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# Organic carbon in *Rhizophora* and *Avicennia* mangrove litter of South Kalimantan, Indonesia

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**Abstract.** *Lestarina PM, Bengen DG, Prartono T, Rifa'i MA, Zamani NP, Selviani. 2026. Organic carbon in* Rhizophora *and* Avicennia *mangrove litter of South Kalimantan, Indonesia. Biodiversitas 27 (1): d270132. https://doi.org/10.13057/biodiv/d270132.* Mangrove ecosystems serve as major blue carbon sinks due to their high productivity and slow decomposition under anaerobic conditions. This study examined organ and species-level variations in the organic carbon content of *Rhizophora mucronata* and *Avicennia marina* at two coastal sites in South Kalimantan, Indonesia-Kintap and Asam-Asam. Samples of stems, twigs, leaves, roots, and flowers were analyzed using the Walkley-Black method. The average organic carbon content of *R. mucronata* was 7.603%, while that of *A. marina* was 6.193%. The highest carbon concentration occurred in stems and twigs, followed by roots, leaves, and flowers. Mean carbon content was slightly higher in Kintap (7.091%) than in Asam-Asam (6.704%), though the difference was not statistically significant. Regression analysis indicated that plant organs significantly influenced organic carbon levels ($p = 0.004$), whereas location, station, and species did not. These findings emphasize that organ-specific characteristics-particularly lignin-rich woody tissues-are key determinants of carbon retention in mangroves. Incorporating such organ-level variability enhances the accuracy of blue carbon estimates and supports ecosystem-based conservation and climate mitigation strategies. Moreover, these findings highlight the ecological significance of organ-specific carbon storage in dominant mangrove species, reinforcing their role in sustaining ecosystem diversity and supporting blue carbon conservation strategies under global climate change agendas.

**Keywords:** *Avicennia marina*, blue carbon, mangrove litter, organic carbon, *Rhizophora mucronata*

## INTRODUCTION

Mangrove ecosystems are vital for maintaining ecological stability in coastal regions. Acting as natural buffers, they protect shorelines from erosion, mitigate flooding, and safeguard coastal communities from storm surges and tsunamis (Hasim 2021; Rahmadi et al. 2023; Temmerman et al. 2023). Beyond these protective functions, mangroves provide habitats for diverse endemic and migratory species, thereby supporting high coastal biodiversity (Ferreira et al. 2024). They are also globally recognized as one of the most effective blue carbon ecosystems because of their exceptional ability to capture and store carbon, contributing significantly to climate change mitigation (Uddin et al. 2023). These ecological services are closely tied to biodiversity conservation, since mangroves sustain multiple trophic levels and enhance ecosystem resilience.

A key advantage of mangroves lies in their ability to store carbon in anaerobic soils, which slows decomposition and allows long-term accumulation of organic matter. Compared with terrestrial ecosystems, mangroves maintain larger and more stable carbon pools (Kida and Fujitake 2020). This storage occurs across various plant organs with distinct physiological roles: roots contribute to belowground sequestration, stems serve as long-term reservoirs due to their lignin and cellulose content, and short-lived leaves and flowers contribute primarily through litter production and rapid decomposition (He et al. 2020; Li et al. 2021; Ray et al. 2021; Sun et al. 2023). Understanding these organ-specific patterns is crucial for evaluating mangrove efficiency as carbon sinks and for developing ecosystem-based conservation strategies. An organ-level approach also links physiological traits to ecosystem functioning, emphasizing the role of intra-species variation in shaping biodiversity and resilience.

Species-specific adaptations further influence carbon allocation. In South Kalimantan, Indonesia, coastal mangrove forests are dominated by *Rhizophora mucronata* Lam. and *Avicennia marina* (Forssk.) Vierh.. These species show distinct morphological and physiological features reflected in their carbon storage strategies. *Rhizophora*, with its stilt-root system, enhances sediment trapping and belowground accumulation, whereas *Avicennia*, through pneumatophores and aerenchyma tissues, adapts to salinity and oxygen limitations with unique allocation patterns (Nizam et al. 2022; Wang et al. 2022). Such interspecific differences underscore the importance of combining organ- and species-level perspectives when assessing carbon stocks. Maintaining species diversity enhances adaptive capacity in changing environments, which is critical for biodiversity-based management.

Despite their ecological importance, mangroves in South Kalimantan face significant pressures that threaten their degradation. Large areas have been converted into aquaculture ponds and infrastructure, reducing both the extent and quality of mangrove stands. Such disturbances not only lower carbon storage potential but also risk releasing previously stored carbon from biomass and sediments, exacerbating climate change (Zhang et al. 2021). These threats highlight the urgency of obtaining detailed scientific data to guide restoration and conservation. Without insights at the organ and species levels, management risks overlooking functional diversity essential for resilience.

Globally, the role of mangroves in the carbon cycle has been widely acknowledged. However, research has often emphasized total biomass estimates or sediment stocks, with less focus on organ-level contributions. Such data remain particularly scarce in Southeast Asia, where mangroves are extensive but unevenly studied. In South Kalimantan, previous assessments have offered general estimates without distinguishing between roots, stems, and leaves or capturing site-level variability. This absence of detailed organ- and site-specific information introduces uncertainties in regional blue carbon accounting. Bridging this gap is essential for connecting biodiversity research with ecosystem service valuation and climate policy implementation.

These knowledge gaps present challenges for integrating mangrove carbon into national climate policies, including Indonesia's Nationally Determined Contributions (NDCs). Without robust organ- and site-level datasets, carbon stock estimates risk being unrepresentative, thereby undermining mitigation strategies. Moreover, accurate and spatially explicit assessments are increasingly critical for supporting emerging blue carbon economy initiatives in Indonesia, where ecosystem service valuation requires empirical evidence. Organ-specific and location-based data also provide the foundation for biodiversity-informed restoration, ensuring that conservation strategies incorporate ecological and socio-economic perspectives.

To address these challenges, the present study investigates organ and site-specific carbon storage in the dominant mangrove species *R. mucronata* and *A. marina* along the coast of South Kalimantan. The research quantifies variation in carbon content across plant organs (roots, stems, and leaves) and compares patterns between different coastal sites. By combining biological and spatial scales, the study aims to provide a more accurate foundation for blue carbon assessments, reinforce the scientific basis for regional mangrove management, and strengthen national carbon accounting systems. Ultimately, the findings are expected to contribute to ecosystem-based climate mitigation strategies while emphasizing the importance of mangrove biodiversity in sustaining ecosystem services and guiding long-term conservation policy.

## MATERIALS AND METHODS

### Study area

The research was conducted in June 2024 in Kintap Village (TKP) and Asam-asam Village (ASM), Tanah Laut District, South Kalimantan, Indonesia (Figure 1). The geographical position of each sampling station is presented in Table 1. Muara Asam-asam Village is located at the mouth of the river, dominated by *Rhizophora apiculata* with muddy substrate. Muara Kintap Village is located on the riverbank and has a fishing port.

**Table 1.** Geographical position of sampling stations

| Station | Coordinate point |
|---|---|
| Muara Asam-asam Village, Jorong Sub-district | 03°59’03.8” S - 115°04’17.21” E |
| Muara Kintap Village, Kintap Sub-district | 03°52’52” S - 115°18’49.29” E |

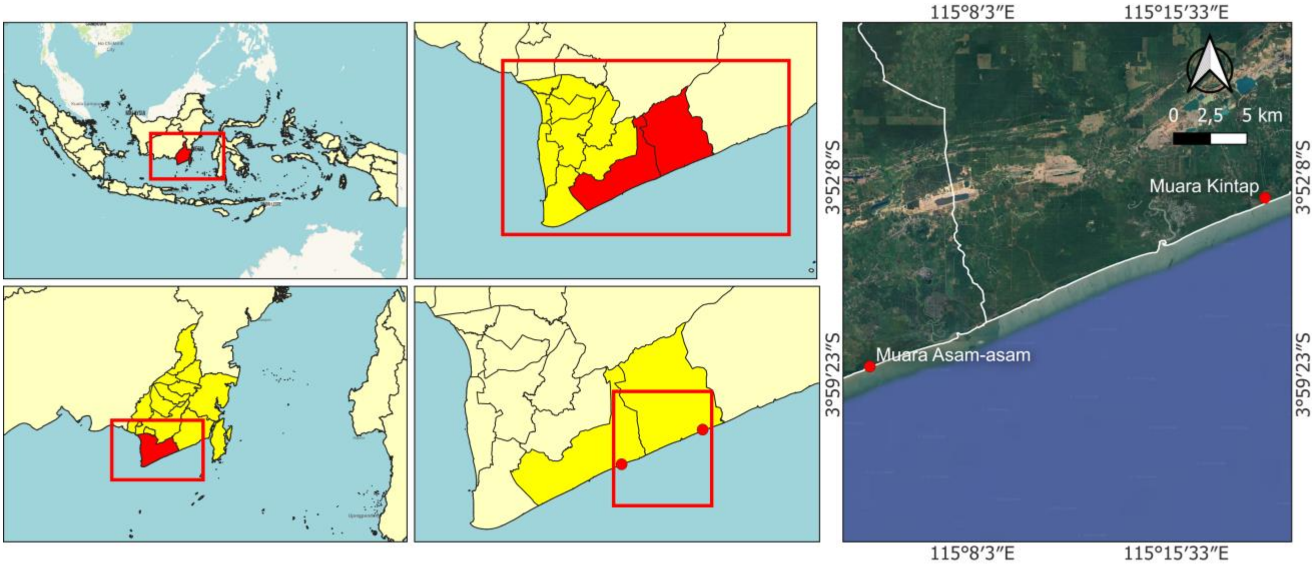

**Figure 1.** Sampling station in Muara Asam-asam Village and Muara Kintap Village, Tanah Laut District, South Kalimantan, Indonesia

### Sampling procedures (biomass and carbon sampling)

At each location, a minimum of five mature trees per species (*R. mucronata* and *A. marina*) were selected as biological replicates. From each tree, at least three subsamples were collected per organ (leave, flower, stem, twig, and roots) to capture intra-tree variability.

The sample trees taken were only a small portion of the mangrove sampling area, an allometric approach was used so as not to cut down trees and damage the mangrove ecosystem. The trunks and branches were divided into 100-200 cm segments, and the diameter was measured at both the base and end of each segment (Ketterings et al. 2001).

Roots were classified as either superficial (visible on the soil surface) or subterranean (penetrating the soil). Samples were collected using the trench method (Komiyama et al. 2005), assuming root length and width corresponded to crown length and width. Soil was excavated on both sides to a depth and width equal to the crown length, with 1 m spacing between excavations, and divided into five layers down to 1 m. In each layer, roots were cut with a saw, then washed to remove soil and to distinguish living from dead roots.

The mass of all extracted components was determined by weighing to obtain their wet weight. Each component was weighed with a precision of 500 g for laboratory analysis. If the wet weight of a sample was less than 500 g, the entire biomass of the sample was weighed and taken as a subsample (Komiyama et al. 2005).

### Laboratory analysis

Laboratory analysis uses the Walkley-Black method. This method quantitatively determines the total amount of organic carbon present in the soil. Total carbon (TC) is determined using an instrument that utilizes a combustion system with an induction furnace coupled with an infrared (IR) detector system. This method is based on the oxidation of samples through "flash combustion" which converts all organic and inorganic substances into combustion gases ($N_2$, NOx, $CO_2$, and $H_2O$). Total inorganic carbon (TIC) is quantitatively determined by measuring the calcium carbonate content using gravimetric analysis, then using a factor of 0.12 to convert calcium carbonate to total inorganic carbon (TIC). Total organic carbon in soil (TOC) is calculated as the difference between total carbon and total inorganic carbon. This method has a detection limit of approximately 0.02% carbon. The sample material must be ground into a fine powder that can pass through a 60 mesh sieve (<0.25 mm).

### Data analysis

The organic carbon stocks within the mangrove biomass were estimated using biomass-to-carbon conversion factors. Several previous studies have determined the carbon content of mangrove biomass through combustion methods and elemental analyzers. Regression analysis was conducted to test the effects of plant organ, species, station, and location on carbon content using SPSS Statistics version 29 (IBM Corp., Armonk, NY, USA). A $p<0.05$ indicates a significant effect.

## RESULTS AND DISCUSSION

The analysis showed that the average organic carbon content in the Kintap mangrove ecosystem was 7.091%, slightly higher than that in Asam-Asam, which averaged 6.704%. However, the difference in carbon content between the two locations was not significantly different, as shown in Figure 2.

Table 2 presents the overall carbon content of the two mangrove species at each location. In Asam-Asam, the *R. mucronata* showed organic carbon content ranging from 5.699% to 8.393%, while *A. marina* ranged from 0% to 8.557%. In comparison, *R. mucronata* in Kintap ranged from 6.842% to 9.721%, and *A. marina* ranged from 0% to 8.641%.

The regression analysis showed that of the four variables tested, only productivity-related to plant components like leaves, flowers, stems, and twigs-had a statistically significant impact on organic carbon content, with a significance value (Sig.) of 0.004 ($p<0.05$). In comparison, the variables station (Sig. = 0.188), location (Sig. = 0.166), and species (Sig. = 0.271) exhibited no significant effects (Table 3).

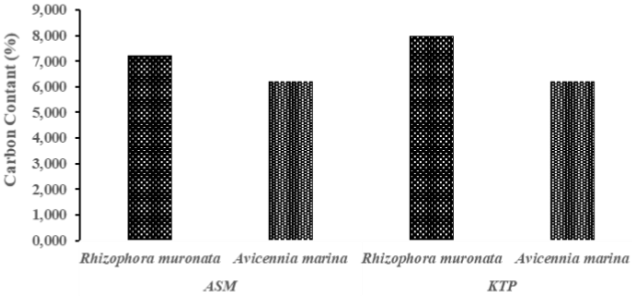

**Figure 2.** Organic carbon content by location

**Table 2.** C-Organic carbon content by type and location

| Location | Mangrove type | Mangrove section | Carbon content (%) |
|---|---|---|---|
| ASM | *Rhizophora mucronata* Lam. | Leave | 6.696 |
| | | Flower | 7.395 |
| | | Stem | 8.393 |
| | | Twig | 7.892 |
| | | Roots | 5.699 |
| | *Avicennia marina* (Forssk.) Vierh | Leaves | 7.208 |
| | | Flower | 0.000 |
| | | Stem | 8.557 |
| | | Twig | 7.853 |
| | | Roots | 7.346 |
| KTP | *Rhizophora mucronata* Lam. | Leaves | 6.842 |
| | | Flower | 8.268 |
| | | Stem | 8.182 |
| | | Twig | 9.721 |
| | | Roots | 6.938 |
| | *Avicennia marina* (Forssk.) Vierh | Leaves | 7.270 |
| | | Flower | 0.000 |
| | | Stem | 8.641 |
| | | Twig | 8.590 |
| | | Roots | 6.460 |

Note: ASM: Asam-asam; KTP: Kintap; Carbon Content (%) of 0.000% means undetected values

**Table 3.** Significance of variables affecting organic carbon content based on regression analysis

| Variable | Sig (p-value) | Effect |
|---|---|---|
| Productivity | 0.004 | Significant |
| Station | 0.188 | Not significant |
| Location | 0.166 | Not significant |
| Species | 0.271 | Not significant |

## Discussion

### *Organ-specific patterns of carbon allocation*

The distribution of organic carbon among mangrove organs revealed a consistent pattern in which stems and twigs contained higher concentrations compared to roots or flowers (Table 2). This observation aligns with the structural roles and biochemical properties of woody tissues, which are rich in lignin and cellulose. Lignin, a complex and hydrophobic biopolymer, confers rigidity and decomposition resistance, allowing woody organs to serve as long-term carbon sinks that are less prone to microbial breakdown (Dai et al. 2022; Kawai et al. 2022). Conversely, leaves and flowers, which are shorter-lived and characterized by lower lignin content, decompose more rapidly and thus contribute relatively less to long-term carbon storage. In *A. marina*, flowers were absent at the time of sampling, but pneumatophores and fine roots, although contributing to belowground biomass, exhibited lower carbon concentrations due to their faster turnover rates. It is important to note that the Walkley-Black method used in this study partially oxidizes organic matter and therefore tends to underestimate carbon content, particularly in lignin-rich woody tissues such as stems and twigs. As a result, the values reported here should be interpreted as relative rather than absolute carbon concentrations, with future studies encouraged to apply dry combustion or elemental analyzers for higher precision. This organ-level differentiation reinforces the importance of accounting for tissue-specific traits when evaluating carbon storage in mangrove ecosystems.

### *Interspecies comparisons*

Both *R. mucronata* and *A. marina* displayed similar intra-organ carbon distribution, yet *R. mucronata* exhibited marginally higher concentrations in structural organs such as stems and twigs. This difference may be attributable to the denser wood anatomy and stilt-root system of *R. mucronata*, which enhances sediment trapping and contributes to more stable carbon deposition. However, regression analysis revealed that species identity itself was not a statistically significant predictor of carbon content ($p = 0.271$, Table 3). This suggests that organ-specific characteristics exert a stronger influence on carbon variability than species-level differences. Similar conclusions have been reached in earlier studies, which emphasized that carbon storage potential in mangroves is more strongly determined by organ-level biochemical properties than by taxonomic identity (Rovai et al. 2018). These findings highlight that although species-specific adaptations play a role in shaping carbon allocation strategies, accurate estimations of carbon stocks require organ-specific rather than species-level measurements.

### *Spatial variation across sites*

The mean organic carbon content was slightly higher in Kintap (7.091%) than in Asam-asam (6.704%) (Figure 2), but this disparity was not statistically significant. The absence of strong spatial variation may indicate that site-level environmental factors such as salinity, sediment type, and anthropogenic disturbance did not differ sufficiently to produce measurable effects within the scope of this study. It is also possible that similarities in sediment composition and vegetation structure across both sites attenuated detectable location effects. Nonetheless, the unique root architecture of *R. mucronata*, particularly its buttress and stilt roots, likely contributes to enhanced sediment trapping and long-term subsoil carbon accumulation (Sierra et al. 2024).

Regression analysis confirmed that among the four tested variables-organ productivity, station, location, and species-only organ productivity had a statistically significant effect on carbon content ($p = 0.004$, Table 3). This underscores the primacy of organ-specific structural and biochemical properties in determining carbon storage. The lack of significant effects for species and location should not be interpreted as the absence of biological or environmental influence, but rather as an indication that organ-level variability overshadows broader spatial or taxonomic patterns in carbon storage. These results align with earlier research showing that tissue-specific characteristics often dominate over site-level or species-level differences in mangrove carbon dynamics (Ragavan et al. 2021; Zaman et al. 2023).

### *Environmental factors and site-specific pressures*

Despite the lack of statistical differences, field observations indicate that environmental pressures likely shape carbon storage potential at local scales. At Asam-Asam, land conversion, aquaculture development, and domestic waste inputs may have contributed to reduced carbon content in mangrove vegetation and litter (Ahmed et al. 2022; Nugroho et al. 2022). Soil texture is also a critical factor: clay-dominated soils generally retain more carbon than sandy soils due to their ability to stabilize organic matter (Swangjang and Panishkan 2021). Such environmental heterogeneity highlights the need for site-specific management approaches that recognize local drivers of carbon variability.

Vegetation density emerged as another key determinant. The higher mean carbon content in Kintap corresponds with its denser mangrove stands, dominated by *R. mucronata* and *A. marina*. Previous studies confirm that denser mangrove canopies with long-lived woody tissues contribute disproportionately to carbon storage through both standing biomass and litter accumulation (Alongi 2020, 2025). Therefore, conserving high-density mangrove stands is essential not only for maintaining ecosystem diversity but also for optimizing carbon sequestration.

## Conservation and policy implications

The efficiency of mangrove carbon storage reflects a complex interplay of organ-level traits, species adaptations, and site-specific environmental conditions. This study demonstrates that tissue-specific properties, especially those of stems and twigs, should be prioritized in carbon accounting models and conservation planning. Restoration strategies should emphasize reestablishing lignin-rich woody components, which are most effective in sustaining long-term carbon reservoirs.

At the same time, site-specific pressures such as land conversion and pollution require targeted interventions. Maintaining ecological integrity is critical not only for carbon storage but also for biodiversity conservation, as mangroves provide habitat for diverse aquatic and terrestrial species (Edwin et al. 2021; Kusuma 2023). At the policy level, incorporating organ- and site-level variability into Indonesia's Nationally Determined Contributions (NDCs) will enhance the reliability of blue carbon estimates and strengthen commitments to climate change mitigation.

Beyond climate policy, accurate carbon accounting has wider implications for valuing ecosystem services and the developing blue carbon economy in Indonesia. Reliable data on organ-specific and spatial carbon variability offer the scientific basis for payments for ecosystem services, carbon credit systems, and international conservation funding. Therefore, empirical evidence from studies like this one can connect local ecological processes with global policy frameworks, ensuring that mangrove conservation effectively supports both biodiversity protection and climate mitigation.

In conclusion, this study demonstrated that organ-specific characteristics play a decisive role in mangrove carbon storage, particularly lignin-rich stems and twigs. The highest organic carbon concentrations were found in the stems and twigs of *R. mucronata* and *A. marina*, reflecting the contribution of lignin-rich woody tissues to long-term carbon retention. In contrast, leaves and flowers exhibited lower carbon contents due to rapid turnover and decomposition. The average organic carbon content across sites ranged from 6.704% to 7.091%, with no significant difference between locations, indicating relatively uniform environmental conditions in the study area. Regression analysis confirmed that only the plant organ significantly affected carbon content ($p = 0.004$), while species and site factors showed no measurable influence. The study was spatially limited to two sites and conducted during a single sampling period, without assessing seasonal or belowground carbon dynamics. The use of chemical analysis without isotopic or biochemical validation may also restrict the interpretation of carbon sources. Subsequent research should explore seasonal variability, belowground carbon pools, and biochemical profiling of lignin and cellulose to refine blue carbon estimates. These findings emphasize the importance of incorporating organ-specific variability into blue carbon assessments and of conserving woody structural components to maximize long-term carbon sequestration. For conservation and policy, the results underscore the necessity of preserving dense, structurally complex mangrove stands and integrating fine-scale carbon data into Indonesia's NDCs, thereby enhancing both ecosystem resilience, national climate commitments and supporting national blue carbon policy frameworks in Indonesia.

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