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Characteristics of mangroves and carbon stocks estimation in Sampang and Pamekasan Districts, Madura Island, Indonesia

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Abstract. *Ainindya DG, Rarasti KA, Farikha KN, Wiraatmaja MF, Yap CK, Setyawan AD. 2024. Characteristics of mangroves and carbon stocks estimation in Sampang and Pamekasan Districts, Madura Island, Indonesia. Intl J Bonorowo Wetlands 14: 19-24.* Mangrove forests represent unique coastal ecosystems with inherent characteristics and substantial biological diversity. Flourishing in tidal regions submerged during high tide yet devoid of puddles during low tide, mangroves exhibit remarkable salt tolerance. This complex, diverse, and heterogeneous ecosystem serves diverse functions concerning physical, biological, and socio-economic aspects. Madura Island, Indonesia has extensive mangrove forests, especially along the southern coasts of Sampang and Pamekasan, which serve as centers of robust economic activity. This study aims to elucidate the characteristics and assess the carbon storage and absorption capacity of mangroves in Sampang and Pamekasan Districts, Madura, Indonesia. Employing direct observational methods, this study established plots measuring 10×10 m at four stations in December 2023. The average carbon stock in the study area stands at 42,605 tons/ha, with an estimated sequestration value averaging 1,5625 tons/ha. These findings align with the range prescribed by the IPCC for tropical wet areas, falling between 8.7 and 384 tons/ha. Among the three extant mangrove species, *Sonneratia alba* Sm. emerged as the primary contributor to the high carbon sequestration observed in the region. The study area hosts three mangrove species: *Avicennia marina* (Forssk.) Vierh., *Rhizophora stylosa* Griffith, and *S. alba*. The Importance Value Index (IVI) of *R. stylosa* was 111.91%, *S. alba* was 56.52% and *A. marina* was 25.32%. Mangrove stands with a Diameter at Breast Height (DBH) of less than 10 cm predominate across all stations, comprising 80% of *A. marina*, 98% of *R. stylosa*, and 63% of *S. alba*.

Keywords: Allometric equations, *Avicennia marina*, biomass, carbon sequestration, IVI, *Rhizophora stylosa, Sonneratia alba*

INTRODUCTION

Mangrove forests, thriving in some coastal ecosystem areas, exhibit unique characteristics, such as salinity tolerance achieved through salt secretion in leaves or roots (Srikanth et al. 2016), and have substantial biological wealth potential. Recognized for their relatively high productivity (Dali 2023), these mangrove forests typically flourish in tidal zones flooded at high tide, remaining free of inundation during low tide and having remarkable salt tolerance. Mangroves have complex, diverse, and heterogeneous ecosystem characteristics and are widely found in tropical and subtropical climates (Nauta et al. 2023). The distinctive characteristics of mangrove ecosystems endow mangrove forests with several physical, biological, and socio-economic functions. In terms of their physical function, mangroves serve as protective barriers for coastal areas, mitigating abrasion, waves, wind, seawater intrusion, and the impact of large storms. The structural configuration of mangrove trees, including their trunk and root systems, exerts an attractive force that disperses wave energy and diminishes wave height (Damastuti et al. 2023). In Indonesia, efforts to mitigate climate change have included the conservation and restoration of mangrove ecosystems (Ickowitz et al. 2023). Biologically, mangrove forests function as habitats for various marine species, including crabs and mollusks. Economically, these forests benefit communities through the utilization of wood and non-timber products for handicrafts, construction, medicine, and tourism.

Furthermore, mangrove forests play a vital role in conserving soil and water resources, sequestering carbon, providing wildlife habitats, and maintaining ecological balance (Sobhani and Danehkar 2023). On Madura Island, mangrove forests grow densely and are characterized by moderately sized trees. These ecosystems are typically situated along coastal areas and river estuaries that lead to the sea (Rosadi et al. 2018).

Mangroves, known as wave protection plants found around the coast of Indonesia, including Madura Island (Prihantini et al. 2022), play a crucial role in safeguarding the south coast of Sampang and Pamekasan districts, where economic centers thrive. The economic activity on the Southern coast of Madura Island highlights the significance of mangroves providing essential resources and protection against coastal abrasion. Typically confined to tidal zones, such as estuaries, coastlines, and muddy beaches (Hidayah et al. 2015; Muzaki et al. 2017), mangroves on Madura Island exhibit notable diversity, with the assemblage of species like *Avicennia marina* (Forssk.) Vierh. and

Sonneratia alba Sm., which are represented by pneumatophore root systems and species such as *Rhizophora* spp. and *Bruguiera* spp. having a tap root system. Muzaki et al. (2017) reported 12 true mangroves and around 25 associated mangroves on Madura Island, covering a total area of 15,118 ha, with a dominant density of over 1,500 individuals per hectare (Muhsoni and Pi 2014).

The capacity of mangrove forests to absorb carbon dioxide (CO_2) and release oxygen (O_2) is better than that of terrestrial forests (Shiau and Chiu 2020). Adaptation of mangrove plants to anaerobic environments enhances their ability to store carbon for extended periods. Carbon stocks in mangrove forests are primarily distributed in plant biomass, and only about 11% are stored in sediments (Li et al. 2018). The considerable carbon sequestration potential of mangroves positions them favorably within the Clean Development Mechanism (CDM) program under the Kyoto Protocol (Cui et al. 2018). Trees and plants absorb carbon dioxide (CO_2) through sequestration during photosynthesis, with a portion returning to the atmosphere through respiration, while the rest is stored in leaves, stems, and roots (Hidayah et al. 2022). Given the significant variability in carbon storage and sequestration rates across mangrove locations and districts, this study provides crucial insights into mangrove characteristics and estimates of carbon storage and uptake in Sampang and Pamekasan Districts, Madura Island.

MATERIALS AND METHODS

Study area

This study was conducted in December 2023 within a mangrove area on the south coast of Madura Island, East Java Province, Indonesia. The study was confined to 4 stations, i.e., Taddan and Aeng Sareh Villages in Sampang District, as well as Tlanakan and Branta Tinggi Villages in Pamekasan District (Table 1, Figure 1). Table 1 also presents various abiotic parameters measured at the study site, including temperature, pH, salinity, and humidity. The lowest water and soil temperatures were recorded at Taddan at low tide, where seawater was still present on the surface, with temperatures of 30.67°C and 30.33°C, respectively. Conversely, the highest temperatures were observed in Tlanakan, with water temperature reaching 36°C and soil temperature reaching 35°C. Air temperature varied from 31.7°C in Taddan Village to 37.17°C in Branta Tinggi Village.

Additionally, the pH of water across the four study stations showed alkaline properties in the range of 7.6-8.03, while soil pH ranged slightly acidic, between 6-7.1. Salinity levels ranged from 19.67-32.67 ppt. Salinity and pH have been recognized as limiting factors influencing biodiversity in mangrove areas (Sarker et al. 2019). Ahmed et al. (2022) highlighted that low salinity levels contribute to maintaining the ecological stability of mangroves. Moreover, soil moisture across all stations exceeded 10.

Table 1. Location, coordinates, and abiotic parameters of the sampling station

Station name	Location	Coordinates	Water temp (°c)	Soil temp (°c)	Air temp (°c)	Water pH	Soil pH	Salinity (ppt)	Soil Moist
1	Taddan, Sampang District	7°12'59.6"S 113°16'27.4"E	30.67	30.33	31.7	7.6	6	28.22	>10
2	Branta Tinggi, Pamekasan District	7°13'18.0"S 113°27'13.9"E	34.33	34.33	37.17	7.37	6.97	19.67	>10
3	Tlanakan, Pamekasan District	7°13'17.3"S 113°26'18.2"E	36	35	36.33	8.03	7.1	32.67	>10
4	Song Osong Beach, Aeng Sareh, Sampang District	7°13'19.9"S 113°12'13.4"E	35.67	34.67	36.33	7.53	6.97	19.67	>10

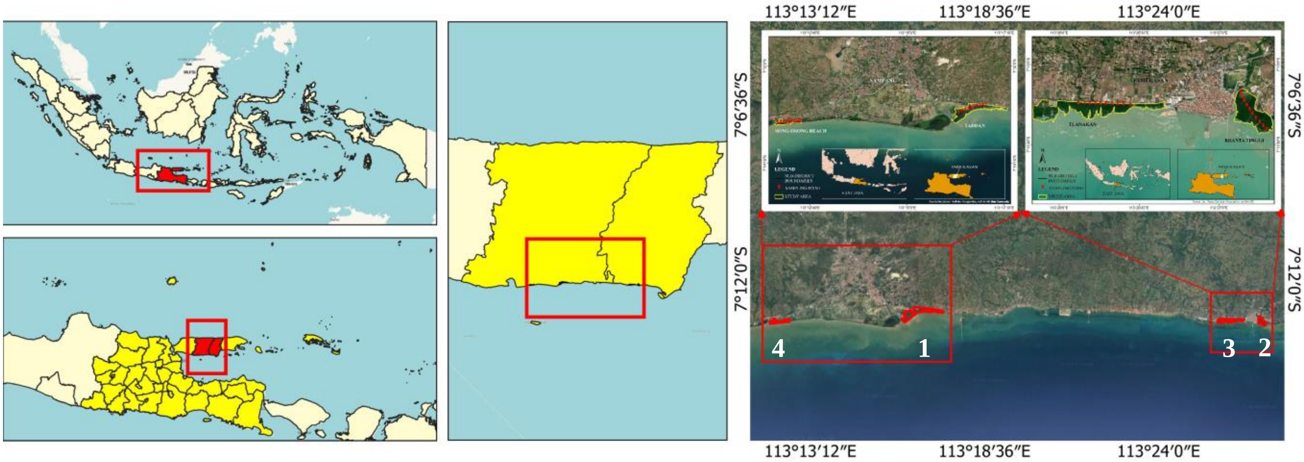

Figure 1. Study area in Madura Island, East Java Province, Indonesia. Note: 1. Taddan, Sampang District, 2. Branta Tinggi, Pamekasan District, 3. Tlanakan, Pamekasan District, 4. Aeng Sareh, Sampang District

Data collection

Data collection involved establishing plots measuring 10 m × 10 m in mangrove area. The study was conducted across four stations, each exhibiting distinct environmental conditions: the first station had muddy terrain subject to flooding, while the second, third and fourth stations had sandy terrain without flooding. Data collection was carried out with 10 repetitions at each station, resulting in a total of 40 plots. Measurements were carried out using the Diameter at Breast Height (DBH) method, where the circumference of mangrove trunks was measured at the height corresponding to an adult's chest (Fatma et al. 2018). Stem diameter measurements were obtained from samples collected at each plot, followed by the assessment of species abundances within each plot at every station. Species names and individual counts were recorded using a tally sheet.

Additionally, abiotic parameters were recorded at the four stations with three in-situ repetitions. These parameters included temperature (water, soil and air), measured using a soil thermometer; pH (water and soil), assessed with a pH meter; salinity, determined using a refractometer; and soil moisture, gauged with a soil moisture meter. The collected data were subsequently averaged.

Importance Value Index (IVI)

One of the objectives of mangrove vegetation analysis is to calculate the Importance Value Index (IVI), as proposed by Bray and Curtis (1957), which is derived from the sum of relative frequency, relative density, and relative dominance (Hanggara et al. 2021). The IVI of a species typically ranges from 0 to 300. This important value provides an overview of the influence or role of a type of mangrove plant in the mangrove community. According to Hidayah et al. (2022), the IVI of each species for each transect is calculated using the following formula:

$$Di = ni/A; \quad Rdi = [ni/\Sigma n] \times 100$$

Where :
Di : Species-i density
Rdi : Relative density of species i
ni : Total number of i-species
Σn : Total number of all species
A : Total sampling area (1000 m^2)

$$Fi = pi/\Sigma F; \quad RFi = [Fi/\Sigma F] \times 100$$

Where :
Fi : Frequency of species-i
Rfi : The relative frequency of species-i
Pi : Number of plots where species-i found
ΣF : Number of plots on each transect

$$Ci = \Sigma BA/A; \quad RCi = [Ci/\Sigma c] \times 100$$

Where :
Ci : Species-i coverage
Rci : Relative coverage of i-species
ΣBA : $\pi d/4$ (π=3.14; d=DBH)
ΣC : Total coverage of the entire species
A : Total sampling area (1000 m^2)

$$IVI = RDi + RFi + RCi$$

Biomass and carbon stock estimation

This study employed allometric methods incorporating DBH-independent variables to estimate Aboveground Biomass (AGB) and Belowground Biomass (BGB) for each recorded mangrove species. AGB refers to the total mass of a plant's living component located above the ground, including stems, branches, leaves, flowers, and other structures (Xu et al. 2020). Conversely, BGB encompasses the total weight of all plant parts located below the soil surface, such as root systems, bulbs, rhizomes, and others (Dayathilake et al. 2020). The relationship between AGB and BGB is often used to assess the impact of biotic and abiotic effects on the growth and development of individual plants. Table 2 presents an allometric model for estimating the biomass of each species.

Following the assessment of carbon biomass, an estimate of the carbon stock (Cn) and carbon sequestration potential (Sn) was carried out. Several studies have employed specific values tailored to distinct forest types to estimate carbon stocks at various plant structural levels and within plant communities (Zhou et al. 2023). The carbon content value was derived by multiplying the biomass content of mangrove trees by a fixed organic carbon content factor, typically set at 0.47 as established by the National Standardization Agency (BSN: *Badan Standardisasi Nasional*) (Dewanti et al. 2020). Carbon sequestration potential signifies the capacity of plants to bind and store atmospheric carbon for extended periods (Nwankwo et al. 2023). The equation used to determine the values of Sn and Cn derived from Hidayah et al. (2022) is presented below:

Table 2. Allometric equation for calculating biomass (kg)

Species	Species Allometric Model		References
	Aboveground Biomass (kg)	**Belowground Biomass (kg)**	
Avicennia marina (Forssk.) Vierh.	$0.079211 \times D^{2.478095}$	$0.079211 \times D^{2.478095} \times 0.25$	Sutaryo (2009)
Rhizophora stylosa Griffith	$0.128 \times D^{2.60}$	$0.134 \times D^{2.40}$	Clough and Scott (1989) Gevana and Im (2016)
Sonneratia alba Sm.	$0.251 \times \rho \times D^{2.46}$	$0.3841 \times \rho \times D^{2.101} \times 0.25$	Komiyama et al. (2005)

Note: D: DBH (cm); ρ: density of wood (gr/cm^3); *Avicennia marina* ρ: 0.506; *Sonneratia alba* ρ: 0.475

$$C = B \times 0{,}47$$

$$C_n = \frac{C_X}{1000} \times \frac{10000}{L_{tr}}$$

$$SCO_2 = \frac{MR\ CO_2}{Ar\ C} \times C_n$$

$$S_n = \frac{SCO_2}{1000} \times \frac{10000}{L_{tr}}$$

Where :
C : Carbon stock (kg)
C_x : Total carbons for each transect (kg)
B : Biomass (kg)
Ltr : Total transect area (m^2)
Cn : Carbon per hectare (ton/ha)
MR CO_2: Relative molecular mass (44)
Ar C : Atom mass C (12)
Sn : Carbon sequestration (ton/ha)

RESULTS AND DISCUSSION

Characteristics of mangrove community structure

The Importance Value Index (IVI) analysis revealed that *R. stylosa* exhibits the highest value among all species within the study area. This dominance likely stems from its remarkable adaptation and tolerance to local climatic and soil conditions. The *R. stylosa* thrives in diverse environments, including muddy, sandy, stony soils and even coral areas. Notably, its anchor roots system has an important role, especially in facilitating gas exchange within sediments characterized by low oxygen levels (Azahra et al. 2020). Mangrove habitats are typically characterized by low-oxygen mud, and the lenticels on these anchor roots enable efficient gas exchange.

Additionally, these roots contribute to the species' ability to withstand tidal fluctuations (Mori et al. 2022). This adaptation aligns perfectly with the study area's location in the proximal coastal zone, directly exposed to the sea. Consequently, the species composition within this zone is heavily influenced by seawater presence. For instance, sandy areas tend to be dominated by *S. alba*, while muddy areas favor *A. marina* and *R. stylosa*.

Characteristics of mangrove stands based on Diameter at Breast Height (DBH)

Further analysis of variations in stand characteristics among the three prevalent mangrove species revealed that most individuals possessed DBH of less than 10 cm. This indicates that the mangrove stand at the study site falls within the young vegetation category. Table 4 summarizes the DBH data for all species, presenting minimum and maximum statistical parameters with a range value from 3.18-64.65 cm. The *A. marina* exhibited a DBH range of 4.14-25.48 cm across all stations, while *R. stylosa* ranged from 3.18 cm to 14.65 cm. The *S. alba* demonstrated the widest DBH range, spanning from 3.18 cm to 64.65 cm, across all four stations. In terms of stand density, *R. stylosa* displayed abundance, with 367 individuals at station 2 and 191 individuals at station 3. This dominance likely coincides with the observation from Figure 2 that the majority of *R. stylosa* possesses a DBH of less than 10 cm.

Moreover, Figure 2 visually confirms that young mangroves with DBH less than 10 cm dominate all three species across the stations. On average, 80% of *A. marina*, 98% of *R. stylosa*, and 63% of *S. alba* individuals fall into this young category. Considering the prevalence of mangroves with DBH less than 10 cm in Sampang and Pamekasan districts, the mangrove vegetation at these locations can be classified as relatively young compared to stand characterized by larger DBH values (Hidayah et al. 2022). This notion is further supported by station 2, which exhibits the highest stand density but also the lowest average DBH (5.01 cm), placing it within the young plant category (as shown in Table 4).

Table 3. Characteristics of mangrove species structure in Sampang and Pamekasan Districts, East Jawa, Indonesia

Mangrove Species	Relative Density (RDi)	Relative Frequency (RFi)	Relative Coverage (RCi)	IVI
Sonneratia alba	40.52	16.00	0.01	56.52
Avicennia marina	14.31	11.00	0.00	25.32
Rhizophora stylosa	83.91	28.00	0.00	111.91

Table 4. Statistics of mangrove stands observed in Sampang and Pamekasan Districts, East Jawa, Indonesia

Statistical Parameters of DBH (cm)	Station 1		Station 2	Station 3		Station 4		
	Avicennia marina	*Sonneratia alba*	*Rhizophora stylosa*	*Avicennia marina*	*Rhizophora stylosa*	*Avicennia marina*	*Rhizophora stylosa*	*Sonneratia alba*
Number of stands (N) per 1000 m^2	10	77	367	56	99	6	191	64
Minimum	8.6	3.18	3.18	4.46	3.50	4.14	3.18	4.14
Maximum	16.56	52.23	11.15	25.48	14.65	4.78	13.38	64.65
Median	13.38	11.78	4.46	6.37	6.05	4.30	5.73	7.64
Sample variance	6.34	78.21	2.28	12.62	5.83	0.07	2.13	65.83

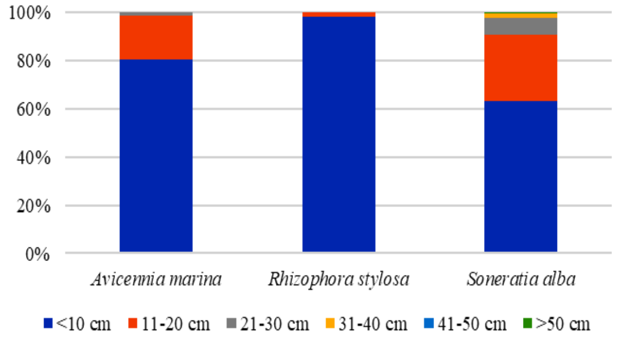

Figure 2. DBH class of mangrove species in Sampang and Pamekasan regencies, East Jawa, Indonesia

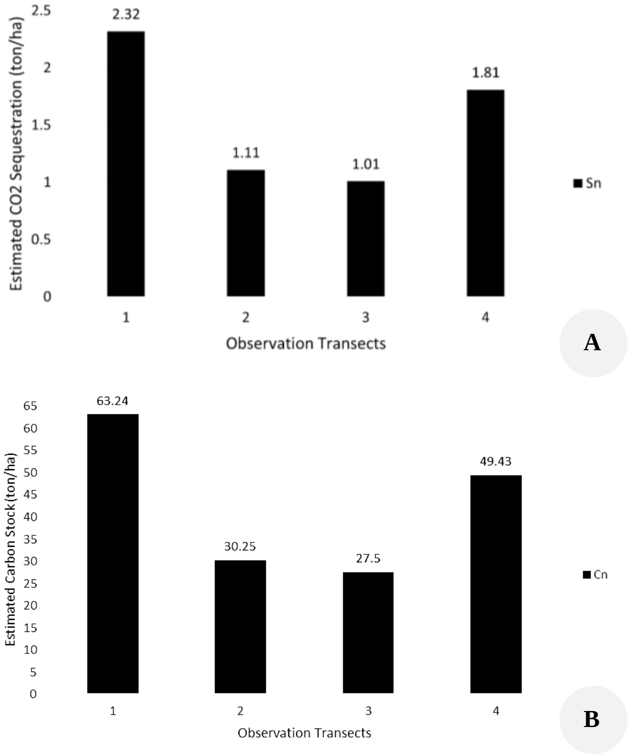

Figure 3. A. Sequestration of carbon and B. CO_2 stocks from 4 stations in Sampang and Pamekasan Districts, East Jawa, Indonesia

Carbon stock and sequestration estimation

Analysis of 40 plots spread across four observation stations revealed a range in AGB of 3,716.10-11,965.53 kg/1000 m^2, with an average value of 6,849.81 kg/1000 m^2. Similarly, BGB ranged from 2,100.27-2,719.42 kg/1000 m^2, with an average value of 2215.2875 kg/1000 m^2. Carbon stock estimates, derived from AGB and BGB values, varied between 27.50-63.24 tons/ha, with an average of 42.605 tons/ha. The estimated sequestration potential ranged from 1.01-2.32 tons/ha, with an average of 1.5625 tons/ha. The spatial distribution of carbon stocks and sequestration values across the transects are depicted in Figure 2.

Discussion

The estimated average carbon stock (42.605 tons/ha) in this study falls within the range established by the IPCC for tropical wet regions (8.7-384 tons/ha) (Alimbon and Manseguiao 2021). However, this value is considerably lower compared to other mangrove ecosystems in Java, Indonesia, such as Karimunjawa (124.44 tons/ha) (Hickmah et al. 2021), Harapan and Kelapa Island, Jakarta (634.54 tons/ha) (Easteria et al. 2022), Damas Beach Trenggalek (200.53 tons/ha) (Nur et al. 2022), Bregasmalang, Central Java (713.13 tons/ha) (Sugiatmo et al. 2023), and Ijo river estuari, Kebumen (1143.31 MgC/ha) (Ningtyas et al. 2023).

Several environmental factors likely contribute to these variations in carbon storage. Data on water, soil, and air temperature parameters were collected across the four study locations. Station 1 exhibited the highest carbon uptake, potentially due to temperatures more favorable for mangrove growth (20-28°C) (Farhaby et al. 2020). Soil and water pH varied from 6-7.1 and 7.37-8.03, respectively, whereas Dewiyanti et al. (2021) have highlighted pH values of 6-7 to be suitable for mangrove growth. Notably, the measured salinity values fell outside the range considered suitable for optimal mangrove growth (23.33-26.33).

The size of mangrove trees is another critical factor influencing biomass and carbon stocks. Older stands have a higher potential for soil carbon storage due to the accumulation of organic matter in sediments (Arif et al. 2017). As evidenced by Figure 2, the majority of mangroves in the study, especially Sampang and Pamekasan districts, possess a DBH of less than 10 cm, suggesting a relatively young stand compared to areas with larger DBH values (Hidayah et al. 2022). This younger stand structure likely contributes to the lower overall carbon stock. Species composition and stand density are also key determinants of carbon stock density (Kauffman et al. 2020). Station 1, dominated by *A. marina* and *S. alba* (with the largest average DBH and high IVI value according to Tables 3 and 4), exhibited the highest carbon stock (Figure 3). Conversely, station 4, containing a mix of three species (*A. marina*, *R. stylosa*, and *S. alba*), had a lower estimated carbon stock. This is different from the research of Purwanto et al. (2021) in the Pangarengan mangrove forest, Cirebon, Indonesia, which shows that carbon stocks on multispecies land are higher than on monospecies land.

In conclusion, a study on mangrove areas on the Southern coast of Madura Island, East Java Province, found an average stock of 42.605 tons/ha and an estimated carbon sequestration value ranging from an average of 1.5625 tons/ha. These values fall within the range set by IPCC for tropical wet regions (8.7-384 tons/ha). Among the three existing species (*A. marina*, *R. stylosa*, and *S. alba*), *R. stylosa* had the highest IVI (111.91%). The dominating stands across the stations were young mangroves with DBH less than 10 cm (an average of 80% for *A. marina*, 98% for *R. stylosa*, and 63% for *S. alba*). The dominance of young mangrove stands suggests the importance of stand maturity for enhancing carbon storage potential in this area.

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