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Carbon stocks in selected rehabilitated mangrove sites across Indonesia: A multi-site inventory

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ABSTRACT

Although Indonesia possesses 20% of the world's mangroves (3.36 million hectares), these ecosystems face rapid degradation due to land conversion across Sumatra, Kalimantan, Java, and Sulawesi. Mangrove rehabilitation efforts have been slow, with only 130,000 hectares rehabilitated by 2024 against a 600,000-hectare target. Moreover, standardized multi-site carbon stock data from rehabilitated mangroves remain limited due to most research efforts involving single-location studies. This study evaluates carbon stock potential across five rehabilitation sites under World Wildlife Fund Indonesia programs: Pati, Situbondo, Jember, Tarakan, and Jeneponto. Field surveys were conducted across these five distinct sites utilizing a cluster sampling design. A total of 14 plots were established, comprising 10 plots within the rehabilitation zones and 4 external comparison plots. To capture the primary data, these plots were further subdivided into 47 subplots, of which 34 were internal and 13 external. Vegetation and necromass were inventoried using circular plot methods. For soil analysis, sampling was performed using a soil auger at vertical depth intervals ranging from 5 to 200 cm. Soil organic matter was subsequently determined via the loss on ignition method, and total soil carbon stocks were calculated by integrating bulk density, carbon fraction, and the respective horizon depths. The Mann-Whitney pairwise comparisons were applied for total carbon stock comparison among sites. Correction for multiple comparisons was performed using the Bonferroni correction method (28 pairwise tests, adjusted $\alpha = 0.05/28 \approx 0.00179$). The results indicated substantial variation in carbon stocks among rehabilitation sites, ranging from 258.64±105.78 to 802.42±72.00 MgC ha^{-1}. The highest carbon stock was recorded in Pati, which was dominated by sediment carbon at 764.67±69.04 MgC ha^{-1}, while the lowest was observed in Jember. Sediment carbon represents the primary carbon storage component (>80% of total stock). Differences in carbon stocks across locations were not associated with ecosystem conditions or the age of rehabilitation; in contrast, sites with longer rehabilitation periods generally exhibited higher vegetation biomass. Across all rehabilitation sites, necromass contribution remained low (<5%), with its highest density of 4.55±5.87 MgC ha^{-1} recorded in Tarakan. These findings provide a scientific basis for further monitoring and the improvement of mangrove rehabilitation programs by responsible stakeholders.

Keywords: mangrove rehabilitation, carbon stock, mangrove biomass, sediment carbon

INTRODUCTION

Studies in tropical riverine wetlands have demonstrated that mangroves and peat swamps store substantially higher mean carbon stocks (784.5±73.5 and 722.2±63.6 MgC ha^{-1}, respectively) than marsh ecosystems (336.5±38.3 MgC ha^{-1}) (Adame et al., 2015). Wetland ecosystems, including mangroves, have substantial total natural climate solutions (NCS) mitigation potential

(41.1±1.4 $MtCO_2e$ yr^{-1}), with significantly higher mitigation density (12.2 $MgCO_2e$ ha^{-1} yr^{-1}) when compared to terrestrial ecosystems (2.9 $MgCO_2e$ ha^{-1} yr^{-1}) (Novita et al., 2022). In mangrove ecosystems, carbon is stored in both sediment and vegetation biomass (roots, stems, and leaves) (Kauffman et al., 2014). Through photosynthesis, mangrove vegetation absorbs CO_2 from the atmosphere, reinforcing its role as a highly efficient natural carbon sink (Alongi, 2014; Kristensen et al., 2008). Most carbon in mangrove ecosystems, typically exceeding 50% of the total ecosystem stock, is stored within mangrove sediments (Donato et al., 2011). The anaerobic and anoxic conditions of these sediments inhibit organic matter decomposition and facilitate long-term carbon sequestration (Alongi, 2014; Kristensen et al., 2008).

Indonesia holds a highly strategic position in global mangrove ecosystem conservation. According to the national mangrove map produced by the Ministry of Forestry of the Republic of Indonesia based on 2021 data, Indonesia possesses approximately 3.36 million hectares of mangroves (Gunawan et al., 2025). Despite containing approximately 20% of the world's total mangrove area, Indonesia's mangroves continue to decline. Between 2009 and 2019, the estimated annual rate of mangrove deforestation was 18,209 ha yr^{-1} (Arifanti et al., 2022). The loss of mangrove cover through conversion to aquaculture ponds, settlements, and infrastructure not only releases stored carbon into the atmosphere but also degrades ecosystem integrity, disrupting ecological functions such as coastal protection and fish habitat provision (Arifanti et al., 2021). Notably, halting the deforestation of primary and secondary mangroves, when combined with active restoration efforts, could reduce carbon emissions by an amount equivalent to 8% of Indonesia's 2030 forestry sector Nationally Determined Contribution targets (Arifanti et al., 2022). To effectively incorporate mangrove rehabilitation into blue carbon frameworks, it is necessary to obtain verifiable quantitative data on both biomass and soil organic carbon (Alongi, 2020).

Several studies on carbon storage potential in rehabilitated mangroves have been conducted in various areas, including Yanbu, Saudi Arabia (Al-Guwaiz et al., 2021), the Luoyang River Estuary, China (Chen et al., 2021), Thailand (Matsui et al., 2010), as well as several areas in Indonesia, such as Sulawesi (Cameron et al., 2018), Cirebon, Java (Purwanto et al., 2021), and Kupang (Matatula et al., 2023). Some studies have also been conducted at the five focal mangrove rehabilitation sites examined in the present study. At the Pati site, previous studies have examined community structure (Nugraha et al., 2023), changes in mangrove area (Kepel et al., 2018; Prihantoro et al., 2019), as well as bulk density and C:N ratio (Kepel et al., 2018). In Situbondo, studies have focused on mangrove rehabilitation status (Vidayanti et al., 2024), stand density (Insani et al., 2019), canopy cover percentage, mean stem diameter, and sapling density (Zakiyah et al., 2025). At the Jember site, research has included land suitability analysis for mangrove rehabilitation (Rohman, 2014). In Tarakan, mangrove research has focused on stand density (Salim et al., 2019), mangrove litter productivity and decomposition rate (Hardianto et al., 2015), and the rehabilitation dynamics of vegetation (Wiharyanto et al., 2025). At the Jeneponto site, research has examined mangrove vegetation structure (Tang, 2025). Although numerous studies on mangroves have been conducted across the five rehabilitation sites, only the Tarakan site features comprehensive research on carbon storage (Mulyoto et al., 2021). Notably, research conducted at the Jeneponto site (Jalil et al., 2026) only estimated the aboveground carbon (AGC) and belowground carbon (BGC) stocks based on vegetation biomass alone. In Tarakan, the estimated amount of vegetation carbon is 95.28 MgC ha^{-1} (Mulyoto et al., 2021), while in Jeneponto, this figure is 45.70±5.07 MgC ha^{-1} for AGC and 16.08±1.49 MgC ha^{-1} for BGC (Jalil et al., 2026).

Mangrove rehabilitation efforts in Indonesia have been carried out by various stakeholders, including environmental organizations, government institutions, and the private sector. WWF Indonesia, together with corporate partners, has implemented coastal ecosystem rehabilitation programs in various regions of Indonesia. However, these rehabilitation efforts did not involve the collection of the specific, detailed data required for comparative carbon stock assessment. Notably, most mangrove studies conducted in Indonesia lack consistent information about the distribution of biomass and necromass, as well as the depth of organic carbon in the sediment. Currently, no comprehensive assessment of carbon stock inventories across rehabilitated mangrove sites in Indonesia, particularly spanning the five study locations, has been conducted. Additionally, existing studies have rarely integrated above- and below-ground vegetation carbon, necromass, and sediment carbon within a multi-site framework. Moreover, many rehabilitation initiatives have proceeded without detailed ecological evaluations of their carbon storage potential. Therefore, this study provides a multi-site assessment of carbon stocks across rehabilitated mangrove ecosystems in Indonesia, addressing an important gap in the existing literature.

MATERIALS AND METHODS

Study sites and rehabilitation characteristics

This study was conducted at five mangrove rehabilitation and conservation sites established through programs implemented by WWF Indonesia and its corporate partners, with each site characterized by different ecosystem conditions and rehabilitation ages (Table 1). The rehabilitation approaches applied at the study sites included single-species planting and natural regeneration. No hydrological restoration interventions were implemented at any of the sites. The sampling plots established at each site are presented in Figure 1.

Sampling design and data collection

Primary data collection was conducted through field surveys using a clustered plot design to capture the representative ecological variation of the mangrove ecosystems. The study area was clustered based on management and ecological zones, specifically distinguishing between company-assisted rehabilitation areas and existing mangrove coverage. Selection criteria targeted mangrove areas, both within the active rehabilitation sites and reference/comparison plots located

Table 1. Overview of the five rehabilitation areas included in this study

Parameter	Pati	Situbondo	Jember	Tarakan	Jeneponto
Address	Kertomulyo Village, Pati Regency, Central Java	Ketah Village, Situbondo Regency, East Java	Mayangan Village, Jember Regency, East Java	Mangrove and Bekantan Conservation Area (KKMB), Tarakan City, North Kalimantan	Balang Baru Village, Jeneponto Regency, South Sulawesi
Coordinate*	S6°37'53.80" E111°7'23.74"	S7°43'8.29" E113°43'21.29"	S8°22'35.58" E113°24'6.15"	N 3°17'30" E117°34'17"	S5°36'37.74" E119°51'55.26"
Location position	Coastline	Coastline	Riverbank and coastal mangrove area	Coastal mangrove area	Bay
Rehabilitation area (ha)	3	35.60	19.3	12	0.86
Methods	Rehabilitation (single-species planting; 1 × 1 m spacing) and natural regeneration	Rehabilitation (single-species planting; 1 × 1 m spacing) and natural regeneration	Rehabilitation (single-species planting; 3 × 3 m spacing) and natural regeneration	Rehabilitation (single-species planting; 1 × 1 m spacing) and natural regeneration	Rehabilitation (single-species planting; 1 × 1 m spacing) and natural regeneration
Objective	Restoration of degraded coastal ecosystems and support for sustainable ecotourism	Coastal mangrove rehabilitation, ecosystem recovery in buffer areas, and ecotourism zones	Rehabilitation of mangrove ecosystems in aquaculture areas and riparian buffer zones	Ecosystem restoration within conservation areas affected by pond conversion	Mangrove ecosystem recovery and reduction of coastal degradation
Site selection	Degraded abandoned ponds affected by abrasion	Sedimentation coastal buffer area near ponds	Riverbanks and sedimentation ponds within pond area	Degraded former ponds within conservation area	Sedimentation zone suitable for mangrove recovery
Implementation Partner/ Stakeholder	PT Misaja Mitra Pati	PT Ketah Makmur	PT Delta Guna Sukses	PT Mustika Minanusa Aurora	PT Bogatama Marinusa
Year of Replantation	2018–2020	2002–2022	2008–2023	2006–2020	2020
Species	Rhizophora mucronata	Rhizophora mucronata	Rhizophora mucronata	Rhizophora apiculata	Rhizophora mucronata
Maintentance	Waste removal	n.a	Visual inspection of the site condition	Visual inspection of the site condition	Mangrove condition monitoring

Note: * Coordinates were recorded in the WGS 84 geographic coordinate system.

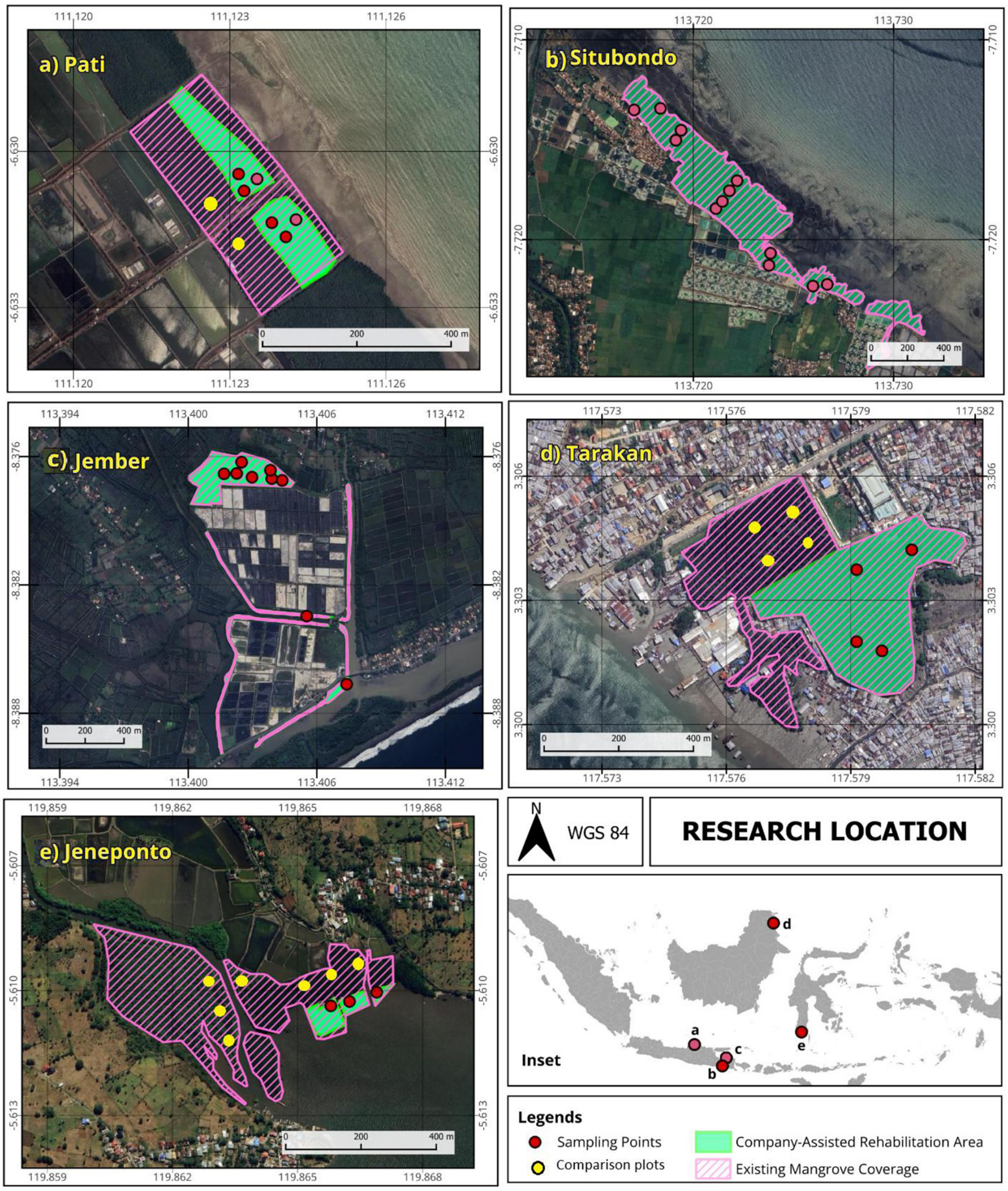

Figure 1. Map of study sites for carbon stock assessment in rehabilitated mangroves

outside the rehabilitation boundaries, to serve as ecological baselines. The rehabilitation site in Pati was divided into two plots representing areas separated by a river. Meanwhile, the site in Jember was divided into three plots based on the site characteristics, consisting of two plots representing riverbank areas and one plot representing a coastal mangrove area. The rehabilitation sites in Tarakan and Jeneponto only included one plot due to the relatively homogeneous conditions at these restoration sites. Across these study sites, a total of 14 plots were identified, comprising 10 plots within the rehabilitation zones and 4 external comparison plots, which were further subdivided into 47 subplots (34 internal and 13 external) (Table 2). To minimize selection bias arising from safety or logistical constraints, sampling points and comparison plots were strategically

Table 2. Number of plots and subplots for each study site

Location	Plot	Sub Plot
Pati	2 + 1*	6 + 2*
Situbondo	3	12
Jember	3	9
Tarakan	1 + 1*	4 + 4*
Jeneponto	1 + 2*	3 + 7*
Total	10 (14*)	34 (47*)

Note: *Plot and subplot outside the rehabilitation site as comparison plots.

distributed across the accessible area while ensuring representation across the different geographic locations and management actions, effectively balancing rigorous spatial coverage with operational feasibility.

A structured procedure for mangrove vegetation sampling was used in this study (Figure 2). At each of the six subplots, the collection of ecosystem and vegetation data was conducted through a series of nested measurements. All saplings and trees with a diameter at breast height (DBH) ≥ 5 cm were measured within a large circle (7-meter radius); smaller seedlings and regeneration vegetation (DBH < 5 cm) were tracked within a smaller, nested circle (2-meter radius) at the subplot's center. Concurrently, downed dead wood/necromass was assessed by establishing and sampling a 12-meter crossed transect (A, B, C, D) intersecting the center of designated subplots (e.g., subplot 3). Soil core samples were collected at each subplot location, as indicated by the triangle symbols in subplot 6, to determine soil carbon content and properties across the entire environmental gradient.

Necromass (dead wood) biomass was quantified within each subplot using a cross-transect sampling design. In each subplot, two 24-m transects were established in an "X" configuration, extending from the central point at a 45° angle. Along each transect, all pieces of dead wood intersecting the transect line were identified and measured, with diameters recorded using digital calipers (Figure 3). Size class-specific sampling was conducted along discrete distance intervals: large woody debris (diameter > 7.6 cm) was measured along the entire 0–12 m segment, and each piece was further classified as sound or decayed based on a tactile tapping test; medium woody debris (2.5–7.6 cm) was sampled within the 2–7 m segment; small woody debris (0.6–2.5 cm) was sampled within the 7–10 m segment; and fine woody debris (< 0.6 cm) was sampled within the 10–12 m segment.

Sediment carbon in mangrove ecosystems was measured by collecting sediment samples using a soil probe at designated sampling points during low tide, avoiding inundated areas, disturbed areas, and crab burrows. Samples were collected

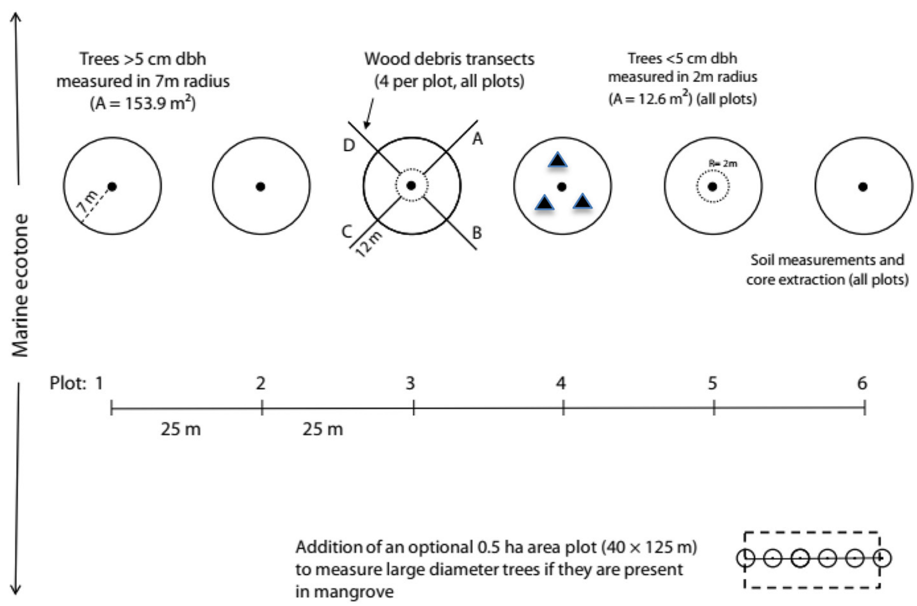

Figure 2. Standard plot design for vegetation sampling (Kauffman and Donato, 2012)

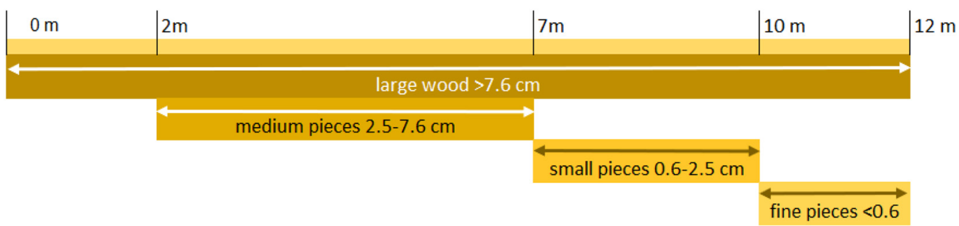

Figure 3. Necromass sampling transect

vertically at specific depth intervals (0–15, 15–30, 30–50, 50–100, 100–200 cm), wrapped in aluminum foil, placed in labeled plastic bags, and promptly transported to the laboratory for analysis. Soil carbon content was analyzed using the loss on ignition (LOI) method, which involves heating soil samples to approximately 550 °C to estimate organic matter loss. Air-dried samples (WS) were dried at 105 °C for 12–24 hours to obtain the dry weight at 105 °C (DW_{105}). The loss on ignition at 105 °C (LOI_{105}) was calculated as $LOI_{105} = 100 \times (WS - DW_{105}) \div WS$. Dried samples were then ignited at 550 °C for 4 hours to determine the weight after ignition (DW_{550}). The loss on ignition at 550 °C (LOI_{550}) was calculated as $LOI_{550} = 100 \times (DW_{105} - DW_{550}) \div WS$, where LOI_{550} represents the percentage mass loss upon ignition at 550 °C (Santisteban et al., 2004). Sediment carbon was analyzed at the International Tropical Marine and Earth Science Laboratory, Universitas Jenderal Soedirman.

Data analysis

Vegetation biomass was estimated using species-specific allometric equations (Table 3). Biomass values were converted to carbon stocks by applying a conversion factor of 0.494 for above-ground biomass and 0.39 for below-ground biomass (Fourqurean et al., 2019), based on the average carbon content proportions in tree tissues.

For each transect segment, the number of dead wood pieces per size class (fine, small, medium, large sound, large decayed) was recorded, and the quadratic mean diameter was calculated for each size class to estimate volume per unit area. Volume was then converted to biomass using size-specific wood density values (fine: 0.34 g cm^{-3}; small: 0.38 g cm^{-3}; medium: 0.50 g cm^{-3}; large sound: 0.58 g cm^{-3}; large decayed: 0.43 g cm^{-3}) following Sasmito et al. (2020). Necromass biomass (Mg ha^{-1}) was subsequently converted to necromass carbon stock using a conversion factor of 0.50 (Kauffman et al., 1995). The mean necromass carbon stock per subplot was calculated by averaging values from the two transects, and final values were expressed as megagrams of carbon per hectare (MgC ha^{-1}). Descriptive statistics (mean, standard deviation, range) were computed for each site and for total necromass carbon.

Soil carbon stock (MgC ha^{-1}) was calculated for each soil core or depth interval using the following equation:

Table 3. Allometric equations for aboveground biomass (AGB) and belowground biomass (BGB)

Species	AGB	BGB
Avicennia alba	$W_{top} = 0.251 \times \rho \times DBH^{2.46}$ (Komiyama et al., 2005) *Common equation* (ρ=0.506)	$WR = 1.28 \times DBH^{1.17}$ (Comley & McGuinness, 2005)
Avicennia marina	$Wtop = 0.308 \times DBH^{2.11}$ (Comley & McGuinness, 2005)	$WR = 1.28 \times DBH^{1.17}$ (Comley & McGuinness, 2005)
Rhizophora apiculata	$Wtop = 0.38363 \times DBH^{2.2348}$ (Vinh et al., 2019)	$WR = 0.00698 * DBH^{2.61}$ (Komiyama et al., 2008)
Rhizophora mucronata	$Wtop = 0.128 \times DBH^{2.60}$ (Fromard et al., 1998)	$WR = 0.00974 \times (DBH^2 \times H)^{1.05}$ (Tamai et al., 1986) (*Rhizophora* sp.)
Rhizophora stylosa	$\log Biomass = -0.9789 + 2.6848 \times \log DBH$ (Clough & Scott, 1989)	$WR = 0.261 \times DBH^{1.86}$ (Comley & McGuinness, 2005)
Bruguiera gymnorrhiza	$Wtop = 0.186 \times DBH^{2.31}$ (Clough & Scott, 1989)	$WR = 0.0188 \times (DBH^2 \times H)^{0.909}$ (Tamai et al., 1986) (*Bruguiera* sp.)
Bruguiera parviflora	$Wtop = 0.168 \times DBH^{2.42}$ (Clough & Scott, 1989)	$WR = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ (Komiyama et al., 2005) *Common equation* (ρ=0.741)
Ceriops tagal	$Wtop = 0.251 \times \rho \times DBH^{2.46}$ (Komiyama et al., 2005) *Common equation* (ρ=0.746)	$WR = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ (Komiyama et al., 2005) *Common equation* (ρ=0.746)
Sonneratia alba	$Wtop = 0.2019 \times DBH^{2.291}$ (Bui et al., 2025)	$WR = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ (Komiyama et al., 2005) *Common equation* (ρ=0.510)
Sonneratia caseolaris	$Wtop = 0.4975 \times DBH^{1.94748}$ (Hanh et al., 2016)	$WR = 0.1420 \times DBH^{2.12146}$ (Hanh et al., 2016)
Excoecaria agallocha	$Wtop = 0.251 \times \rho \times DBH^{2.46}$ (Komiyama et al., 2005) *Common equation* (ρ=0.450)	$WR = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ (Komiyama et al., 2005) *Common equation* (ρ=0.450)

Note: W_{top} = weight top of vegetation (Mg ha^{-1}); WR = weight of root (Mg ha^{-1}); ρ = wood density (g cm^{-3}); H = height (m); DBH = diameter at breast height (cm).

$$Carbon\ stock\ (\text{MgC ha}^{-1}) = \rho b \times C_{frac} \times D \times 100 \quad (1)$$

where: ρb is soil bulk density (g cm^{-3}) determined as ovendried soil mass (105 °C to constant weight) divided by core volume; C_{frac} is soil organic carbon content expressed as a decimal fraction (measured via LOI and converted to %C/100); D is the soil depth (cm) of the sampled interval; and 100 is the conversion factor that accounts for unit conversions from g cm^{-3} and cm to MgC ha^{-1} (since 1 gC cm^{-2} over 1 ha equals 100 MgC ha^{-1}).

Total ecosystem carbon stock (MgC ha^{-1}) was calculated as the sum of necromass carbon stock, vegetation biomass carbon stock (AGC + BGC), and soil carbon stock. Uncertainty was propagated using standard error propagation methods or reported as the sum of individual component variances, assuming independence among components. To compare total carbon stocks among the different sites, pairwise Mann–Whitney U tests were conducted. Given a total of 28 pairwise comparisons, a Bonferroni correction was applied to control the family-wise error rate. Accordingly, the significance level was adjusted to $\alpha' = 0.05/28 \approx 0.00179$. All tests were two-tailed, and differences were considered statistically significant when the resulting p-value was less than this adjusted threshold.

RESULTS

Carbon stock in mangrove ecosystem rehabilitation sites

Carbon contents varied across the five rehabilitation sites (Figure 4). The highest vegetation biomass carbon was observed in Tarakan at 111.96±28.36 MgC ha^{-1}, while the lowest was recorded in Jeneponto at 0.36±0.31 MgC ha^{-1} (Table 4). Necromass contributed only a small proportion (0.32%) to the total carbon stock. Sediment carbon was the dominant component across all sites, accounting for over 90% of the total carbon stock, while biomass carbon contributed approximately 9.82%. The highest sediment carbon was recorded in Pati at 764.67±69.04 MgC ha^{-1}, and the lowest in Jember at 214.95±64.31 MgC ha^{-1} (Table 5). The results indicated that the highest carbon content was observed in sediment, suggesting that even in areas with limited vegetation biomass, sediment plays a significant role in long-term carbon storage within mangrove ecosystems. Across the surveyed regions, total carbon density exhibited pronounced spatial variability, ranging from a minimum regional average of 258.64±105.78 MgC ha^{-1} in Jember to a maximum of 802.42±72.00 MgC ha^{-1} in Pati. While the aboveground vegetative and necromass layers demonstrated considerable discrepancies among locations, the sedimentary layer consistently represented the overwhelming majority of sequestered carbon across nearly all sampled sites.

After applying the Bonferroni correction ($\alpha = 0.00179$) for 28 pairwise comparisons, only two differences in total carbon stock remained statistically significant: Situbondo vs. Jember ($p = 0.001$) and Jeneponto (cp) vs. Jember ($p = 0.001$). Therefore, the carbon stock in Jember (median ≈259 MgC ha^{-1}) was significantly lower than in both Situbondo (median ≈732 Mg C/ha) and the Jeneponto (cp) (median ≈ 798 MgC ha^{-1}). All other pairwise comparisons, including Jember vs. Pati ($p = 0.002$), Jember vs. Tarakan ($p = 0.003$), and any differences among the remaining locations (e.g., Pati vs. Situbondo, $p = 0.286$; Pati (cp) vs. Tarakan, $p = 0.629$; Jeneponto vs. Jeneponto (cp), $p = 0.119$), were not statistically significant at the corrected threshold. Thus, while

Table 4. Carbon content (MgC ha^{-1}; mean±SE) at rehabilitation sites and comparison plots (cp)

Location	Subplot (n)	Vegetation	Necromass	Sediment	Total carbon	U test notation
Pati	6	37.11±9.67	0.65±0.16	764.67±69.04	802.42±72.00	ab
Pati (cp)	2	52.05±7.04	0.70±0.12	796.75±66.17	849.50±73.34	ab
Situbondo	12	110.94±41.21	3.51±5.85	618.04±58.69	732.50±72.59	b
Jember	9	42.15±46.61	1.54±1.25	214.95±64.31	258.64±105.78	a
Tarakan	4	111.96±28.36	4.55±5.87	649.94±232.16	766.44±261.24	ab
Tarakan (cp)	4	123.42±92.48	16.29±17.66	372.27±41.26	511.98±101.94	ab
Jeneponto	3	0.36±0.31	0.17±0.12	676.49±34.84	677.02±34.59	ab
Jeneponto (cp)	7	69.85±18.59	7.16±3.97	721.34±112.14	798.36±121.65	b

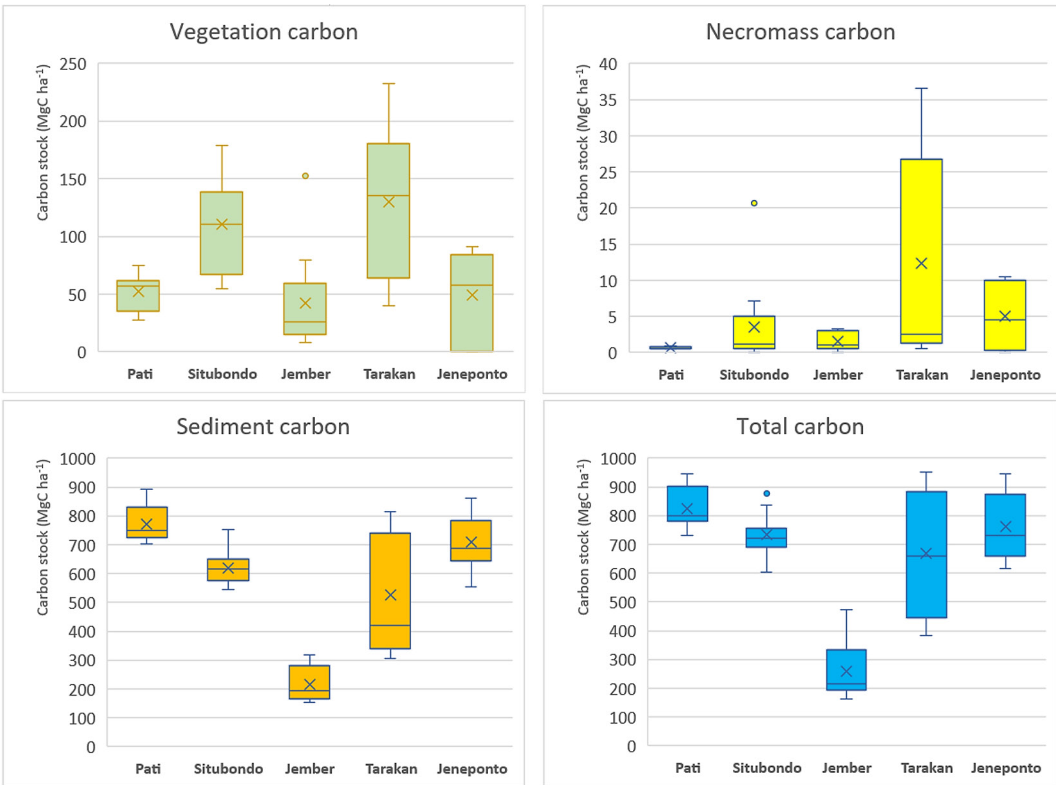

Figure 4. Comparison of carbon stock (MgC ha^{-1}) in three primary carbon compartments (vegetation, necromass, and sediment) and total carbon between rehabilitation sites

Table 5. Carbon biomass (MgC ha^{-1}; mean±SE) in rehabilitation sites and comparison plots (cp)

Location	n	Tree AGC	Tree BGC	Sapling AGC	Sapling BGC	Seedling carbon	Vegetation
Pati	6	5.05±4.11	4.19±3.31	11.84±3.75	15.80±8.24	0.007± – (n=1)	37.10±9.67
Pati (cp)	2	22.88±1.00	16.28±1.43	4.66±1.01	8.23±3.60	–	52.05±7.04
Situbondo	12	92.42±33.80	22.38±17.02	2.76±3.57	0.60±0.84	0.011± – (n=1)	110.94±41.21
Jember	9	36.94±43.42	7.70±8.27	2.21±2.40	1.01±1.23	0.013±– (n=1)	42.15±46.61
Tarakan	4	94.40±24.13	16.90±10.39	0.60±0.21	0.04±0.04	0.055±– (n=1)	111.96±28.36
Tarakan (cp)	4	110.43±86.15	9.44±5.52	3.12±3.27	0.43±0.41	–	123.42±92.48
Janeponto	3	0	0	0.31±0.30	0.01±0.01	0.123±– (n=1)	0.36±0.31
Janeponto (cp)	7	61.99±19.60	6.74±5.42	0.66±0.83	0.52±0.77	–	69.85±18.59

Note: AGC = aboveground carbon, BGC = belowground carbon.

Jember stood out as having a lower total carbon value than Situbondo and the Jeneponto (cp), its carbon stock was not significantly different from those in Pati, Pati (cp), Tarakan, Tarakan (cp), or Jeneponto after controlling for multiple comparisons. Therefore, Jember stood out as a location with distinctly lower total carbon stocks, while the remaining seven locations were statistically similar, except for Jeneponto and Tarakan (cp), which were lower than Pati and Situbondo.

An analysis of carbon stocks revealed distinct, contrasting allocation patterns across the studied locations between mature vegetation and regenerating layers. For mature biomass pools, AGC in trees and saplings, as well as total AGC, demonstrated highly consistent geographical variations (Table 5). A comparison test revealed significant differences in total carbon stock across the eight locations ($\chi^2(7) = 27.70$, $p<0.001$), indicating that carbon storage is strongly influenced by location. The most striking contrasts were observed at the extremes: Jeneponto (non-cp) had a median of only ~0.29 MgC ha^{-1}, reflecting minimal carbon accumulation, whereas Situbondo and Tarakan (including cp) exhibited medians exceeding 100 MgC ha^{-1}, suggesting high carbon storage capacity. Pati and Jember occupied intermediate positions but showed substantial within-group variability. Jember's total carbon ranged from 8.1 to 152.7 MgC ha^{-1}, the lowest total carbon compares to other sites. Overall, the test confirms that median carbon stocks are not equal across locations, with land-use history (e.g., cp vs. non-cp) and site conditions likely driving the observed patterns.

The results of carbon measurements for several mangrove species in the seedling category across all sites are presented in Table 6. Seedlings provide the least contribution of vegetation carbon when compared with saplings and trees, ranging from 0.007–0.123 MgC ha^{-1}.

At the comparison plots in Pati, the community was entirely dominated by *A. alba* across all life stages, with maximum index important values (IVI) of 300 for trees and saplings, and 200 for seedlings (Table 7). Tarakan exhibited a more diverse tree community, with *R. apiculata* as the leading species (IVI 116.23), followed by *S. alba* and *Avicennia alba*, while saplings and seedlings were heavily dominated by *R. apiculata* (IVI 218.41 and 141.33, respectively). In both Jeneponto plots, *R. mucronata* and *A. marina* co-dominated; however, their relative importance shifted between life stages and locations: Jeneponto plot 1 showed stronger *R. mucronata* dominance across all stages, whereas Jeneponto plot 2 had more balanced tree and sapling communities, with *A. marina* slightly outcompeting *R. mucronata* in dominance for trees (56.4% vs. 43.6%).

DISCUSSION

Total mangrove carbon stock

Total ecosystem carbon stock (TECS) in studied mangrove ecosystems varied markedly among the five study sites (Figure 4), indicating strong spatial heterogeneity in mangrove carbon storage. TECS ranged from 258.64±105.78 MgC ha^{-1} in Jember to 802.42±72.00 MgC ha^{-1} in Pati, with intermediate values recorded in Tarakan (766.44±261.24 MgC ha^{-1}), Situbondo (732.50±72.59 MgC ha^{-1}), and Jeneponto (677.02±34.59 MgC ha^{-1}). This variability is consistent with global patterns, where mangrove carbon stocks exhibit substantial site-level variation driven by differences in geomorphology, hydrology, and forest conditions. Global estimates have reported TECS values ranging from 856±32 to 1.023 MgC ha^{-1} across more than 190 sites (Donato et al., 2011; Kauffman et al., 2020). Overall, the observed values fall within the lower to mid-range of global estimates, highlighting both the ecological variability of Indonesian mangroves and the potential influence of local environmental and anthropogenic factors on carbon storage capacity.

National-scale studies indicate that Indonesia's mangrove carbon stock potential is exceptionally high, with an average nationwide TECS of 1.083±378 MgC ha^{-1} (Murdiyarso et al., 2015). This value is comparable to findings from local studies; for example, in Pati, Central Java, carbon stocks in conserved and rehabilitated mangroves

Table 6. Carbon estimates for the seedling category

Location	Species	Density	Seedling carbon (g)	Seedling carbon (g C ha^{-1})	Seedling carbon (MgC ha^{-1})	Seedling carbon content per site (MgC ha^{-1})
Pati	*A. alba*	357.47	8.79	3142.14	0.0031	0.007
	R. mucronata	178.73	23.41	4184.16	0.0042	
Jember	*R. mucronata*	534.40	23.41	12510.22	0.0125	0.013
	S. alba	7.22	8.79	63.48	0.0001	
Situbondo	*R. mucronata*	357.47	23.41	8368.32	0.0084	0.011
	A. marina	135.40	8.79	1190.21	0.0012	
	R. stylosa	43.33	23.41	1014.34	0.0010	
Tarakan	*A. alba*	7.11	8.79	62.46	0.0001	0.055
	R. apiculata	2043.69	23.41	47842.86	0.0478	
	R. mucronata	310.53	23.41	7269.59	0.0073	
	S. alba	7.11	8.79	62.46	0.0001	
Jeneponto	*A. marina*	617.44	8.79	5427.34	0.0054	0.123
	R. mucronata	5004.55	23.41	117156.51	0.1172	
Carbon content (MgC ha^{-1})						0.208

Table 7. Mangrove community structure in comparison plots

Category	Species	No of individu	Relative density (%)	Relative frequency (%)	Relative dominance (%)	Important value index (IVI)
Location: Pati						
Tree	*Avicennia alba*	107	100	100	100	300
Sapling	*Avicennia alba*	132	100	100	100	300
Seedling	*Avicennia alba*	16	100	100	-	200
Location: Tarakan						
Tree	*Rhizopora apiculata*	19	38	36.36	41.87	116.23
	Sonneratia alba	9	18	18.18	34.21	70.39
	Avicennia alba	8	16	18.18	17.37	51.55
	Rhizopora mucronata	9	18	9.09	3.15	30.24
	Ceriops tagal	4	8	9.09	0.83	17.92
	Bruguiera parviflora	1	2	9.09	2.57	13.67
Sapling	*Rhizopora apiculata*	69	85.19	50	83.23	218.41
	Avicennia alba	5	6.17	16.67	6.48	29.32
	Rhizopora mucronata	4	4.94	16.67	6.33	27.93
	Ceriops tagal	3	3.7	16.67	3.97	24.34
Seedling	*Rhizopora apiculata*	229	84.19	57.14	-	141.33
	Rhizopora mucronata	42	15.44	28.57	-	44.01
	Sonneratia alba	1	0.37	14.29	-	14.65
Location: Jeneponto plot 1						
Tree	*Rhizophora mucronata*	91	77.78	75	69.9	222.68
	Avicennia marina	26	22.22	25	30.1	77.32
Sapling	*Rhizophora mucronata*	4	50	66.67	54.7	171.37
	Avicennia marina	4	50	33.33	45.3	128.63
Seedling	*Rhizophora mucronata*	572	96.13	75	-	171.13
	Avicennia marina	23	3.87	25	-	28.87
Location: Jeneponto plot 2						
Tree	*Rhizophora mucronata*	32	64	50	43.6	157.60
	Avicennia marina	18	36	50	56.4	142.40
Sapling	*Avicennia marina*	26	59.09	50	52.37	161.46
	Rhizophora mucronata	18	40.91	50	47.63	138.54
Seedling	*Rhizophora mucronata*	114	71.25	50	-	121.25
	Avicennia marina	46	28.75	50	-	78.75

ranged from 700 to 900 MgC ha^{-1} (Ati et al., 2024). Other mangrove ecosystems in Indonesia have also demonstrated substantial carbon stocks. Segara Anakan (Central Java) recorded approximately 1.000–1.200 MgC ha^{-1}, among the highest in the country, largely due to high sedimentation from the Citanduy River and surrounding watersheds (Murdiyarso et al., 2015). In Berau (East Kalimantan), carbon stocks ranged from ~500 to 800 MgC ha^{-1} (Sasmito et al., 2016), which is comparable to values observed in Tarakan and Situbondo. Meanwhile, Muara Gembong (West Java) exhibited lower carbon stocks of ~200–400 MgC ha^{-1}, primarily due to anthropogenic pressures (Basyuni et al., 2018). In contrast, Bintuni (West Papua) exhibited relatively high carbon stocks (~800–1.100 MgC ha^{-1}), representing relatively intact ecosystems with thick sediment deposits (Alongi, 2020).

Carbon stocks in Situbondo, Pati, and Tarakan (~700–800 MgC ha^{-1}) were comparable to those in Berau but remained lower than those recorded in Segara Anakan and Bintuni. Ecologically, variations in carbon stocks across locations are influenced by factors such as substrate conditions, species composition and diversity, stand age, and soil fertility (Easteria et al., 2022). Notably, Tarakan represents a relatively healthy mangrove ecosystem with high biomass and necromass, comparable to mangrove systems in Kalimantan and Sulawesi. In contrast, Jember appears as an outlier with very low carbon stock, likely due to ecosystem degradation, including mangrove clearing activities within sedimentation pond areas. These findings highlight the urgent need to strengthen mangrove conservation and restoration efforts – both natural regeneration and active replanting – as key strategies for climate change mitigation and sustainable coastal ecosystem protection.

The site with the longest rehabilitation period (Situbondo) exhibited relatively high total carbon stocks; however, sites with shorter rehabilitation periods (e.g., Pati at 6 years) showed the highest total carbon (802.42±72.00 MgC ha^{-1}), while Jember (16 years) had the lowest (258.64±105.78 MgC ha^{-1}). This indicates that rehabilitation age is not always the primary determinant of carbon accumulation. Sediment carbon is the dominant component contributing to total carbon at nearly all sites (except Jember), ranging from 618.04±58.69 to 764.67±69.04 MgC ha^{-1}. Sediment carbon is strongly influenced by local factors such as tidal dynamics, terrestrial organic matter inputs, and hydrodynamic conditions, which are not directly correlated with stand age. For example, Jeneponto, with rehabilitation age of only approximately 4 years, had a sediment carbon value of 676.49±34.84 MgC ha^{-1}, comparable to Situbondo, which is 22 years old. This suggests that sediment carbon accumulation can occur rapidly in areas with high organic matter input, regardless of rehabilitation age. This pattern is highly evident at the Jeneponto site, where sediment carbon stocks greatly exceeded biomass carbon. Notably, this disparity is primarily driven by the early developmental stage of the plantation, which was only 3 years post-planting. Mangrove degradation was also identified in the Jeneponto and Situbondo sites, primarily caused by coastal abrasion.

Biomass carbon, which is generally associated with vegetation growth and stand age, also did not exhibit a clear pattern. Situbondo and Tarakan, which are relatively old sites, showed high biomass carbon values (110.94±41.21 and 111.96±28.36 MgC ha^{-1}, respectively). However, Jember (16 years) only showed a value of 42.15±46.61 MgC ha^{-1}, while Pati (6 years) was 37.11±9.67 MgC ha^{-1}, and Jeneponto (4 years) was extremely low at 0.36±0.31 MgC ha^{-1}. These variations may be attributed to differences in mangrove species composition, rehabilitation success rates, stand density, soil conditions, sediment input dynamics, and anthropogenic disturbances.

Carbon biomass

The results indicate that carbon biomass varies considerably across sites. In this study, carbon biomass contributed approximately 0.04–19% of the total carbon stock. Notably, these values are comparable to findings from other locations in Indonesia. For example, in Bontang, East Kalimantan, AGB carbon was reported to be 180.74 MgC ha^{-1} (Rahmawani et al., 2025), while in East Belitung, the average AGB carbon reached 509.34 MgC ha^{-1} (Sapriyadi et al., 2023). The relatively high value observed in Tarakan (121.37±31.28 MgC ha^{-1}) is consistent with mature mangrove stands that have been replanted since 2006, whereas the very low value in Jeneponto (0.36±0.31 MgC ha^{-1}) reflects young stands established through recent replanting in 2020. This pattern aligns with the general trend of increasing carbon stocks with mangrove age (Easteria et al., 2022).

Carbon stock in mangrove ecosystem biomass is strongly influenced by various biotic and abiotic factors. The main factors are stand age and replanting history; areas that were replanted earlier tend to have higher carbon stocks because the trees have reached larger sizes and accumulated more significant biomass (Panda et al., 2025; Zakaria et al., 2023). This condition was observed in Tarakan, where replanting has been conducted since 2006, and the biomass carbon stocks reached 111.96±28.36 MgC ha^{-1}, substantially higher than in Jeneponto, which was only replanted in 2020 and exhibited a value of 0.36±0.31 MgC ha^{-1}. Stand density and species composition also influence carbon storage because different species possess varying capacities for biomass accumulation. Additionally, physical environmental conditions such as salinity, tidal regimes, nutrient availability, and sediment stability could potentially influence mangrove growth rates and biomass accumulation (Murdiyarso et al., 2015). Anthropogenic pressure, deforestation, land conversion, and degradation resulting from human activities may also contribute to reducing carbon stocks (Analuddin et al., 2024). Therefore, variations in biomass carbon stocks among locations reflect a combination of ecological factors, management history, and local environmental pressures.

Necromass carbon

Across all sites, the necromass carbon content was relatively low. The highest value was recorded in Tarakan (4.55±5.87 MgC ha^{-1}), followed by Situbondo (3.51±5.85 MgC ha^{-1}), Jember (1.54±1.25 MgC ha^{-1}), Pati (0.65±0.16 MgC ha^{-1}), and Jeneponto (0.17±0.12 MgC ha^{-1}). Necromass carbon contributed only approximately 0.03–0.59% of the total carbon stock observed in this study. These values are consistent with findings from other locations in Indonesia; for example, mangrove necromass in Banten contributed 1.11 and 2.51% of total carbon (Royna et al., 2024), while it ranged from 0.009 to 0.036 MgC ha^{-1} in Lampung (Kusuma, 2024). This further confirms that necromass represents a relatively small fraction compared to soil carbon and living biomass; however, it remains important in decomposition processes and nutrient availability within mangrove ecosystems.

Carbon storage in necromass is generally lower than in living mangrove biomass because dead trees no longer absorb carbon or contribute to biomass accumulation. The carbon contained in necromass represents the residual carbon that remains stored after trees or plant components have died (Kusuma, 2024). Notably, the low necromass carbon values observed in this study could be influenced by several factors. For instance, the amount of carbon stored in necromass is affected by the extent of mangrove mortality (Kusuma et al., 2023). The low necromass values observed here may be associated with younger vegetation age or the limited accumulation of dead organic material such as branches, leaf litter, and fallen trunks. Additionally, low necromass values indicate high rates of decomposition and organic material transport within mangrove ecosystems, resulting in a relatively small carbon pool compared to soil carbon and living biomass.

Sediment carbon

The results indicated that sediment carbon contributed the largest proportion to total carbon stocks, ranging from 80.41 to 99.93%.

The sediment carbon values at each study site, listed from highest to lowest, were as follows: Pati (764.67±69.04 MgC ha^{-1}), Jeneponto (676.49±34.84 MgC ha^{-1}), Tarakan (649.94±232.16 MgC ha^{-1}), Situbondo (618.04±58.69 MgC ha^{-1}), and Jember (214.95±64.31 MgC ha^{-1}). The dominance of the sediment carbon pool is consistent with numerous previous studies, which reported that 80–90% of total carbon stocks in mangrove ecosystems are stored in sediments, making it a key component for long-term carbon storage (Alongi, 2014; Kauffman et al., 2020).

The dominance of sediment carbon observed in this study is consistent with natural mangrove systems in Indonesia, particularly in areas influenced by riverine inputs that transport organic material (Murdiyarso et al., 2021). Variability among sites may be driven by soil physicochemical properties such as temperature, pH, texture, and substrate type (Marbun et al., 2020). For instance, sediment carbon stocks in mangroves in Papua ranged from 28.2 to 883.7 MgC ha^{-1}, in Sumatra from 73.0 to 1,033.5 MgC ha^{-1}, and in Kalimantan from 50.3 to 760.1 MgC ha^{-1} (Purbopuspito et al., 2014). In Bintuni and Segara Anakan, sediment contributed more than 60% of the carbon present due to natural accumulation processes, whereas in Jakarta Bay, sediment carbon content was lower (<50%) due to anthropogenic disturbances (Murdiyarso et al., 2021).

Although mangrove vegetation in Pati remains relatively young due to rehabilitation, the high sediment carbon content observed was likely driven by a combination of physical and ecological processes. Sediment soils in coastal ecosystems, especially mangroves, tend to store large amounts of carbon because they function as natural traps for organic material. Root systems and vegetation density slow water movement and reduce wave energy, thus allowing fine particles rich in organic matter from litter, roots, and external inputs to settle and accumulate (Alongi, 2014; Kauffman et al., 2020).

Input from leaf litter, branches, and roots further contributes to carbon accumulation in the sediment (Donato et al., 2011). Additionally, since waterlogged and low-oxygen conditions slow decomposition, organic material can remain stored for long periods (Kristensen et al., 2008; Zhang et al., 2024). Sediment accretion in estuarine and delta areas also buries older organic layers, allowing them to be preserved over hundreds to thousands of years (Murdiyarso et al., 2023; Sasmito et al., 2020). Local geomorphological and hydrological conditions, such as sheltered coastal areas and sediment input from rivers, further support carbon storage in sediments, making this pool one of the main carbon reservoirs in coastal ecosystems.

CONCLUSIONS

This study shows that carbon stocks in replanted mangrove ecosystems across five locations ranged from 258.64±105.78 to 802.42±72.00

MgC ha^{-1}, with the highest value recorded in Pati and the lowest in Jember. The main carbon pool at these sites was sediment, contributing more than 80% of the total stock, which highlights its role as a long-term carbon sink.

Vegetation biomass varied at the study sites depending on stand age and the success of replanting, with sites that had undergone earlier replanting (e.g., Tarakan and Situbondo) showing higher biomass compared to more recently replanted areas, such as Jeneponto. Although necromass contributed a relatively small proportion across all sites (< 5%), it remains important for nutrient cycling within the mangrove ecosystem.

To maximize the impact of these findings, it is recommended that stakeholders prioritize long-term conservation for high-carbon sites such as Pati, Tarakan, and Situbondo while maintaining intensive rehabilitation and monitoring in lower-cabron stock areas such as Jember and Jeneponto. This dual approach should be supported by further comparative research between replanted and natural mangroves to refine carbon baselines, which could ultimately facilitate the integration of these results into policy through blue carbon credit schemes and ecosystem-based incentives that benefit both the environment and local communities.

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