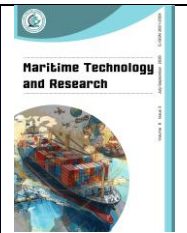




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Research Article

Biomass and carbon stock in restored mangrove forests: Evidence from Indonesia

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Article information	Abstract
Received: November 25, 2025 Revision: March 7, 2026 Accepted: March 30, 2026	Mangrove restoration is widely recognized as a nature-based solution for enhancing blue carbon storage and mitigating climate change. However, quantitative assessments of biomass and carbon recovery in restored mangrove systems remain limited, particularly in Indonesia's ecotourism landscapes. This study evaluated aboveground and belowground biomass and associated carbon stocks in rehabilitated mangrove stands in the Balang Baru Ecotourism Area, Jeneponto Regency, South Sulawesi. Field measurements were conducted in April 2025 across five sampling stations, with 15 nested plots. Tree diameter at breast height (DBH) and height were recorded for all individuals with DBH ≥ 5 cm. Aboveground biomass (AGB) and belowground biomass (BGB) were estimated using allometric equations, and carbon stocks were derived using standard biomass-to-carbon conversion factors. The results indicated substantial biomass accumulation in the restored mangrove stands. Mean AGB and BGB were estimated at 95.20 Mg ha ⁻¹ and 41.23 Mg ha ⁻¹ , respectively. Corresponding carbon stocks averaged 45.70 Mg C ha ⁻¹ for aboveground carbon (AGC) and 16.08 Mg C ha ⁻¹ for belowground carbon (BGC). Biomass and carbon stocks varied spatially among stations, with the highest values recorded at Station 5 (AGB: 126.19 Mg ha ⁻¹) and the lowest at Station 4 (AGB: 67.30 Mg ha ⁻¹). However, one-way ANOVA showed no statistically significant differences among stations ($p > 0.05$), indicating relatively comparable biomass recovery across the rehabilitated area. These findings suggest that restored mangrove stands in Balang Baru have developed substantial biomass and carbon storage capacity despite their relatively young age. The results highlight the potential contribution of community-based mangrove restoration to blue carbon initiatives and coastal ecosystem recovery. Continued long-term monitoring, along with the inclusion of soil organic carbon assessments, is recommended to obtain more comprehensive estimates of total carbon storage in restored mangrove ecosystems.
Keywords Biomass carbon stock; Blue carbon; Climate change mitigation; Ecotourism; Mangrove restoration	

1. Introduction

Mangrove ecosystems are among the most productive and ecologically valuable coastal habitats, providing a wide range of ecosystem services that contribute significantly to local communities and global climate regulation. These intertidal forests act as natural buffers against coastal erosion, storm surges, and sea-level rise, while simultaneously serving as nurseries for numerous marine species that sustain local fisheries and coastal economies (Friess et al., 2022; Kathiresan, 2021). Beyond their ecological functions, mangroves are increasingly recognized for their crucial role in mitigating climate change through carbon sequestration and long-term carbon storage, often referred to as “blue carbon.” Their capacity to accumulate biomass aboveground and belowground, as well as to store substantial amounts of carbon in soils, makes mangroves disproportionately important relative to their global coverage, which represents less than 1 % of global tropical forest area (Leal & Spalding, 2022; Friess et al., 2023).

Despite their ecological importance, mangroves have experienced extensive degradation due to the expansion of aquaculture, agricultural conversion, coastal infrastructure development, and urbanization (Jalil et al., 2020; Alongi, 2023). Indonesia, which hosts the largest extent of mangroves globally, has not been exempt from these pressures. Historical losses have reduced ecological resilience, weakened coastal protection, and contributed to greenhouse gas emissions by releasing previously stored carbon. In response, mangrove restoration has become a national priority, supported by government programs and community-driven initiatives aimed at recovering ecological functions and enhancing climate mitigation potential (Sasmito et al., 2023; Malik et al., 2023).

Although mangrove restoration efforts are increasingly widespread, their ecological effectiveness remains uneven. Success is often evaluated through survival rates or stand density, yet these metrics alone do not capture ecosystem functionality. A more comprehensive evaluation requires assessing structural recovery, biomass accumulation, and carbon stock dynamics, which more directly reflect ecological performance and climate mitigation potential (Arifanti et al., 2022; Alongi, 2023). Importantly, biomass recovery trajectories in restored mangroves are strongly influenced by stand age, species composition, hydrological conditions, and site history (Sasmito et al., 2019; Gerona-Daga & Salmo, 2022).

Studies across Southeast Asia show that restored mangroves can recover biomass and carbon stocks over time, though recovery rates vary considerably depending on restoration age and environmental conditions. Aboveground biomass often increases relatively rapidly, whereas belowground biomass and soil carbon pools may respond more gradually. Species-specific growth strategies also influence biomass allocation patterns; for example, *Rhizophora* species typically contribute substantial aboveground biomass, whereas *Avicennia* species may exhibit distinct growth responses to salinity gradients and sediment characteristics (Gerona-Daga & Salmo, 2022).

Several studies have evaluated mangrove biomass and carbon stocks in Sulawesi and other parts of Indonesia. For example, Malik et al. (2020) reported carbon stock dynamics in restored mangrove ecosystems in Sinjai District, South Sulawesi, while studies conducted in Baluno, West Sulawesi, have quantified biomass and carbon storage capacity in mangrove conservation areas (Carong et al., 2024). These studies provide important regional benchmarks for understanding mangrove carbon dynamics in Sulawesi. However, most previous investigations have focused primarily on natural mangrove stands or single restoration sites, with limited attention given to restored mangrove ecosystems that simultaneously function as community-based ecotourism landscapes.

Ecotourism has increasingly been promoted as a strategy to enhance the sustainability of mangrove restoration by generating economic incentives for local communities to conserve and manage restored ecosystems (Malik et al., 2024, 2025; Hafezi et al., 2023). Nevertheless, integrating ecological restoration with tourism development raises important questions regarding ecosystem

recovery and ecological integrity. For instance, it remains unclear whether restored mangroves located within ecotourism areas exhibit structural development and biomass accumulation patterns comparable to those observed in other restored or natural mangrove systems. Addressing these questions is essential to evaluating the ecological credibility of restoration initiatives that claim environmental and climate-mitigation benefits.

The Balang Baru Ecotourism Area in Jeneponto Regency, South Sulawesi, represents a progressively restored mangrove landscape shaped by sequential rehabilitation efforts. Historical satellite imagery indicates that the area was largely devoid of mangrove vegetation in the mid-1980s, followed by gradual establishment by the mid-2000s. Documented planting activities were conducted in 2012 at specific stations, and additional rehabilitation initiatives were implemented in 2020 in collaboration with the World Wide Fund for Nature (WWF) Indonesia (WWF-Indonesia, 2020). These successive interventions indicate that the site constitutes a mixed-age restored mangrove system influenced by both community-based and NGO-supported restoration programs. Despite its growing socio-economic role as an ecotourism destination, systematic ecological evaluations—particularly concerning biomass accumulation and carbon storage across different restoration phases—remain scarce.

Most studies on mangrove carbon dynamics in Indonesia focus on natural stands or broad regional assessments, with comparatively fewer investigations targeting site-specific restored systems and their internal spatial variability. Moreover, limited attention has been given to biomass allocation patterns between aboveground and belowground pools as indicators of structural development in restored ecotourism landscapes. Addressing these dimensions is essential to strengthening the evaluation of restoration performance and to improving the scientific foundation of blue carbon initiatives at local scales.

Despite increasing interest in blue carbon ecosystems, empirical assessments that simultaneously evaluate biomass recovery, carbon storage, and structural development in mixed-age, ecotourism-associated restored mangrove systems remain limited. Such integrated assessments are important to understanding how restoration outcomes evolve under combined ecological and socio-economic pressures.

Therefore, this study aims to quantify and analyze aboveground and belowground biomass and associated carbon stocks within the restored mangrove stands of the Balang Baru Ecotourism Area. Specifically, the objectives are threefold: (1) to assess stand structure and species composition as baseline ecological characteristics; (2) to estimate aboveground and belowground biomass and carbon stocks across multiple stations and evaluate spatial trends; and (3) to interpret biomass allocation patterns and structural recovery in relation to restoration history and site conditions. By integrating field-based biomass estimation with restoration timeline reconstruction, this study contributes to a more nuanced understanding of ecological performance in mixed-age restored mangrove systems and provides evidence to inform restoration management and local-scale blue carbon strategies.

2. Material and methods

2.1 Study area

This study was conducted in the Balang Baru Ecotourism Area in Tarowang District, Jeneponto Regency, South Sulawesi Province, Indonesia. Geographically, the site lies between 5°36'30.78"S - 5°36'44.95"S and 119°51'47.50"E - 119°52'10.14"E, directly facing the Flores Sea (**Figure 1**). The area covers an estimated 5.86 hectares of rehabilitated mangrove forest, which has been developed into a community-based ecotourism destination.

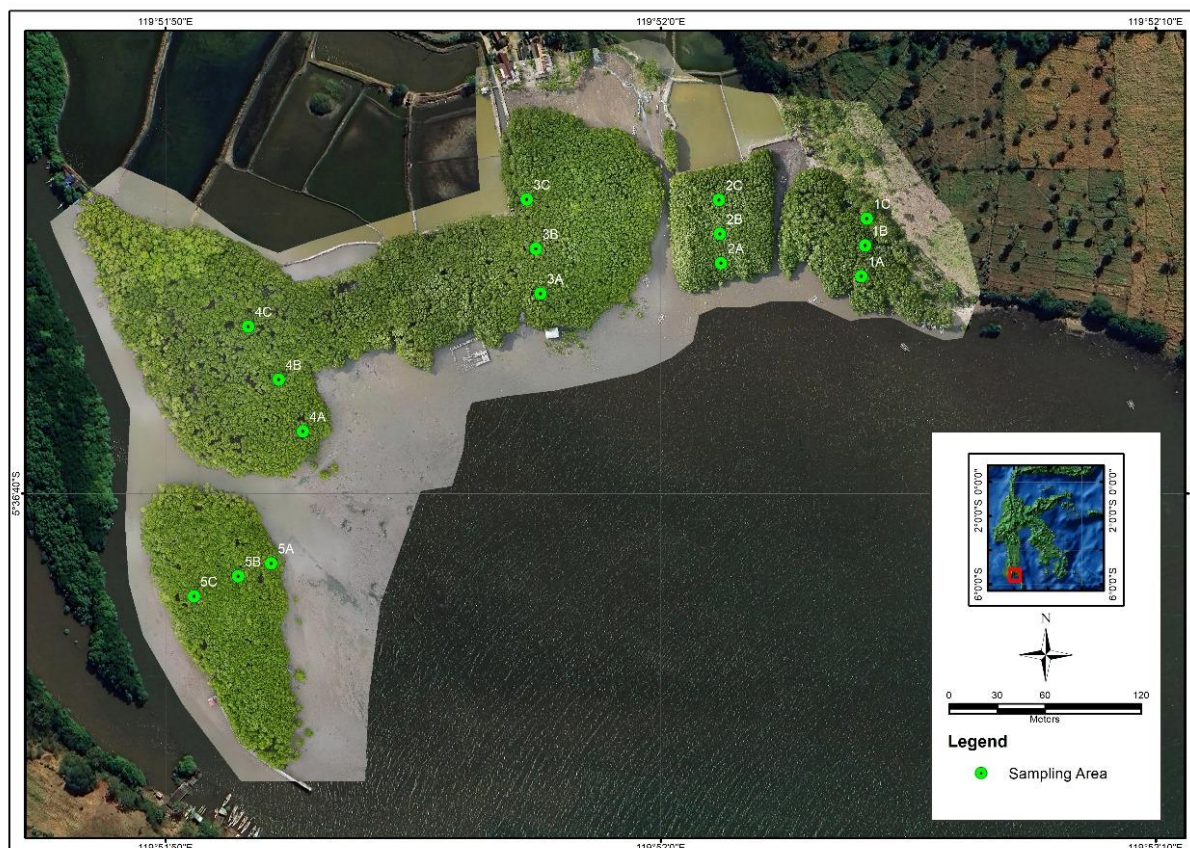


Figure 1 Map of the Balang Baru Ecotourism Area, Tarowang District, Jeneponto Regency, South Sulawesi, Indonesia, showing the five sampling stations with three replicate plots each. The green dots represent the sampling plots for biomass and carbon stock measurements. The inset map shows the study site's location within South Sulawesi Province.

Balang Baru is situated along the arid southern coast of South Sulawesi, characterized by relatively low rainfall (64 - 642 mm/month) and average temperatures ranging from 22 to 23°C in 2024 (BPS Kabupaten Jeneponto, 2025). The coastal system is influenced by semi-diurnal tides, which create periodic inundation patterns that support mangrove establishment and growth.

Historically, this coastline was subject to extensive mangrove clearance for aquaculture ponds and for firewood collection, resulting in severe ecological degradation and the loss of natural coastal protection. Restoration initiatives began in the early 2000s through community-based and local government replanting programs, primarily using *Rhizophora mucronata*. Historical satellite imagery analysis indicates that mangrove vegetation was largely absent in the mid-1980s, followed by progressive establishment by the mid-2000s. A documented planting event occurred in 2012 at specific locations (corresponding to Station 2 in this study), and additional rehabilitation activities were implemented in 2020 in collaboration with the WWF Indonesia (WWF-Indonesia, 2020). These sequential interventions indicate that the study area represents a mixed-age restored mangrove system shaped by multiple rehabilitation phases.

Currently, the Balang Baru mangroves provide shoreline stabilization, habitat for coastal fisheries, and carbon storage functions, while also supporting ecotourism activities that generate alternative livelihoods for local communities.

2.2 Data collection

Field data were collected in April 2025 within the restored mangrove stands of the Balang Baru Ecotourism Area. Five sampling stations were established to represent spatial variability across

the rehabilitation area (**Figure 1**). Stations were selected to capture variation in stand structure, apparent restoration history, and site conditions (e.g., proximity to the shoreline and tidal exposure), based on field reconnaissance and interpretation of historical imagery.

Each station consisted of three replicate plots, for a total of 15. For tree-level measurements, 10×10 m plots were established. Nested subplots of 5×5 m and 1×1 m were used to assess saplings and seedlings, respectively, following standard mangrove vegetation survey protocols. All trees with a diameter at breast height (DBH) ≥ 5 cm were measured for DBH using a diameter tape and for total height using a clinometer. For multi-stemmed individuals, DBH was measured on each stem and converted to an equivalent single-stem DBH following standard forestry procedures. Saplings (DBH < 5 cm, height ≥ 1.5 m) and seedlings (height < 1.5 m) were counted within their respective subplots (Malik et al., 2015; 2020).

Species identification was carried out in the field using regional mangrove identification guides, and voucher specimens were collected for verification when necessary. Geographic coordinates of each plot were recorded using a handheld GPS unit with an accuracy of ± 3 m.

2.3 Data analysis

The density of mangrove trees (D_i , trees ha^{-1}) and basal area (BA , $\text{m}^2 \text{ha}^{-1}$) were determined using Eqs. (1) and (2), following the approach of Malik et al. (2015; 2020):

$$D_i = n_i/A \quad (1)$$

where: n_i = number of mangrove tree of species i ; A = total sample observation area (ha);

$$BA = (\pi \times \text{DBH}^2)/4 \quad (2)$$

where DBH is the diameter of the breast height.

To estimate the aboveground biomass (AGB) and belowground biomass (BGB) of mangroves, allometric Eqs. (3) and (4) developed by Komiyama et al. (2005) were applied:

$$\text{AGB} = 0.251 \times \rho \times \text{DBH}^{2.46} \quad (3)$$

$$\text{BGB} = 0.199 \times \rho^{0.899} \times \text{DBH}^{2.22} \quad (4)$$

where ρ represents species-specific wood density (g cm^{-3}). The wood density values were adopted from Kauffman and Donato (2012), which provide standardized parameters widely used in mangrove biomass assessments.

Further, to estimate the aboveground carbon (AGC) and belowground carbon (BGC) stocks, Eqs. (5) and (6) were used, based on Kauffman and Donato (2012):

$$\text{AGC} = \text{AGB} \times 0.48 \quad (5)$$

$$\text{BGC} = \text{BGB} \times 0.39 \quad (6)$$

where 0.48 and 0.39 represent default carbon fractions for aboveground and belowground biomass, respectively.

This study focused exclusively on tree biomass carbon pools; soil organic carbon was not measured.

2.4 Statistical analysis

One-way Analysis of Variance (ANOVA) was used to examine potential differences in AGB, BGB, AGC, and BGC among the five sampling stations. Before analysis, data were tested for

normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) to verify ANOVA assumptions. A significance level of $\alpha = 0.05$ was applied.

Where statistical differences were not detected ($p > 0.05$), observed variations among stations were interpreted as spatial trends rather than statistically significant differences. All statistical analyses were conducted in Microsoft Excel 2023 using the Data Analysis ToolPak.

3. Results

3.1 Stand density and population structure

A total of 1,211 mangrove individuals were recorded across all sampling stations in the Balang Baru Ecotourism Area, consisting of trees (53.26 %), seedlings (36.09 %), and saplings (10.65 %). Mature trees represented the dominant growth stage, indicating that the rehabilitated mangrove stands have developed a relatively stable forest structure.

Mangrove stand density varied across stations (**Table 1**). Tree density was highest at Station 2, averaging 64.0 ± 5.0 individuals per plot, whereas the lowest density occurred at Station 5 with 27.0 ± 4.0 individuals per plot. Saplings were relatively evenly distributed among stations, ranging from 7.3 ± 1.5 individuals at Station 2 to 9.3 ± 2.5 individuals at Station 4. Seedlings were more abundant than saplings and showed notable spatial variability, with the highest density recorded at Station 3 (34.7 ± 3.1 individuals) and the lowest at Station 2 (20.3 ± 5.9 individuals).

The presence of seedlings across all stations indicates ongoing natural regeneration within the restored mangrove stands, suggesting the potential for continued forest development and structural stability.

Table 1 Mean density of mangrove individuals at different growth stages across sampling stations in the Balang Baru Ecotourism Area (mean $\pm$ SD).

Station	Trees	Saplings	Seedlings	Total
1	46.0 ± 3.0	8.0 ± 1.0	29.0 ± 2.6	82.0 ± 3.0
2	64.0 ± 5.0	7.3 ± 1.5	20.3 ± 5.9	91.7 ± 2.5
3	45.3 ± 3.1	8.3 ± 3.5	34.7 ± 3.1	88.3 ± 1.5
4	32.7 ± 5.0	9.3 ± 2.5	31.0 ± 5.6	73.0 ± 9.2
5	27.0 ± 4.0	9.3 ± 1.5	30.7 ± 3.1	67.0 ± 2.6

3.2 Structural characteristics of mangrove stands

Two mangrove species were recorded within the study area: *R. mucronata* and *A. marina*. *R. mucronata* were the dominant species across most stations, whereas *A. marina* occurred only at Stations 4 and 5.

The structural characteristics of mangrove trees showed moderate variation between species (**Table 2**). The mean diameter at breast height (DBH) of *R. mucronata* was 0.106 ± 0.007 m, while *A. marina* exhibited a slightly larger mean DBH of 0.120 ± 0.020 m. Similarly, the average tree height of *R. mucronata* was 12.97 ± 0.27 m, slightly higher than that of *A. marina* (12.59 ± 0.97 m).

Basal area measurements reflected these diameter differences. The mean basal area of *R. mucronata* was 0.009 ± 0.002 m², whereas *A. marina* recorded a higher value of 0.011 ± 0.004 m². Despite its limited distribution within the study area, *A. marina* demonstrated relatively strong growth, as indicated by DBH and basal area.

Table 2 Structural characteristics of mangrove trees in the Balang Baru Ecotourism Area (mean $\pm$ SD).

Species	DBH (m)	Height (m)	Basal Area (m ²)
<i>Rhizophora mucronata</i>	0.106 $\pm$ 0.007	12.97 $\pm$ 0.27	0.009 $\pm$ 0.002
<i>Avicennia marina</i>	0.120 $\pm$ 0.020	12.59 $\pm$ 0.97	0.011 $\pm$ 0.004

3.3 Aboveground and belowground biomass and carbon stocks

The estimated aboveground biomass (AGB) and belowground biomass (BGB) varied across the five sampling stations (**Table 3**). The highest mean AGB was recorded at Station 5 (126.19 $\pm$ 17.16 Mg ha⁻¹), followed by Station 1 (107.67 $\pm$ 1.04 Mg ha⁻¹) and Station 3 (97.75 $\pm$ 2.37 Mg ha⁻¹). In contrast, Station 4 exhibited the lowest AGB value (67.30 $\pm$ 0.20 Mg ha⁻¹).

A similar pattern was observed for BGB. The highest belowground biomass was also found at Station 5 (51.80 $\pm$ 5.90 Mg ha⁻¹), while Station 4 recorded the lowest value (30.77 $\pm$ 0.08 Mg ha⁻¹). Stations with larger trees tended to exhibit higher biomass.

When converted to carbon stocks, the same spatial pattern was observed. Aboveground carbon (AGC) ranged from 32.30 $\pm$ 0.10 Mg C ha⁻¹ at Station 4 to 60.57 $\pm$ 8.24 Mg C ha⁻¹ at Station 5. Belowground carbon (BGC) ranged from 12.00 $\pm$ 0.03 Mg C ha⁻¹ at Station 4 to 20.20 $\pm$ 2.30 Mg C ha⁻¹ at Station 5.

At the landscape level, the overall mean values across all stations were 95.20 $\pm$ 10.56 Mg ha⁻¹ for AGB, 41.23 $\pm$ 3.83 Mg ha⁻¹ for BGB, 45.70 $\pm$ 5.07 Mg C ha⁻¹ for AGC, and 16.08 $\pm$ 1.49 Mg C ha⁻¹ for BGC.

One-way ANOVA showed no statistically significant differences among stations for AGB ($p = 0.525$), BGB ($p = 0.518$), AGC ($p = 0.525$), or BGC ($p = 0.519$), suggesting that biomass and carbon stocks are relatively comparable across the restored mangrove stands.

Table 3 Aboveground biomass (AGB), belowground biomass (BGB), aboveground carbon (AGC), and belowground carbon (BGC) across sampling stations in the Balang Baru Ecotourism Area (mean $\pm$ SE).

Station	AGB (Mg ha ⁻¹)	BGB (Mg ha ⁻¹)	AGC (Mg C ha ⁻¹)	BGC (Mg C ha ⁻¹)
1	107.67 $\pm$ 1.04	46.66 $\pm$ 0.39	51.68 $\pm$ 0.50	18.20 $\pm$ 0.15
2	77.08 $\pm$ 0.55	34.77 $\pm$ 0.23	37.00 $\pm$ 0.26	13.56 $\pm$ 0.09
3	97.75 $\pm$ 2.37	42.15 $\pm$ 0.86	46.92 $\pm$ 1.14	16.44 $\pm$ 0.33
4	67.30 $\pm$ 0.20	30.77 $\pm$ 0.08	32.30 $\pm$ 0.10	12.00 $\pm$ 0.03
5	126.19 $\pm$ 17.16	51.80 $\pm$ 5.90	60.57 $\pm$ 8.24	20.20 $\pm$ 2.30
Grand mean	95.20 $\pm$ 10.56	41.23 $\pm$ 3.83	45.70 $\pm$ 5.07	16.08 $\pm$ 1.49

3.4 Spatial patterns of biomass and carbon storage

Although statistical tests indicated no significant differences among stations, spatial variability in biomass and carbon stocks remained evident. Station 5 consistently exhibited the highest values for AGB, BGB, AGC, and BGC, indicating relatively greater biomass accumulation at this location. In contrast, Station 4 showed the lowest values across most biomass and carbon metrics.

These variations may reflect differences in stand structure, tree size, and site conditions among stations within the rehabilitated mangrove area. Nonetheless, the overall distribution of biomass and carbon stocks suggests that the restored mangrove stands in Balang Baru have developed to relatively comparable levels of structural growth.

These findings provide an empirical basis for evaluating the effectiveness of mangrove restoration in supporting biomass accumulation and carbon storage within the Balang Baru ecotourism landscape.

4. Discussion

The results of this study demonstrate that restored mangrove stands in the Balang Baru Ecotourism Area have developed measurable biomass and carbon storage capacity despite being relatively young restoration sites. The mean AGB was estimated at $95.20 \pm 10.56 \text{ Mg ha}^{-1}$, while BGB reached $41.23 \pm 3.83 \text{ Mg ha}^{-1}$. In terms of carbon storage, the mean AGC was $45.70 \pm 5.07 \text{ Mg C ha}^{-1}$, and BGC averaged $16.08 \pm 1.49 \text{ Mg C ha}^{-1}$. These findings indicate that mangrove rehabilitation in Balang Baru has contributed to the recovery of important ecosystem functions, particularly biomass accumulation and carbon sequestration.

The biomass values recorded in this study fall within the range reported for restored mangrove ecosystems in tropical regions. For example, restored mangrove stands dominated by *Rhizophora* species in Southeast Asia have been reported to accumulate 80 - 140 Mg ha^{-1} of aboveground biomass, depending on stand age and site conditions (Kauffman et al., 2014). Similarly, rehabilitated mangrove forests in Java have shown AGB values ranging from 70 to 120 Mg ha^{-1} after approximately 15 - 20 years of growth (Sasmito et al., 2019). Compared with these studies, the biomass values observed in Balang Baru are within the expected range for restored mangrove stands, suggesting that the rehabilitation program has successfully supported forest structural development. However, the carbon stocks measured in this study remain lower than those reported for mature natural mangrove forests in Indonesia, which can exceed 100 Mg C ha^{-1} of aboveground carbon (Alongi et al., 2016). This difference is likely related to the relatively younger age of the restored stands, as biomass carbon accumulation in mangroves generally increases with stand maturity and structural complexity.

Stand structure appears to play an important role in explaining the observed biomass accumulation. The mangrove community in Balang Baru was dominated by *R. mucronata*, while *A. marina* was found at only two stations. The dominance of *R. mucronata* is consistent with many mangrove restoration programs in Indonesia, where this species is commonly used due to its relatively high survival rate and adaptability to intertidal environments. The structural characteristics recorded in this study, including a mean DBH of $0.106 \pm 0.007 \text{ m}$ and a mean height of $12.97 \pm 0.27 \text{ m}$ for *R. mucronata*, indicate that the rehabilitated stands have undergone substantial growth and structural development. In addition, the presence of seedlings across all sampling stations suggests that natural regeneration is occurring within the restored mangrove stands, which is an important indicator of ecological recovery and long-term forest sustainability.

Spatial variability in biomass and carbon storage was observed among the sampling stations. Station 5 consistently recorded the highest values for AGB ($126.19 \pm 17.16 \text{ Mg ha}^{-1}$), BGB ($51.80 \pm 5.90 \text{ Mg ha}^{-1}$), AGC ($60.57 \pm 8.24 \text{ Mg C ha}^{-1}$), and BGC ($20.20 \pm 2.30 \text{ Mg C ha}^{-1}$), while Station 4 showed the lowest values for most biomass and carbon parameters. Such spatial variation may reflect differences in local environmental conditions, including tidal inundation patterns, sediment characteristics, and seedling survival rates. Previous studies have shown that hydrological conditions, salinity gradients, and sediment properties strongly influence mangrove growth and biomass accumulation (Ahmed et al., 2023; Dittmann et al., 2022). These site-specific factors likely contributed to the differences observed among stations in the Balang Baru restoration area.

Despite these variations, statistical analysis indicated that the differences in biomass and carbon stocks among stations were not statistically significant ($p > 0.05$). This suggests that, at the landscape scale, the restored mangrove stands exhibit relatively comparable levels of biomass accumulation and carbon storage. Such patterns may indicate that the restoration program has produced relatively uniform stand development across the study area. Similar findings have been

reported in other mangrove restoration sites where plantation-based restoration results in relatively homogeneous stand structures, particularly when dominated by a single species such as *Rhizophora*.

From a broader ecological perspective, the results highlight the potential of restored mangrove ecosystems to mitigate climate change through blue carbon storage. Indonesia contains one of the largest mangrove areas in the world and plays a critical role in global blue carbon conservation (Vinata et al., 2024). Although the carbon stocks measured in Balang Baru are lower than those of mature mangrove forests, the values reported here demonstrate that restored mangrove ecosystems can begin accumulating significant biomass and carbon within a relatively short time after rehabilitation. This supports the role of mangrove restoration as an important nature-based solution for climate change mitigation, while simultaneously providing ecosystem services such as coastal protection and supporting ecotourism development.

However, several limitations of this study should be acknowledged. First, the analysis focused only on aboveground and belowground biomass, while soil organic carbon (SOC) was not measured. Previous studies have shown that soil carbon represents the largest carbon pool in mangrove ecosystems and may account for more than half of the total ecosystem carbon stock (Murdiyarso et al., 2015; Donato et al., 2011; Malik et al., 2023). Consequently, the carbon values reported in this study likely underestimate the total carbon storage capacity of the Balang Baru mangrove ecosystem. Second, biomass estimates were derived using generalized allometric equations, which may not fully capture local variations in growth conditions or wood density.

Future research should therefore incorporate soil carbon measurements, apply species- or site-specific allometric models, and use remote sensing to estimate biomass and carbon stocks at broader spatial scales. Integrating ecological assessments with socio-economic analyses, particularly related to community participation and ecotourism development, would also provide a more comprehensive understanding of the long-term sustainability of mangrove restoration initiatives in Balang Baru.

5. Conclusions

This study demonstrates that restored mangrove stands in the Balang Baru Ecotourism Area have developed measurable biomass accumulation and carbon storage capacity, indicating positive ecological recovery following rehabilitation efforts. The restored mangroves recorded a mean aboveground biomass of $95.20 \pm 10.56 \text{ Mg ha}^{-1}$ and belowground biomass of $41.23 \pm 3.83 \text{ Mg ha}^{-1}$, corresponding to $45.70 \pm 5.07 \text{ Mg C ha}^{-1}$ of aboveground carbon and $16.08 \pm 1.49 \text{ Mg C ha}^{-1}$ of belowground carbon, respectively. These findings suggest that mangrove restoration in Balang Baru has already begun to provide important ecosystem functions, including biomass development and carbon sequestration.

The mangrove community was dominated by *R. mucronata*, with limited occurrence of *A. marina*, and seedlings were observed across all stations, indicating ongoing natural regeneration. Although spatial variability in biomass and carbon stocks was observed among sampling stations, statistical analysis showed no significant differences, suggesting that the restored mangrove stands have developed relatively comparable structural conditions across the study area.

Overall, the results highlight the ecological potential of restored mangrove ecosystems to contribute to blue carbon storage and coastal ecosystem recovery. While carbon stocks remain lower than those of mature natural mangrove forests, the observed values indicate that restored mangroves can accumulate substantial biomass and carbon within a relatively short period of restoration. These findings support the role of mangrove rehabilitation as an important nature-based solution for climate change mitigation, while simultaneously enhancing coastal resilience and supporting community-based ecotourism.

Future studies should incorporate soil organic carbon assessments and broader spatial analyses to obtain a more comprehensive estimate of ecosystem carbon stocks and better evaluate the long-term effectiveness of mangrove restoration programs.

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Declaration of generative AI in scientific writing

The authors did not use any AI-assisted tools in the preparation of this manuscript. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRediT author statement

Abd. Rasyid Jalil: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing-original draft, Writing – review & editing. **Abdul Malik:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing-original draft, Writing – review & editing. **Syafiuddin:** Investigation, Validation, Visualization, Writing-original draft, Writing – review & editing. **Muh. Dalvi Mustafa:** Investigation, Software, Validation, Visualization, Writing – review & editing. **Muhammad Dzaky Hurairah Malik:** Investigation, Project administration, Validation, Writing – review & editing. **Muhammad Alif Kamaruddin:** Investigation, Project administration, Software, Writing – review & editing. **Muhammad Salman Eddy Harmawan:** Investigation, Project administration, Software, Writing – review & editing.

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