



## Estimation of Blue Carbon Ecosystem Potential in the Mangrove Forest Tourism Area of Langsa Protected Zone

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### ARTICLE INFO

#### Article history:

Received December 9<sup>th</sup>, 2025

Revised January 20<sup>th</sup>, 2026

Accepted February 13<sup>th</sup>, 2026

Available online February 28<sup>th</sup>, 2026

E-ISSN: 2622-5093

P-ISSN: 2622-5158

#### How to cite (IEEE):

L. A. Yanti, A. W. Siregar, M. F. Srena, Fikrinda, A. U. Ramadhan, A. Murdi, F. S. L. P. Berutu, M. Jrohna, I. Hanafi, A. Kunaifi, and D. Fitriadi, "Estimation of blue carbon ecosystem potential in mangrove forest tourism area of Langsa protected zone", *Journal of Sylva Indonesiana*, Vol. 09, No. 01, pp. 17-27, Feb. 2026, doi: 10.32734/jsi.v9i01.23828



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<http://doi.org/10.32734/jsi.v9i01.23828>

### ABSTRACT

Mangrove forests are vital coastal ecosystems that sequester large amounts of carbon, helping mitigate climate change. Indonesia has the world's largest mangrove area, including the Langsa Protected Mangrove Forest in Aceh, which holds high biodiversity and significant blue carbon potential. The Mangrove Forest Tourism Area in Langsa is one of the largest in Southeast Asia; therefore, estimating its carbon potential is essential to support Indonesia's commitments to the Paris Agreement and carbon trading initiatives. This study aims to (1) identify tree species diversity in mangrove, and (2) estimate aboveground biomass, carbon stock, and carbon sequestration in the Langsa Mangrove Forest Tourism Area. A purposive sampling method was used for the initial plot, followed by systematic sampling. From 369.01 hectares of mangrove area, 19 plots were established with sizes of 10 m × 10 m for trees, 5 m × 5 m for saplings, and 2 m × 2 m for seedlings. Carbon stock estimation employed species-specific allometric equations. Out of 293 individual trees, four tree species, namely *Rhizophora mucronata*, *Rhizophora apiculata*, *Bruguiera gymnorrhiza*, and *Ceriops tagal*, were identified, with most ranging within 3.18–4.61 cm diameter classes. The highest aboveground biomass, carbon stock, and carbon sequestration were found in plot 19, at 27.66 ± 13.18 tons/ha, 13.00 ± 6.20 tons C/ha, and 47.67 ± 22.71 tons CO<sub>2</sub>/ha, respectively. These findings highlight the substantial blue carbon potential of the Langsa Mangrove Forest in a protected area, emphasizing its importance in regional conservation strategies.

**Keywords:** Allometric Equation, Blue Carbon Ecosystem, Carbon Stock, Mangrove Forest Tourism Area, Species Diversity

## 1. Introduction

Mangrove forests are unique, salt-tolerant tree and shrub ecosystems found in the intertidal zones of tropical, subtropical, and warm-temperate coastal regions. These forests are characterized by their remarkable adaptability to challenging environmental conditions, including salinity, waterlogging, and periodic inundation [1]. Mangrove forests provide multiple critical ecological, economic, and protective functions essential to coastal ecosystems and human communities. The functions of mangrove including as nurseries for marine fauna, provide habitat for fish, crabs and prawns [2], serve as a shield against natural disasters and sequester up to five times more carbon per hectare than tropical rainforests [3], generate economic benefits by sustaining biodiversity and provisioning essential resources such as firewood and construction timber [4] and support extensive biodiversity, hosting hundreds of species across plant, animal and marine categories.

Indonesia has the largest mangrove forests in the world, accounting for 22% of the 3.12 million hectares of global mangroves [5]. To this extent, Indonesia's mangrove forests store around 3 PgC, making the country the world's largest holder of blue carbon [6]. Based on the Research Team's 2025 satellite imagery observations, the mangrove forest within the Protected Area in Langsa covers 1,084.68 hectares. According to [7], the mangrove forest area in Langsa increased by approximately 324.29 hectares between 2007 and 2013. This region has relatively high biodiversity, consisting of two groups of mangroves: true mangroves (19 species across 14 families) and associated mangroves (6 species across 6 families), with vegetation structures spanning all growth stages. Vegetation is predominantly from the families *Rhizophoraceae*, *Avicenniaceae*, and *Sonneratiaceae*.

Blue carbon refers to carbon stored in coastal and marine ecosystems. The Blue Carbon Initiative currently focuses on carbon in coastal ecosystems such as mangroves, tidal marshes, and seagrasses. These ecosystems absorb and store large amounts of blue carbon in their biomass, specifically in aboveground biomass (AGB) such as stems, branches, and leaves within the sediment. This process of capturing and long-term storage of atmospheric carbon dioxide is known as carbon sequestration. Increasing the carbon sequestration potential of mangrove ecosystems has been considered a solution to reducing the rise in atmospheric greenhouse gas (GHG) concentrations. According to [7], mangrove forests in Indonesia store 5.2 Gt of carbon across 3.1 million ha, with a carbon storage potential 13 times greater than that of tropical rainforests. The ability of mangrove ecosystems to trap suspended material through their complex root systems enables them to store significantly more carbon than other wetland ecosystems [8]. The average carbon storage capacity of mangrove ecosystems is estimated to be three to ten times greater than that of other wetland ecosystems, such as peatlands [9].

Estimating carbon in ecosystems such as mangroves is important for regional carbon mapping because it provides scientific data for sustainable environmental management. In Aceh, these results support climate policies, conservation, restoration, and programs such as REDD+. The research site is part of a Protected Area that includes the Mangrove Forest Tourism Area in Langsa. This mangrove tourism area covers 7,783 hectares and is one of the largest mangrove forests in Southeast Asia, containing around 38 mangrove species [10], [12].

Ecotourism plays a crucial role in preserving and documenting blue carbon ecosystems, such as mangroves. In addition to providing economic benefits for local communities, ecotourism also contributes to integrated climate change mitigation efforts [11], [14]. Meanwhile, accurate carbon data supports mitigation planning, implementation of REDD+ schemes, and identification of priority conservation areas, making carbon mapping a strategic tool for low-emission development in regions like Aceh [12].

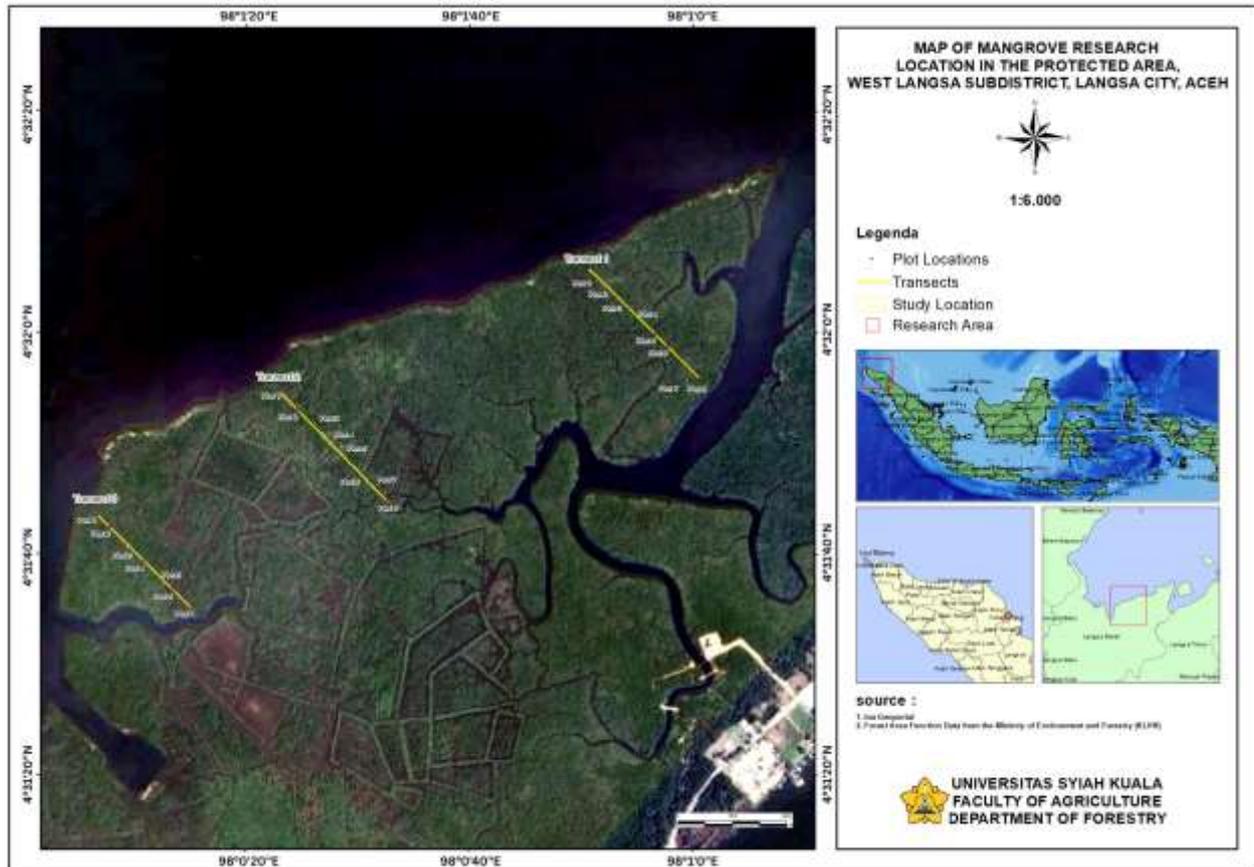
Several studies on blue carbon ecosystems have been conducted in other regions, but none have been carried out in the Langsa Mangrove Forest Tourism Area. This research is highly important given that Indonesia—particularly the Ministry of Environment and Forestry (*Kementerian Lingkungan Hidup dan Kehutanan*/KLHK) and related institutions—is currently prioritizing climate change prevention and mitigation. This study aims to (1) identify tree species diversity in mangrove, and (2) estimate aboveground biomass, carbon stock, and carbon sequestration in the Langsa Mangrove Forest Tourism Area. This research was carried out to address the following questions: (1) what are the mangrove tree species found in the Langsa Mangrove Forest Tourism Area, (2) what is the amount of aboveground biomass, carbon stock, and carbon sequestration in the Langsa Mangrove Forest Tourism Area. As mentioned earlier, the results of this study are expected to serve as a database of carbon sequestration levels in the mangrove forests of the Langsa Mangrove Forest Tourism Area. A database on carbon sequestration must be compiled for each forest type in every province. This will facilitate carbon trading in Indonesia, especially in Aceh, where the Indonesian domestic carbon exchange, established in September 2023, has successfully supported national carbon trading and officially entered the international carbon market as of January 2025.

## 2. Materials and Methods

### 2.1. General Overview of Research

This research was conducted in September 2024 at the Mangrove Forest Tourism Area, Langsa Protected Area (4°32'01.0" - 4°31'39.1" N and 98°00'55.7" - 98°00'11.1" E). As has been mentioned earlier, the Mangrove Forest Tourism Area covers 7,783 hectares [10]. However, the focus of this research is the portion of the Mangrove Forest Tourism Area designated as a protected area, which spans 369.01 hectares. This location was

selected based on its dense mangrove population observed in in satellite imagery. Figure 1 showcases the map of the research location.



**Figure 1.** Research location (Langsa Mangrove Forest Tourism Area)

## 2.2. Data Collection

The tools used in this study were a GPS (Global Positioning System), measuring tape, meter stick, camera, thermohygrometer, and refractometer. The materials used included tally sheets and the *Field Guide to the Identification of Mangroves in Indonesia* [13].

At this preparation stage, a survey of the research location was conducted, along with the processing of permits and administrative requirements, and the preparation of research tools and materials. This study involved the Regional Forest Management Unit Region III, the NGO Balee Juroeng, and the Port of Langsa.

The starting point of the research transect was selected based on areas with high mangrove density using a purposive sampling method. The first plot of each line transect was established exactly 100 meters from the boat landing point. The transect line was oriented perpendicular to the tide direction to ensure representative zonation. According to [14], the research plots were square-shaped, measuring 10 m × 10 m (for trees). Within each main plot, subplots measuring 5 m × 5 m were established for saplings and 2 m × 2 m for seedlings. The sampling intensity was 0.05% of the Langsa Mangrove Forest Tourism Area, which served as the research site (369.01 hectares), with each observation plot covering 100 m<sup>2</sup>. Therefore, the total number of research plots was 18.45, rounded to 19 plots in three line transects. The subsequent placement of plots was carried out using a systematic sampling method, with a distance of 50 meters between plots and 600-800 meters between transect lines, to ensure representative coverage of the entire study site.

Mangrove species were identified using the *Field Guide to the Identification of Mangroves in Indonesia* [13]. In each plot, seedlings, saplings, and trees were counted. Diameter at breast height (DBH) at 1.37 m above the highest prop root was measured followed methods described by reference [15]. The formula used to calculate tree diameter is as follows:

$$DBH = \frac{C}{\pi} \quad (1)$$

Explanation:

DBH = Diameter (cm)

C = Circumference (cm)

$\pi$  = Pi, valued at 3.14 or 22/7

### 2.3. Data Analysis

Data on species diversity, aboveground biomass, carbon stock, carbon sequestration, and oxygen production potential are presented later on in Table 4.

#### 2.3.1 Aboveground biomass (AGB)

Estimation of aboveground biomass for mangrove tree species can be carried out by estimating dry weight using allometric functions and following the standards of SNI 7724:2019. Studies on the analysis of mangrove vegetation in the Langsa Mangrove Forest Tourism Area have not yet been conducted. Biomass calculation was performed using species-specific allometric equations. The following table presents the allometric equations for several mangrove species (Table 1).

**Table 1.** Allometric equations for several mangrove species

Number	Species	Allometric equation	References
1	<i>Rhizophora apiculata</i>	ABG = 0,75. DBH <sup>2,23</sup>	[16]
2	<i>Bruguiera gymnorhiza</i>	ABG = 0,186. DBH <sup>2,31</sup>	[17]
3	<i>Ceriops tagal</i>	ABG = 0,251. $\rho$ . DBH <sup>2,46</sup> $\rho = 0,960$	[18]
4	<i>Rhizophora mucronata</i>	AGB = 0,5. DBH <sup>2,32</sup>	[16]

#### 2.3.2 Calculation of carbon stock per hectare

Mangrove carbon stock can be calculated using the following formula [19].

$$Cb = B \times \% C \text{ organic} \quad (2)$$

Where:

Cb: mangrove carbon stock (kg)

B: Total biomass (kg)

% C organic: percentage of carbon content, equal to 0.47

The total carbon calculated for an area or ecosystem is divided by the plot area to convert it to tons/ha, yielding the carbon value at each observation location [21].

$$Cn = \frac{Cx}{1000} \times \frac{10000}{L_{\text{plot}}} \quad (3)$$

Explanation:

Cn: carbon content per hectare for each carbon pool in each plot (tons C/ha)

Cx: carbon content in each carbon pool in each plot (kg)

L<sub>plot</sub>: plot area for each pool (m<sup>2</sup>)

#### 2.3.2 Total Carbon Sequestration (kg/m<sup>3</sup>)

The formula for measuring total carbon sequestration by [20] is:

$$CO_2 \text{-equivalent} = (44/12) \times \text{carbon stock} \quad (4)$$

Calculation of CO<sub>2</sub> per hectare used the following formula referring to [20]:

$$Sn = (CO_2 \text{-equivalent})/1000 \times 10.000 / (L \text{ plot})$$

#### 2.3.3 The Potential of Vegetation Oxygen Production (tons O<sub>2</sub>/ha)

The formula for estimating the potential of vegetation to produce oxygen is:

$$O_2 \text{-equivalent} = (32/44) \times CO_2 \text{-equivalent} \quad (5)$$

### 3. Results and Discussion

#### 3.1. Species Diversity

Table 2 shows that on seedlings, the species of mangrove found in The Langsa Mangrove Forest Tourism Area were *Rhizophora mucronata* and *Rhizophora apiculata*. *R. mucronata* (20 individuals) was more dominant compared to *R. apiculata* (4 individuals). *R. mucronata* Lamk., adapts to high salinity environments [21], can grow with varying tidal conditions from high to low tide zones [22]. Its ability to withstand and adapt to saline, polluted environments make it a critical mangrove species for ecosystem restoration. The salinity at the study site ranged from 25 to 30 ppt. According to [23] mangrove plants grow well in estuarine areas with salinities of 10–30 ppt.

*R. mucronata* dan *R. apiculata* species dominated the area because their remarkable environmental tolerance makes them highly successful in coastal ecosystems. According to [21], *R. mucronata* develops specialized leaf structures, such as thick, waxy cuticles, low stomatal density, and cork warts, to survive high-salinity conditions. Furthermore, [24] that *Rhizophora* species have robust root systems capable of resisting wave forces, thriving in inundated habitats, and enduring elevated salinity levels.

**Table 2.** Mangrove species and number of individuals across the study site

The number of plot	Local name	Scientific name	Number of individual		Total (ind.)
			Seedlings	Saplings	
1	Red mangrove	<i>Rhizophora apiculata</i>	0	8	8
2	Red mangrove	<i>Rhizophora apiculata</i>	0	6	6
3	Red mangrove	<i>Rhizophora apiculata</i>	0	10	10
4	Red mangrove	<i>Rhizophora apiculata</i>	0	14	14
5	Red mangrove	<i>Rhizophora apiculata</i>	1	14	15
6	Red mangrove	<i>Rhizophora apiculata</i>	0	8	8
7	Red mangrove	<i>Rhizophora apiculata</i>	0	11	11
8	Red mangrove	<i>Rhizophora apiculata</i>	0	14	14
9	Red mangrove	<i>Rhizophora apiculata</i>	0	18	
	Tengar	<i>Ceriops tagal</i>	0	1	21
	Black mangrove	<i>Rhizophora mucronata</i>	1	1	
10	Red mangrove	<i>Rhizophora apiculata</i>	2	8	
	Tancang	<i>Bruguiera gymnorrhiza</i>	0	1	17
	Black mangrove	<i>Rhizophora mucronata</i>	5	1	
11	Red mangrove	<i>Rhizophora apiculata</i>	0	13	14
	Black mangrove	<i>Rhizophora mucronata</i>	0	1	
12	Red mangrove	<i>Rhizophora apiculata</i>	0	9	10
	Tancang	<i>Bruguiera gymnorrhiza</i>	0	1	
13	Red mangrove	<i>Rhizophora apiculata</i>	0	14	14
14	Red mangrove	<i>Rhizophora apiculata</i>	0	14	14
15	Black mangrove	<i>Rhizophora mucronata</i>	3	14	17
16	Red mangrove	<i>Rhizophora apiculata</i>	0	13	13
17	Red mangrove	<i>Rhizophora apiculata</i>	0	23	23
18	Red mangrove	<i>Rhizophora apiculata</i>	1	18	19
19	Black mangrove	<i>Rhizophora mucronata</i>	11	34	45
Total			24	269	293

Table 2 also shows that the highest number of seedlings was found in plot 19. This presumed to be because this plot located furthest inland on transect 3 and experiences minimal illegal logging activity. Research by [25] indicates that illegal logging severely damages mangrove ecosystems by disrupting carbon storage, reducing forest cover, and compromising coastal environmental protection.

At the sapling level (Table 2), there were four mangrove species recorded: Red Mangrove (*Rhizophora apiculata*) with 215 individuals, Black Mangrove (*Rhizophora mucronata*) with 51 individuals, *Bruguiera gymnorrhiza* with 2 individuals, and *Ceriops tagal* with 1 individual. At the sapling level, it was evident that *Rhizophora apiculata* was more dominant than the other three mangrove species. According to [13], *Rhizophora apiculata* grows on muddy, fine-textured, deep soils that are inundated during normal high tides. This species does not prefer substrates with a higher sand content. Its dominance level can reach up to 90% of the vegetation in a given location. It thrives in tidal waters that consistently receive strong freshwater input. Although the species grows slowly, it flowers year-round. Several studies have reported that as DBH classes increase in a forest, the number of individual trees significantly decreases, indicating higher densities of regeneration (seedlings and saplings) per unit area than mature trees [26]-[28].

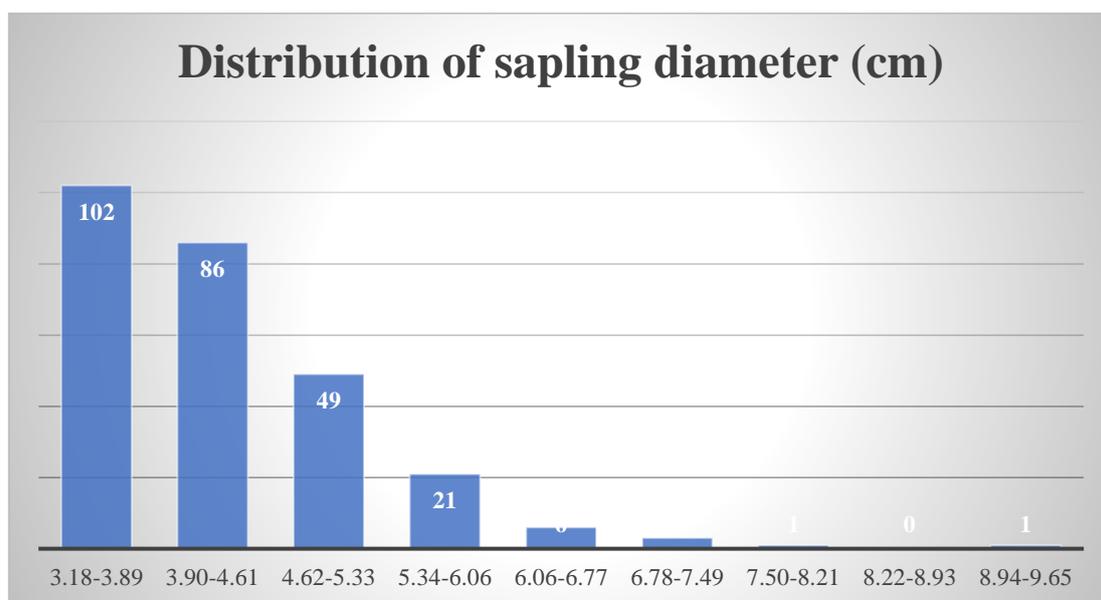
Table 3 shows that the total tree density in the Langsa Mangrove Forest Tourism Area was 1542.10 ind/ha. This value indicates the mangrove ecosystem in good condition. The community structure was heavily dominated by *Rhizophora apiculata* (1,152.63 ind/ha) and *Rhizophora mucronata* (373.68 ind/ha) which together accounted for approximately 99% of the total density. The dominance of the genus *Rhizophora* indicates that the study site is located within the typical middle mangrove zone, characterized by deep, muddy substrates and regular tidal inundation, conditions where *Rhizophora* species exhibit greater adaptability and competitive advantage than other species. The presence of *Ceriops tagal* and *Bruguiera gymnorrhiza* within the transect was presumed to occur because the propagules of these species were carried by tidal currents and settled in suitable microhabitats. In addition, natural regeneration in areas with minimal disturbance allows non-dominant species to emerge among the dominant *Rhizophora* vegetation. According to [29] natural regeneration enables these species to emerge alongside dominant *Rhizophora* spp. vegetation. However, the specific claim about tidal current propagule dispersal lacks direct empirical validation in the provided sources. The temperature and humidity ranges at the study site were 27.2–31.2°C and 75–99%, respectively. According to [30] *Rhizophora stylosa* and *Ceriops* species grow optimally at temperatures of 26–28°C, while *Bruguiera* grows optimally at around 27°C. High tree density dominated by *Rhizophora* contributes significantly to the ecosystem's carbon storage capacity, as this genus typically possesses high wood density and biomass accumulation potential.

**Table 3.** Species density per ha in the study area

No	Local name	Famili	Scientific name	Total individuals	Species density (ind. per ha)
1	Red mangrove	Rhizophoraceae	<i>Rhizophora apiculata</i>	219	1,152.63
2	Tengar	Rhizophoraceae	<i>Ceriops tagal</i>	1	5.26
3	Black mangrove	Rhizophoraceae	<i>Rhizophora mucronata</i>	71	373.68
4	Tancang	Rhizophoraceae	<i>Bruguiera gymnorrhiza</i>	2	10.53
<i>Total</i>					1,542.10

### 3.2. Above Ground Biomass (AGB (tons/ha), Carbon Stock per Hectare, Total of CO<sub>2</sub> Sequestration, and Vegetation Potential to Produce O<sub>2</sub>)

Figure 2 showed that the diameter distribution of saplings at the Mangrove Forest Tourism area in the Protected Area of Langsa ranged from 3.18 to 9.65 cm. The highest number of individuals was found in the diameter class of 3.18 – 3.89 cm (102 individuals), followed by 3.90 – 4.61 cm (86 individuals), 4.62 – 5.33 cm (49 individuals), and 5.34 – 6.06 cm (21 individuals). The remaining individuals were distributed in the diameter classes of 6.06 – 6.77 cm (6 individuals), 6.78 – 7.49 cm (3 individuals), and 7.50 – 8.21 cm and 8.94 – 9.65 cm, with 1 individual each. This condition is considered normal because smaller diameter classes generally contain a greater number of individuals compared to larger diameter classes. This finding is consistent with the study by [31], which reported that the mangrove forest in Sapa Village, South Minahasa Regency, exhibited a normal natural regeneration pattern, as the number of individuals with a lower diameter (10 – <20 cm) was higher than those in the 20 – <30 cm diameter class.



**Figure 2.** Distribution of sapling diameter of Langsa Mangrove Forest Tourism Area

Table 4 displays that the highest total biomass (tons/ha) was recorded in plot 19, at 66.21 tons/ha. Total biomass (tons/ha) is influenced by tree diameter and the number of individuals per plot. Plot 19 consisted of 34 sapling individuals with diameter ranges of 3.18–7.32 cm. According to [32], biomass is defined as the total weight or volume of all organisms within a particular area or volume. The findings of [33] support this, showing that stand biomass significantly influences the potential carbon stored. Biomass values within each diameter class vary with the number of trees in that class. Tree diameter plays an important role in determining biomass as larger tree diameters correspond to greater biomass storage. As plants age increased, the amount of biomass tends to increase. This increase occurs due to the growth in tree stem diameter [34]. The highest biomass was due to this plot containing of 41 individuals of *Rhizophora mucronata*, including five trees with diameters of 41–50 cm.

**Table 4.** Aboveground biomass (tons/ha), carbon stock per hectare, carbon stock per hectare, total of CO<sub>2</sub> sequestration, and vegetation potential to produce O<sub>2</sub> per plot

The Number of Plot	Aboveground Biomass (tons/ha)	Carbon Stock (tons C/ha)	Total of CO <sub>2</sub> Sequestration (tons CO <sub>2</sub> /ha)	Vegetation Potential to Produce O <sub>2</sub> (tonO <sub>2</sub> /ha)
1	28.97	13.62	49.93	36.31
2	9.96	4.68	17.17	12.49
3	22.05	10.37	38.01	27.64
4	19.25	9.05	33.18	24.13
5	20.78	9.77	35.81	26.04
6	21.30	10.01	36.70	26.69
7	23.36	10.98	40.25	29.27
8	22.59	10.61	38.92	28.31
9	30.04	14.12	51.77	37.65
10	14.53	6.83	25.03	18.21
11	27.95	13.13	48.16	35.02
12	19.02	8.94	32.77	23.83
13	37.83	17.78	65.16	47.41
14	29.88	14.04	51.49	37.45
15	18.77	8.82	32.35	23.53
16	29.66	13.94	51.12	37.18
17	52.95	24.89	91.26	63.30
18	30.52	14.34	52.59	38.25
19	66.21	31.12	114.10	82.98
Total	525.61	247.04	905.80	655.69
Mean ± SD	27.66 ± 13.18	13.00 ± 6.20	47.67 ± 22.71	34.51 ± 16.20

The highest carbon stock (tons C/ha) was found in plot 19, with a value of 31.12 tons C/ha (Table 4). This is consistent with the above ground biomass values in Table 4, where plot 19 has the highest AGB. The carbon stock (tons C/ha) is strongly influenced by biomass (tons/ha). This aligns with [35], which stated that an increase in biomass content will follow any increase in carbon stock. This explains that carbon and biomass have a positive relationship; therefore, any factor that increases or decreases biomass will also increase or decrease carbon stock. According to [36], carbon stock potential can be assessed from the existing stand biomass. The amount of carbon stored in each part of the tree is influenced by its biomass. Therefore, any increase in biomass will be accompanied by an increase in carbon stock. A study by [37] notes that across three study locations (sites 46, 48, and 49), greater aboveground biomass corresponds to increase total carbon stocks.

The highest carbon sequestration (tons CO<sub>2</sub>/ha) and potential of vegetation to produce O<sub>2</sub> (tons O<sub>2</sub>/ha) in the Mangrove Forest Tourism Area of Langsa occurred in plot 19, with a value of 114.10 tons CO<sub>2</sub>/ha and 82.98 tons O<sub>2</sub>/ha (Table 2). Aboveground biomass (tons/ha), carbon stock (tons C/ha), and carbon sequestration (tons CO<sub>2</sub>/ha) generally show a positive correlation with the vegetation's potential to produce O<sub>2</sub> (tons O<sub>2</sub>/ha). According to [32], carbon stock estimates reflect tree's ability to store carbon. The amount of carbon stored is influenced by the tree's biomass, soil fertility, and the vegetation's capacity to absorb carbon. Research by [38] show that a plant's ability to produce oxygen is strongly influenced by its size. Oxygen production occurs when green plants absorb CO<sub>2</sub> with the help of sunlight and subsequently release O<sub>2</sub> into the atmosphere as a result of photosynthesis. The potential of vegetation to generate oxygen reflects the extent to which an ecosystem, such as forests, grasslands, or other vegetation types, can produce oxygen through this process. Moreover, the capacity of vegetation to produce oxygen serves as an indicator of environmental health and an ecosystem's ability to absorb carbon dioxide.

**Table 5.** Aboveground biomass (tons/ha), total carbon stock per hectare, carbon stock per hectare, total of CO<sub>2</sub> sequestration, and vegetation potential to produce O<sub>2</sub> in the Langsa Mangrove Forest Tourism Area

Tree density (ind/ha)	Aboveground biomass (tons/369.01 ha)	Carbon stock (tonsC/369.01 ha)	Total of CO <sub>2</sub> Sequestration (tons CO <sub>2</sub> /369.01 ha)	Vegetation Potential to Produce O <sub>2</sub> (tonO <sub>2</sub> /369.01 ha)
1542.10	10208.12 ± 4864.07	4797.91 ± 2286.18	17591.48 ± 8381.94	12734.54 ± 5979.70

Table 5 shows that total AGB, carbon stock, total of CO<sub>2</sub> sequestration and vegetation potential to produce O<sub>2</sub> were 10208.12 ± 4864.07 tons, 4797.91 ± 2286.18 tons C, 17591.48 ± 8381.94 tons CO<sub>2</sub> and 12734.54 ± 5979.70 ton O<sub>2</sub> respectively. These figures demonstrate the significant contribution of this specific mangrove to regional carbon budget and environmental quality. The values of total AGB, carbon stock, total CO<sub>2</sub> sequestration, and vegetation potential to produce O<sub>2</sub> were different because of the type of forest. Similar findings in these ranges were reported by [39] in Lambusango forests and pine forests in Buton District, Southeast Sulawesi Province, Indonesia.

#### 4. Conclusion

In conclusion, the Mangrove Forest Tourism Area exhibits a high aboveground biomass (10,208.12 ± 4,864.07 t), substantial carbon stock (4,797.91 ± 2,286.18 t C), considerable CO<sub>2</sub> sequestration capacity (17,591.48 ± 8,381.94 t CO<sub>2</sub>), and strong potential for oxygen (O<sub>2</sub>) production (12,734.54 ± 5,979.70 t O<sub>2</sub>). These findings highlight the ecological importance of the area. Therefore, continued protection and regular monitoring are recommended to maintain its biomass and carbon sequestration functions. Strengthening conservation efforts, supporting community-based rehabilitation, and integrating the area into carbon policy and ecotourism programs will further enhance and sustain its ecological benefits.

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