Journal of Fisheries and Marine Resource Management
Vol. 1, Issue 3, 2026 (Hal. 108-116) e-ISSN: 3124-2561
https://ejurnal.itbm.ac.id/marfig/index

Carbon Content of Mangrove Species with Different Root Systems at Pokko Beach, Takalar Lama, South Sulawesi, Indonesia

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***DOI**: https://doi.org/10.63249/marfig.v1i3.197*

Abstract

Mangrove ecosystems are major blue carbon sinks, but their capacity to store carbon varies with species, root architecture, and habitat conditions. This study characterised the physicochemical conditions of mangrove habitats and compared the carbon content of the substrate and plant organs (roots, branches, leaves, and flowers/fruits) of three species with contrasting root systems, Rhizophora stylosa (stilt roots), Avicennia marina (pneumatophores), and Sonneratia caseolaris (cone-shaped pneumatophores), at Pokko Beach, Takalar Lama, South Sulawesi, Indonesia. A quantitative survey was conducted from December 2025 to February 2026 in a purposively selected 40 m × 40 m quadrat. Water temperature, salinity, and pH were measured in situ, diameter at breast height (DBH) was recorded, and the carbon content of substrate (0–30 cm) and organ samples was determined in the laboratory. Water temperature was uniform (28 °C), salinity ranged from 13 to 15 ppt, and pH ranged from 3.74 under R. stylosa to 7.51 under S. caseolaris. Sonneratia caseolaris had the largest DBH (18.77 cm) and the highest carbon content in the substrate (4.56%), roots (17.50%), and branches (15.56%), whereas R. stylosa had the highest content in leaves (16.22%) and flowers/fruits (13.95%). Avicennia marina had the smallest DBH (9.86 cm) and generally intermediate to low values, although its substrate carbon (3.73%) exceeded that of R. stylosa (2.62%). Across species, carbon content was higher in plant organs than in the substrate. These patterns indicate that carbon allocation among organs is species-specific and associated with tree size and root architecture, supporting the conservation of mixed-species mangrove stands to maintain diverse carbon storage pathways at Pokko Beach.

Keywords: blue carbon; carbon content; mangrove; root system; Takalar

*Manuscript received **September**; revised **October**; accepted **November**; date of publication November 2026. MARFIG is licensed under a Creative Commons Attribution-Share Alike 4.0 International License*

INTRODUCTION

Mangrove forests occupy a unique position in tropical coastal landscapes because they simultaneously stabilise shorelines and act as highly efficient sinks of blue carbon. Together with tidal marshes and seagrass meadows, mangroves store large quantities of organic carbon in their biomass and sediments, and their protection and restoration have been proposed as natural climate solutions capable of contributing measurably to climate change mitigation (Macreadie et al., 2021). Mangroves also provide coastal protection, fisheries support, and livelihoods for millions of people, yet they have experienced extensive losses through conversion to aquaculture and agriculture, overextraction, and pollution, particularly in Southeast Asia (Friess et al., 2019). Climate change adds further pressures through sea-level rise, altered precipitation, and extreme events, which may affect both carbon stocks and the fluxes that sustain them (Alongi, 2022). Understanding the factors that control carbon storage in mangroves is therefore essential for climate

policy, coastal management, and the design of conservation and rehabilitation programmes.

The carbon stored in mangrove ecosystems is distributed among aboveground biomass, belowground roots, dead wood, and sediments. A global network of 190 sites showed that belowground components, including roots and soils, account for most of the total ecosystem carbon stock and that aboveground forest structure alone is a weak predictor of total storage (Kauffman et al., 2020). Regional studies have revealed tremendous variation in ecosystem carbon stocks across environmental gradients, with soils frequently comprising more than 80% of the total (Kauffman & Bhomia, 2017). Improved estimates that account for all carbon pools indicate that global mangrove ecosystem carbon stocks are substantial, but that methodological choices, such as conversion factors between organic matter and organic carbon, strongly influence the results (Ouyang & Lee, 2020). High-resolution mapping has further demonstrated large spatial variability in mangrove soil carbon, with Indonesia, Malaysia, and Myanmar accounting for most of the recent losses (Sanderman et al., 2018). At the global scale, coastal environmental settings, such as deltaic, estuarine, lagoonal, and carbonate systems, explain much of the variation in soil carbon storage (Rovai et al., 2018).

Indonesia holds the largest mangrove area of any country and therefore plays a central role in global blue carbon budgets. Continued mangrove loss in Southeast Asia, driven mainly by conversion to aquaculture and agriculture, is projected to generate substantial carbon emissions over the coming decades (Adame et al., 2021). Land-use and land-cover change transforms mangroves from carbon sinks into sources, reducing biomass and soil carbon stocks, while rehabilitation can restore biomass carbon over several decades (Sasmito et al., 2019). In response, Indonesia has placed mangrove rehabilitation on its national priority agenda, although management faces complex ecological, social, and governance challenges (Arifanti et al., 2022). Locally specific data on mangrove carbon are needed to support these efforts, particularly for small coastal sites that are under pressure from wood harvesting and land conversion but remain poorly documented in the scientific literature.

Habitat physicochemistry adds a further layer of complexity. Salinity, pH, temperature, tidal inundation, and sediment texture regulate mangrove productivity, decomposition rates, and the preservation of organic matter in sediments. In West-Central Africa, total ecosystem carbon stocks were only weakly related to soil salinity and aboveground forest structure, even though these factors varied widely, which indicates that local conditions interact in ways that cannot be captured by any single variable (Kauffman & Bhomia, 2017). Global syntheses similarly show that climate, tidal regime, and geomorphic setting jointly shape both biomass and soil carbon (Kauffman et al., 2020; Rovai et al., 2018). Under future climate scenarios, changes in sea level, rainfall, and temperature are expected to alter these environmental controls, with consequences for carbon burial and the stability of existing stocks (Alongi, 2022). Describing the physicochemical setting of a mangrove stand is therefore a prerequisite for interpreting species-level differences in carbon content and for comparing local results with regional and global estimates.

The capacity of mangroves to store carbon is not uniform. It varies with species composition, stand structure, substrate characteristics, tidal dynamics, salinity, temperature, and pH, all of which influence growth, adaptation strategies, and the distribution of species along the intertidal zone. Among the biological traits that shape carbon storage, root systems are particularly important. In mangroves, roots are not only

structures of support but also adaptive organs that enable respiration in anoxic sediments, trap suspended particles, and retain organic matter. Root production is a major but often overlooked component of the mangrove carbon budget, with global rates of belowground production approaching those of the most productive tropical forests (Arnaud et al., 2023). Different root types, such as the stilt roots of Rhizophora, the pencil-like pneumatophores of Avicennia, and the cone-shaped pneumatophores of Sonneratia, also respond differently to sedimentation and can develop new roots and anatomical adaptations when buried (Okello et al., 2020). Pneumatophores and belowground roots act together to facilitate sediment deposition and stabilise accreted sediments, thereby promoting the accumulation of organic matter (Hongwiset et al., 2022).

Species also differ in the carbon content of their tissues. Carbon fractions in mangrove wood vary significantly among species, from about 45.8% in Avicennia marina to 49.8% in Ceriops tagal, and differ among stems, aerial roots, and branches within species (Gillerot et al., 2018). In Indonesia, species-specific analyses have shown that Rhizophora spp. tend to have higher carbon percentages than Sonneratia and Avicennia, which affects carbon storage estimates at the landscape scale (Hilmi et al., 2024). Such differences imply that carbon accounting based on default carbon fractions or on stand-level estimates may obscure important variation among species and organs. Organ-specific studies are particularly valuable because roots, branches, leaves, and reproductive structures differ in their chemical composition, turnover rates, and contributions to litter and sediment carbon.

The three species examined in this study illustrate these contrasts clearly. Rhizophora stylosa develops arching stilt roots that elevate the trunk above the sediment surface and provide mechanical anchorage on exposed or eroding shores, whereas Avicennia marina produces dense networks of slender, pencil-like pneumatophores, and Sonneratia caseolaris forms thicker, cone-shaped pneumatophores that are typical of low-salinity, riverine fringes. Field surveys in the Mekong Delta have shown that stilt roots of Rhizophora and pneumatophores of Avicennia dominate erosion and accretion sites, respectively, and that pneumatophore density and biomass increase where new sediment is deposited (Nguyen et al., 2023). Pneumatophore abundance of A. marina also increases with tree height, girth, and sediment mud content and decreases with sediment oxygen, indicating that root architecture adjusts to the anaerobic conditions that favour organic matter preservation (Al-Khayat & Alatalo, 2021). These observations suggest that root morphology is not merely a taxonomic trait but a functional attribute that links tree growth, sediment dynamics, and carbon retention. Nevertheless, most carbon studies treat root type only as a background description, and empirical comparisons that relate root architecture to the carbon content of both plant organs and the underlying substrate in the same stand remain scarce, particularly in Indonesia, where these three species frequently co-occur along estuarine and coastal fringes.

Previous studies in Indonesia have focused mainly on estimating aboveground carbon, vegetation carbon sequestration, or carbon stocks in stands and substrates using allometric approaches. Few studies have specifically compared the carbon content of different organs and the associated substrate among species with contrasting root systems, and such comparisons are rare for small coastal sites in South Sulawesi. Pokko Beach in Takalar Lama, Takalar Regency, is a coastal area that combines ecological and socio-economic functions but faces pressure from mangrove wood harvesting, coastal land conversion, and limited management. Information on habitat conditions and species-specific carbon content at this site could therefore strengthen the scientific basis

for conservation and rehabilitation. This study aimed to (1) characterise the physicochemical conditions of mangrove habitats at Pokko Beach, and (2) compare the carbon content of the substrate and plant organs, namely roots, branches, leaves, and flowers/fruits, among Rhizophora stylosa, Avicennia marina, and Sonneratia caseolaris, three species with contrasting root systems.

METHOD

The study was conducted from December 2025 to February 2026 in the mangrove area of Pokko Beach, Takalar Lama, Takalar Regency, South Sulawesi, Indonesia, using a quantitative descriptive survey design. A 40 m × 40 m quadrat was established by purposive sampling in a stand where Rhizophora stylosa, Avicennia marina, and Sonneratia caseolaris co-occurred, representing stilt roots, pencil-like pneumatophores, and cone-shaped pneumatophores, respectively; root types were classified according to their aerial root morphology (Nguyen et al., 2023; Al-Khayat & Alatalo, 2021). Water temperature, salinity, and pH were measured in situ in the habitat of each species at the lowest low tide using residual pore and surface water, because these physicochemical variables are known to modulate mangrove carbon stocks across environmental gradients (Kauffman & Bhomia, 2017; Kauffman et al., 2020). Diameter at breast height (DBH) was measured at 1.3 m above the ground, or 30 cm above the highest stilt root for R. stylosa, on the sampled tree of each species.

Samples of roots, branches, leaves, and flowers or fruits were collected from the sampled tree of each species, because carbon fractions differ among organs and species and should not be assumed from a single default value (Gillerot et al., 2018; Hilmi et al., 2024). Substrate samples were collected beneath each species by coring to a depth of 30 cm. All samples were labelled, stored in sealed bags, transported to the Laboratorium Produktivitas dan Kualitas Perairan, Faculty of Marine Science and Fisheries, Universitas Hasanuddin, oven-dried, ground, and analysed for carbon content, which is expressed as a percentage of sample mass; the conversion basis between organic matter and organic carbon was considered when comparing values with the literature (Ouyang & Lee, 2020). Because one tree and one composite substrate sample were analysed per species, the data were tabulated and compared descriptively among species and organs, without inferential statistical testing.

RESULT AND DISCUSSION

The physicochemical conditions of the three mangrove habitats are summarised in Table 1. Water temperature was uniform (28 °C) across habitats, and salinity was brackish, ranging narrowly from 13 ppt under *R. stylosa* and *A. marina* to 15 ppt under *S. caseolaris*. These values indicate a strong freshwater influence at Pokko Beach and fall within the tolerance range of all three species. In contrast, pH differed markedly: the *R. stylosa* habitat was strongly acidic (pH 3.74), whereas the *A. marina* (7.17) and *S. caseolaris* (7.51) habitats were near neutral to slightly alkaline.

Table 1.
Physicochemical parameters of the mangrove habitats at Pokko Beach, Takalar Lama.

Species	Root system	Temperature (°C)	Salinity (ppt)	pH
Avicennia marina	Pencil-like pneumatophores	28	13	7.17

Rhizophora stylosa	Stilt (prop) roots	28	13	3.74
Sonneratia caseolaris	Cone-shaped pneumatophores	28	15	7.51

The low pH under *R. stylosa* is unusual for tidally flushed mangrove water and warrants careful interpretation. Mangrove sediments accumulate reduced iron sulfides, and when these are exposed to air during low tide or drainage, their oxidation can generate acidity; measurements taken from small volumes of residual water at the lowest low tide are particularly sensitive to such local effects. Kauffman and Bhomia (2017) explicitly considered soil pH, salinity, and forest structure as potential controls on mangrove carbon stocks and found that no single factor explains local and regional patterns. The acidic condition recorded here should therefore be regarded as a site-specific observation that requires confirmation through repeated measurements of pore-water pH and redox potential across tidal cycles before it is used to explain differences in carbon content.

Table 2 presents tree size and carbon content of the substrate and organs. *Sonneratia caseolaris* had the largest DBH (18.77 cm), followed by *R. stylosa* (14.32 cm) and *A. marina* (9.86 cm). Carbon content was consistently higher in plant organs (10.17–17.50%) than in the substrate (2.62–4.56%). *Sonneratia caseolaris* showed the highest values in the substrate (4.56%), roots (17.50%), and branches (15.56%), whereas *R. stylosa* showed the highest values in leaves (16.22%) and flowers/fruits (13.95%). *Avicennia marina* generally had intermediate to low organ values, although its substrate carbon (3.73%) was higher than that of *R. stylosa* (2.62%).

Table 2.

Diameter at breast height (DBH) and carbon content (%) of the substrate and plant organs of three mangrove species at Pokko Beach

Species	DBH (cm)	Substrate	Root	Branch	Leaf	Flower/fruit
Avicennia marina	9.86	3.73	13.34	10.63	15.23	11.03
Rhizophora stylosa	14.32	2.62	15.66	11.81	16.22	13.95
Sonneratia caseolaris	18.77	4.56	17.50	15.56	16.15	10.17

The ranking of root and branch carbon content followed the ranking of DBH, with *S. caseolaris* > *R. stylosa* > *A. marina*. Larger trees possess a greater proportion of lignified woody tissue, which is rich in carbon, and global syntheses show that forest structure and tree size contribute *to* the aboveground and root carbon pools, even though they are weak predictors of total ecosystem carbon (Kauffman et al., 2020). The high root carbon of *S. caseolaris* (17.50%) is also consistent with the major role of root production in the mangrove carbon budget (Arnaud et al., 2023). Woody organs differ in carbon fraction among and within species, including between stems, aerial roots, and branches of *Rhizophora* (Gillerot et al., 2018), which supports the species-specific differences observed here. However, the absolute values in Table 2 are considerably lower than the carbon fractions typically reported for mangrove tissues, which range from about 43% to 56% on a dry-mass basis (Gillerot et al., 2018; Hilmi et al., 2024). Such a discrepancy commonly reflects differences in analytical method and in the basis of expression, such as organic matter versus organic carbon or fresh versus dry mass, and conversion factors strongly affect carbon estimates (Ouyang & Lee, 2020). The values reported here are

therefore best interpreted as relative indicators for comparing species and organs within this study rather than as absolute carbon fractions for carbon stock calculations.

Leaf carbon content was high and similar among species (15.23–16.22%), suggesting that photosynthetic tissues of all three species function as important, though short-lived, carbon pools that feed litterfall and sediment organic matter. *Rhizophora stylosa* had the highest leaf and flower/fruit carbon, which may reflect its investment in thick, coriaceous leaves and large viviparous propagules. Species-level carbon percentages in Indonesian mangroves are typically higher for Rhizophora than for Sonneratia and Avicennia (Hilmi et al., 2024), a pattern partly mirrored in the reproductive organs and leaves of this study but not in the roots and branches, where tree size appeared to dominate.

Substrate carbon content was highest under S. caseolaris (4.56%), intermediate under A. marina (3.73%), and lowest under R. stylosa (2.62%). Both Sonneratia and Avicennia produce dense pneumatophores that reduce flow velocity, trap fine sediments, and promote the deposition of organic particles (Hongwiset et al., 2022). Pneumatophore abundance increases with tree size and with sediment mud content, which in turn is associated with anaerobic conditions that slow organic matter decomposition (Al-Khayat & Alatalo, 2021). Pneumatophores and knee roots tend to dominate accreting sites, whereas stilt roots of Rhizophora often dominate sites exposed to erosion (Nguyen et al., 2023), which could reduce the retention of fine organic material. The low substrate carbon under R. stylosa may also be linked to the acidic, possibly oxidised conditions in its habitat, which favour the decomposition of organic matter. In addition, the ability of mangrove roots to respond to sediment burial by forming new roots (Okello et al., 2020) suggests that root architecture influences not only sediment trapping but also the amount of root-derived carbon delivered to the substrate.

Although the substrate showed lower carbon content per unit mass than plant organs, mangrove soils hold most of the total ecosystem carbon because of their large mass and depth, often accounting for more than 80% of total stocks (Kauffman & Bhomia, 2017; Kauffman et al., 2020). Soil carbon storage is also strongly influenced by coastal environmental setting (Rovai et al., 2018), and mangrove soil carbon is highly variable at fine spatial scales (Sanderman et al., 2018). The relatively low substrate values at Pokko Beach, measured only to 30 cm, therefore do not imply a small soil carbon stock; quantifying bulk density and deeper soil layers would be required to estimate stocks per unit area. Protecting these sediments is critical, because land-use change can turn mangroves into carbon sources and rehabilitation recovers soil carbon only slowly (Sasmito et al., 2019).

The findings have practical implications for mangrove management at Pokko Beach. Because each species stores carbon differently among its organs and substrate, mixed-species stands that combine stilt-rooted and pneumatophore-bearing species are likely to maintain more diverse carbon storage pathways than monospecific plantings. Sonneratia caseolaris appears to be a strong candidate for rehabilitation in brackish, low-salinity zones because of its large size and high root, branch, and substrate carbon content, while R. stylosa and A. marina contribute complementary pools in leaves, reproductive organs, and pneumatophore-trapped sediment. Such site-specific evidence supports Indonesian efforts to integrate mangrove conservation into climate commitments (Arifanti et al., 2022) and is relevant given that continued mangrove loss in Southeast Asia could generate large future emissions (Adame et al., 2021). Nevertheless,

the results are based on one tree and one substrate core per species without replication, so they should be considered preliminary. Future studies should include replicated plots, allometric biomass estimation, dry-combustion carbon analysis, soil bulk density, and repeated measurements of pH and redox potential to convert carbon content into reliable carbon stocks.

CONCLUSION

This study showed that the mangrove habitats at Pokko Beach, Takalar Lama, were characterised by uniform water temperature (28 °C), brackish salinity (13–15 ppt), and contrasting pH, ranging from strongly acidic conditions under Rhizophora stylosa (3.74) to near-neutral and slightly alkaline conditions under Avicennia marina (7.17) and Sonneratia caseolaris (7.51). Carbon content was consistently higher in plant organs than in the substrate, and its distribution among organs was species-specific. Sonneratia caseolaris, the species with the largest diameter and cone-shaped pneumatophores, had the highest carbon content in the substrate, roots, and branches, whereas R. stylosa, with stilt roots, had the highest content in leaves and flowers/fruits, and A. marina, with pencil-like pneumatophores, showed intermediate to low organ values but higher substrate carbon than R. stylosa. These patterns suggest that tree size and root architecture jointly shape how carbon is allocated between woody tissues, short-lived organs, and the underlying sediment. Conserving and rehabilitating mixed-species stands that include both stilt-rooted and pneumatophore-bearing species is therefore recommended to sustain diverse carbon storage pathways at this site. Because the results rest on unreplicated samples, future work should apply replicated plots, standardised dry-mass carbon analysis, soil bulk density, and allometric biomass models to convert carbon content into robust carbon stock estimates.

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