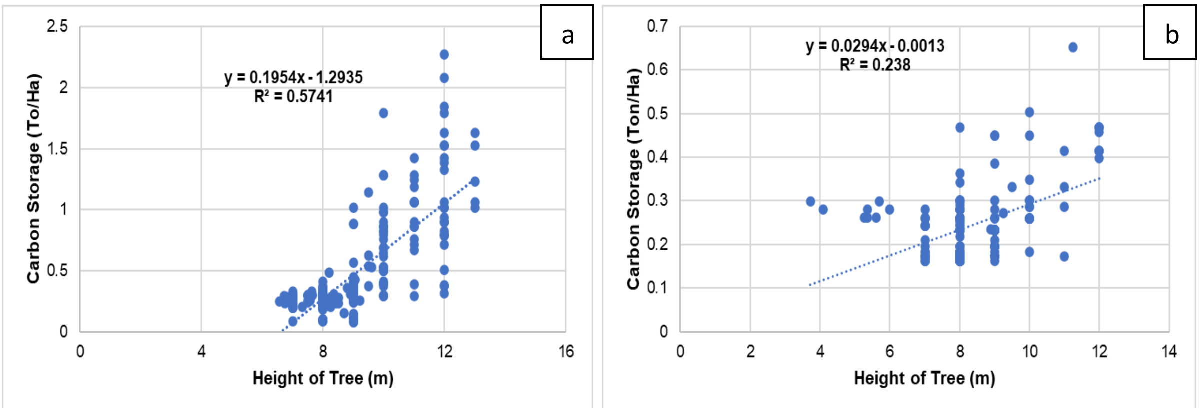

Fig. 4. Relationship between tree height and carbon storage

(a. Staion 1; b. Station 2)

5.2 Tree diameter parameters

Tree diameter at breast height (DBH) was identified as a primary determinant of carbon storage, given its direct relationship with aboveground biomass. At Station 1, the regression coefficient for DBH was 0.107, implying that a 1 cm increase in DBH resulted in a 0.107-ton/ha increase in carbon storage. The coefficient of determination (R^2) was 96.36%, indicating that DBH was a strong predictor of carbon storage in this location (Fig. 5a). Similarly, at Station 2, the regression coefficient was 0.0423, with an R^2 value of 63.11% (Fig. 5b). These results align with previous research demonstrating that larger DBH values correspond to higher biomass and carbon sequestration potential **(Zhou *et al.*, 2025)**. The variations between the two stations may be linked to differences in species dominance, with *Rhizophora apiculate*-a species known for its dense wood and extensive root system-being more prevalent at Station 1, thereby enhancing carbon storage capacity **(Komiyama *et al*., 2008)**.

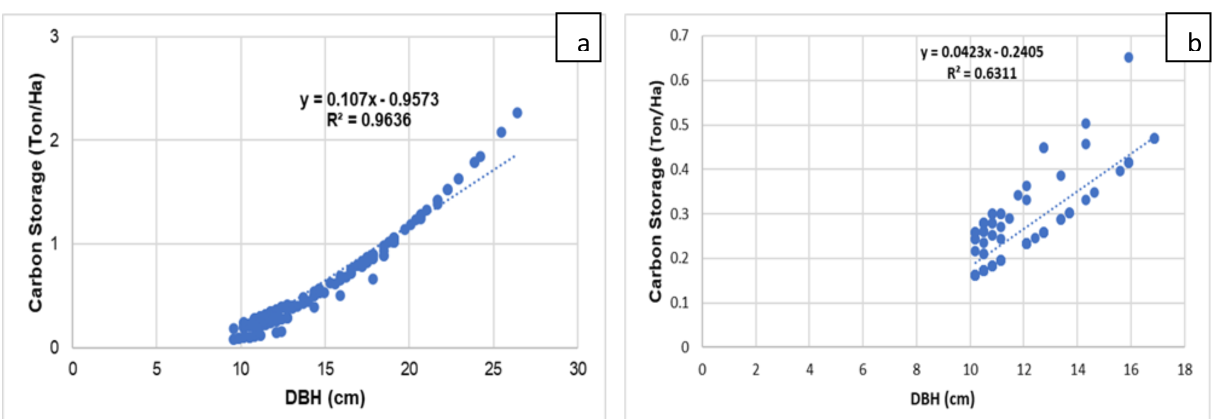

Fig. 5. Relationship between DBH and carbon storage
(a. Staion 1; b. Station 2)

5.3 Density parameters

The relationship between tree density and carbon storage was also examined. At Station 1, the regression coefficient was 0.0903, with an R^2 value of 98.51%, indicating that tree density was a major driver of carbon storage (Fig. 6a). At Station 2, the regression coefficient was 0.0255, with an R^2 of 99.78% (Fig. 6b), suggesting that even small changes in tree density had a notable effect on carbon sequestration. However, high tree density does not always equate to higher carbon storage, as tree size and species composition play a critical role **(Hendrayana *et al.*, 2023)**. The findings highlight the need to consider both density and biomass-related attributes when evaluating carbon sequestration potential in mangrove ecosystems.

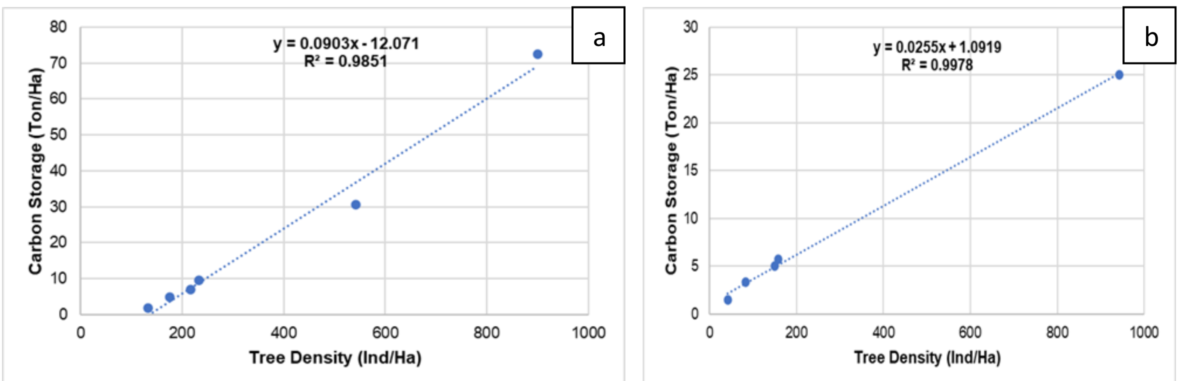

Fig. 6. Relationship between density and carbon storage
(a. Staion 1; b. Station 2)

6. Modeling the relationship of tree stand structure parameters with aboveground carbon storage estimates

A regression model was developed to predict carbon storage based on tree height and DBH. At Station 1, the regression coefficient for tree height was -0.0238, indicating no significant influence on carbon storage. In contrast, DBH exhibited a strong positive effect, with a coefficient of 0.1151, suggesting that each 1 cm increase in DBH resulted in a 0.1151-ton/ha increase in carbon storage. The adjusted coefficient of determination (R^2(adj)) was 96.63%, meaning that 96.63% of the variation in carbon storage at Station 1 could be explained by DBH. At Station 2, tree height similarly showed no significant influence on carbon storage (-0.0121), while DBH exhibited a weaker but still notable effect (0.0507). The R^2(adj) for Station 2 was 64.57%, indicating that additional environmental and structural variables influenced carbon storage in this rehabilitated mangrove site.

The stronger influence of DBH over tree height aligns with findings from previous studies, which emphasize the role of diameter growth in biomass accumulation and carbon sequestration **(Bai *et al.*, 2021)**. These results suggest that mangrove management strategies should prioritize maintaining and enhancing stand diameter rather than focusing solely on increasing tree height. Furthermore, the higher predictive power of the model at Station 1 indicates that mature mangrove forests provide more reliable carbon storage estimates compared to rehabilitated sites, which may still be undergoing structural development.

CONCLUSION

This study highlights the significant role of tree stand structure in determining aboveground carbon storage in the Pancer Cengkrong Mangrove ecosystem. Tree diameter at breast height (DBH) was identified as the strongest predictor of carbon sequestration, showing a positive correlation with biomass accumulation. Tree height had a weaker influence, while tree density contributed to carbon storage depending on species composition and growth patterns. Mature mangrove stands stored significantly more carbon than rehabilitated areas, emphasizing the need for long-term monitoring in restoration programs. The dominance of *Rhizophora apiculata* at Station 1 resulted in higher carbon sequestration, while *Avicennia marina* at Station 2 exhibited lower sequestration rates due to differences in wood density and growth dynamics. These findings reinforce the importance of species selection in mangrove rehabilitation. Future research should explore belowground carbon storage and long-term sequestration trends to enhance mangrove conservation as a climate change mitigation strategy.

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