



Research article

Soil organic carbon study in mangroves with diverse vegetation and seasonal variations

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Article Info

Article history:

Received 16 April 2025

Revised 29 December 2025

Accepted 11 March 2026

Available 17 April 2026

Keywords:

Mangrove,
Season,
Segara Anakan Lagoon,
Soil organic carbon

Abstract

Importance of the work: Mangroves are major global carbon sinks, where effective coastal ecosystem management is crucial to understand seasonal soil organic carbon (SOC) dynamics.

Objectives: To analyze the spatial distribution and seasonal variation in SOC in the mangrove forest of Segara Anakan Lagoon, Indonesia.

Materials and Methods: An observational method with purposive sampling was used across two primary stations, each containing three sites with five replicate plots (30 plots total). Sampling was conducted during four seasonal periods May 2023–February 2024. The main parameter measured was SOC concentration, with supporting variables including temperature, salinity and pH.

Results: The highest mean $\pm$ SD SOC concentration ($3.09 \pm 0.61\%$) was at Station 1.1, dominated by *Sonneratia caseolaris* (L.) Engl., while the lowest ($1.61 \pm 0.34\%$) occurred at Station 2.1, characterized by *Acanthus ilicifolius* L. and *Derris trifoliata* Lour., indicating ecosystem degradation. Seasonally, the SOC peaked in February ($3.98 \pm 0.12\%$) and was lowest in August ($1.20 \pm 0.39\%$). Dunn's *post-hoc* test showed significant differences in SOC between the dry and rainy seasons and across transitional periods. Principal components analysis revealed strong associations between SOC, rainfall and the number of rainy days. During the rainy season, increased litterfall and soil moisture supported anaerobic conditions, slowing decomposition and enhancing SOC accumulation.

Main finding: The distribution of SOC concentrations in the Segara Anakan Lagoon was influenced by litter productivity and rainfall patterns.

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<https://doi.org/10.34044/j.anres.2026.60.2.09>

Introduction

Soil organic carbon (SOC) has been used as a key indicator in assessing soil quality and its capacity to store carbon over the long term (Siddique et al., 2025). In coastal ecosystems, such as mangrove forests, SOC plays a crucial role not only in supporting soil productivity and stability but also in mitigating climate change through its function as a blue carbon reservoir (Chen et al., 2023). Mangroves are recognized as one of the ecosystems with the highest rates of carbon accumulation due to their ability to store carbon both in biomass and in waterlogged, anaerobic sediments (Zakaria et al., 2021; Alongi, 2022; Akram et al., 2023).

Organic matter in mangrove forests originates from both autochthonous sources (mangrove vegetation itself) and allochthonous inputs (sedimentation and river flow) (Wang et al., 2024; Ye et al., 2024). Sedimentary carbon in mangrove areas is predominantly autochthonous, contributing approximately 27–97%, while allochthonous sources account for about 0–35% (Xiong et al., 2018). However, the SOC content in mangrove soils is not static, being influenced by a variety of environmental dynamics, including seasonal fluctuations that affect soil moisture and salinity (Sofawi et al., 2017; MacKenzie et al., 2021), tidal patterns (Chen et al., 2023) and the input and decomposition of organic matter (Zhang et al., 2021). Seasonal variations between the rainy and dry seasons can substantially alter the microclimatic conditions of mangrove ecosystems, thereby affecting microbial activity, organic matter decay (Nguyen et al., 2022) and the movement of water and nutrients in the soil (González-Farías et al., 2024).

During the rainy season, water availability can stimulate plant phenological cycles, potentially increasing litterfall input to the soil. Often, this increased moisture and water saturation lead to anaerobic conditions and slower decomposition rates, thereby promoting higher SOC accumulation. In contrast, during the dry season, limited water availability, elevated salinity and temperature and higher evaporation rates may lead to plant dieback, reducing litter productivity and consequently lowering SOC levels (Kida and Fujitake 2020). These variations demonstrate that seasonal changes exert a complex influence on SOC dynamics in mangrove forests.

Segara Anakan, located in Cilacap Regency, Central Java, Indonesia is one of the largest and most ecologically important mangrove areas on the island of Java. This region has unique hydrological characteristics due to its connection with the Citanduy River to the north and the Indian Ocean to the south, resulting in highly dynamic tidal flows and sediment supply

(Cahyo et al., 2024). Furthermore, anthropogenic pressures, such as land conversion and fishing activities, impact ecosystem stability (Jennerjahn et al., 2022; Syafina et al., 2024), as well as the area's capacity for organic carbon storage (Widyastuti et al., 2018).

Kresnasari and Gitarama (2021) studied sedimentary SOC in this region and reported concentrations in the range 0.48–3.324%. However, research remains limited focusing on seasonal variations in the SOC concentration within the Segara Anakan mangrove ecosystem. Understanding the seasonal dynamics of SOC is crucial as a foundation for sustainable conservation planning and ecosystem management. Identifying how seasonal shifts influence the accumulation and distribution of soil organic carbon can help to determine critical periods and develop appropriate adaptive strategies to maintain the ecological and climatological functions of mangrove forests.

Therefore, the current study aimed to analyze differences in SOC concentrations between the rainy and dry seasons in the mangrove forest of Segara Anakan, Cilacap. The research hypothesis posited that seasonal variation significantly affected SOC levels in the Segara Anakan mangrove ecosystem, with the expectation that extreme dry-season conditions resulted in decreased SOC due to increased temperature, salinity and decomposition activity. Conversely, during the rainy season, the SOC levels were anticipated to increase. This research should contribute to scientific understanding of coastal ecology and support the blue carbon conservation policy in Indonesia.

Materials and Methods

The study was conducted in the Segara Anakan mangrove forest, located in Cilacap, Indonesia (7°06'–7°09' S, 108°08'–108°08' E), as shown in Fig. 1. This mangrove forest is characterized by diverse vegetation without clear zonation. The study used an observational method with purposive sampling. Sampling sites were selected based on vegetation density and composition. Two sampling stations were established: Station 1 (St 1) had high tree density and was dominated by *Sonneratia caseolaris* (L.) Engl., while Station 2 (St 2) had low tree density and was dominated by shrubs, specifically *Derris trifoliata* Lour. and *Acanthus ilicifolius* L. Each station used three sampling points. The research was conducted from May 2023 to February 2024, with the sampling periods determined based on seasonal variations in Indonesia: May 2023 (transition period 1, from rainy to dry season), August 2023 (dry season), November 2023 (transition period 2, from dry to rainy season) and February 2024 (rainy season).

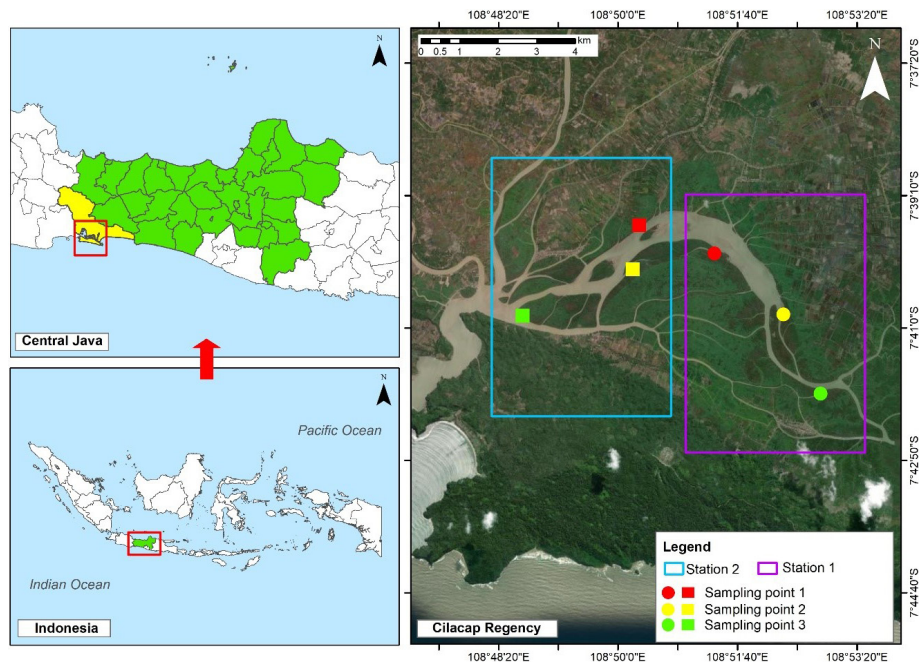


Fig. 1 Research location consisting of two stations, with each station having three sampling points.

Sediment samples were collected during low tide using a polyvinyl chloride corer (5 cm diameter, 30 cm length) that was lowered to the desired depth of 30 cm. Soil samples were cleaned of large particles such as stones and macroorganisms. Then, each sample was oven-dried at 80°C for 24 hr or until a constant weight was recorded. The percentage SOC content was measured using the Walkley and Black colorimetric method (Sulaeman et al., 2005), followed by analysis with an ultraviolet-visible spectrophotometer (U-3900) at a wavelength of 561 nm. The absorbance values obtained were used to calculate the SOC content based on Equation 1:

$$\text{SOC} = \text{Curve ppm} \times (100 / \text{Sample mass}) \times \text{fk} \quad (1)$$

where Curve ppm is the concentration in parts per million derived from the regression curve of standard solutions after subtracting the blank, the mass is measured in milligrams and fk is the moisture correction factor calculated as $100 / (100 - \% \text{ moisture content})$, according to Sulaeman et al. (2005).

The primary variable measured was the SOC concentration, with supporting variables consisting of water salinity, soil salinity, pH, water temperature, air temperature and substrate texture.

Statistical analysis

Statistical analysis used the non-parametric one-way Kruskal-Wallis test, followed by Dunn's *post hoc* test

(Agbangba et al., 2024) to evaluate seasonal differences in the SOC. In addition, principal component analysis (PCA) was used as a multivariate approach to assess the relationships between environmental parameters (soil, water, climate variables) and the SOC concentration. Statistical analysis used the SPSS software (version 26) (IBM Corp., Armonk, NY, USA).

Results and Discussion

Soil organic content distribution

The mean ($\pm$ SD) SOC content and the vegetation composition of the communities are presented in Table 1. The highest SOC concentration was at Station 1.1 ($3.09 \pm 0.61\%$), while the lowest was recorded at Station 2.1 ($1.61 \pm 0.34\%$). This was supported by the results from the current study, with the litter productivity being highest at Station 1.1 ($152.21 \text{ g/m}^2.\text{mth}$) and the lowest at Station 2.1 ($28.59 \text{ g/m}^2.\text{mth}$) (Kresnasari et al., 2025). A key factor influencing the SOC content in an area is litter productivity because organic litter material, such as leaves, twigs and plant parts that fall to the ground serve as the primary raw materials for SOC formation. The low litter productivity at Station 2.1 was attributed to the low tree density and the dominance of shrub vegetation, namely *A. ilicifolius* and *D. trifoliata*. These two species indicated that the area had undergone degradation.

Table 1 Mean $\pm$ SD soil organic content (SOC), with higher SOC values at stations dominated by tree mangroves (Station 1.1) and lower values at stations with greater shrub presence (Station 2.1).

Station	Vegetation distribution	Mean $\pm$ SD SOC (%)
1.1	<i>S. caseolaris</i> , <i>Avicennia alba</i> Blume, <i>Avicennia marina</i> (Forssk.) Vierh, <i>Nypa fruticans</i> Wurmb., <i>Acrosticum aureum</i> L.	3.09 $\pm$ 0.61
1.2	<i>N. fruticans</i> , <i>S. caseolaris</i> , <i>A. alba</i>	1.83 $\pm$ 0.40
1.3	<i>S. caseolaris</i> , <i>A. alba</i> , <i>A. marina</i> , <i>N. frutican</i> , <i>Rhizophora mucronata</i> Poir.	2.34 $\pm$ 0.37
2.1	<i>S. caseolaris</i> , <i>Aegiceras corniculatum</i> (L.) Blanco, <i>A. ilicifolius</i> , <i>D. trifoliata</i>	1.61 $\pm$ 0.34
2.2	<i>S. caseolaris</i> , <i>A. alba</i> , <i>A. marina</i> , <i>R. mucronata</i> , <i>N. frutican</i> .	1.71 $\pm$ 0.58
2.3	<i>A. alba</i> , <i>A. marina</i> , <i>S. caseolaris</i> , <i>N. frutican</i> , <i>A. ilicifolius</i> , <i>D. trifoliata</i> .	1.77 $\pm$ 0.48

Their proliferation is linked to prior uncontrolled deforestation and increased sedimentation, which can lead to elevated freshwater input and the sedimentation can reduce seedling numbers and bury mangrove roots, thereby inhibiting growth and even causing mangrove mortality (Kusumaningtyas et al., 2019; Nordhaus et al., 2019; Winarso et al., 2023). Deforestation negatively impacts litter productivity, which subsequently affects soil fertility, particularly the SOC content. For example, Cooray et al. (2021) noted that soil carbon stocks tended to be substantially higher in areas with dense mangrove cover and substantial vegetative biomass.

Another factor influencing the SOC is the decomposition process carried out by microorganisms. The high SOC content observed at Station 1.1 could have been related to the accumulation of litter due to slow decomposition rates and a low population of decomposer microorganisms. The slower the decomposition rate, the greater the potential for organic carbon to form and be stored in the soil. Conversely, if decomposition proceeds too quickly, more carbon is lost to the atmosphere rather than being retained in the soil (Lyu et al., 2023). The decomposition of litter begins with the leaching phase. Newly fallen mangrove litter loses 20–40% of its organic carbon due to leaching when submerged in seawater for 10–14 days, with the most soluble compounds, such as simple carbohydrates and non-lignocellulosic substances, degrading first (Kristensen et al., 2008). The next phase is fragmentation, where organisms, such as mangrove crabs, gastropods and isopods, break down coarse organic material into smaller particles (Kresnasari and Gitarama, 2024). Next, more complex compounds, such as cellulose and hemicellulose, begin to degrade and subsequently, aerobic microbes (bacteria and fungi) decompose organic matter in oxygen-rich conditions, producing CO₂ as the end product (Gao et al., 2025). Anaerobic microbes (methanogenic bacteria) operate in sediment layers with limited oxygen, producing CH₄ (methane) and CO₂, while microbial enzymes, such as cellulase, ligninase and protease, break down complex compounds into simpler substances such as glucose, amino acids and phosphate (Conrad 2020). Undecomposed organic residues undergo humification, forming stable compounds such as humus and the remaining

organic carbon can bind with soil minerals to form organo-mineral complexes, which protect the carbon from further decomposition, enabling long term carbon storage (Kristensen et al., 2008; Mamidala et al., 2023).

The lignin and tannin contents of vegetation plays a major role in influencing the rate of organic matter decomposition. These two phenolic compounds are antimicrobial and enzyme inhibitors, slowing the decay process of litter, which contributes to the accumulation of SOC (Guo et al., 2024). Research at the location of the current study was conducted by Hilmi et al. (2021), which showed differences in the tannin content between mangrove vegetation types. In *S. caseolaris*, the tannin content was 13.05% in the leaves and 26.17% in the stems, while *A. ilicifolius* had a tannin content of 11.26% and 21.35%, respectively. In *N. fruticans*, the tannin content reached 14.56% in the leaves and 28.12% in the stems, while *R. mucronata* had tannin levels of 14.50% in the leaves and 25.65% in the stems and *A. alba* contained 13.30% tannin in the leaves and 24.66% in the stems. Although the leaves of *S. caseolaris* contained relatively lower tannin concentrations than the other mangrove species, the bark and stem tissues exhibited substantially higher levels indicating that an elevated tannin content in specific vegetative organs, particularly the bark and stems, may play a major role in slowing down litter decomposition processes. Consequently, this may limit the accumulation of SOC within mangrove ecosystems.

Substrate texture plays a major role in SOC storage. For example, in the current study, all observation stations had higher clay percentages (41.54–67.12%) than silt (27.63–42.15%) and sand (0.63–25.05%). Fine-textured soils can store and contain more SOC than coarse-textured soils from the same source material (Krull et al., 2009). A similar pattern was found in mangrove forests in Zhejiang Province, China, where Zou et al. (2023) reported SOC was strongly correlated with the clay fraction (correlation coefficient = 0.85). This fraction has a high surface area and strong interactions with organic matter, thus inhibiting microbial decomposition and slowing carbon loss (Li et al., 2024). Estuarine areas with a finer substrate texture have a higher SOC, which declines as the sand content increases (Wu et al., 2025).

Soil organic carbon concentration based on seasonal variation

The highest SOC concentration across all stations was in February 2024 (3.98%, rainy season), while the lowest was in August 2023 (1.20%, dry season), as shown in Table 2. The *post hoc* Dunn's analysis revealed significant differences in the SOC content based on seasonal variations, specifically between the dry season and transition season 2, the dry season and rainy season, transition season 1 and rainy season, as well as transition season 2 and rainy season (Table 3).

Table 2 Seasonal variation in soil organic content (SOC) across different sampling locations during transition season 1, dry season, transition season 2, and rainy season. Values are expressed as mean $\pm$ SD.

Location	Transition season 1	Dry season	Transition season 2	Rainy season
1.1	2.73 $\pm$ 0.05	2.41 $\pm$ 0.03	3.24 $\pm$ 0.11	3.98 $\pm$ 0.12
1.2	1.75 $\pm$ 0.04	1.38 $\pm$ 0.04	1.78 $\pm$ 0.17	2.39 $\pm$ 0.31
1.3	2.20 $\pm$ 0.06	1.89 $\pm$ 0.04	2.37 $\pm$ 0.04	2.88 $\pm$ 0.06
2.1	1.45 $\pm$ 0.05	1.25 $\pm$ 0.05	1.61 $\pm$ 0.08	2.14 $\pm$ 0.07
2.2	1.33 $\pm$ 0.41	1.20 $\pm$ 0.39	1.93 $\pm$ 0.36	2.38 $\pm$ 0.19
2.3	1.48 $\pm$ 0.05	1.33 $\pm$ 0.05	1.73 $\pm$ 0.09	2.53 $\pm$ 0.06

Table 3 Pairwise comparisons of soil organic content (SOC) among seasons based on Dunn's *post hoc* test.

Comparison	<i>p</i> -value	Adjusted <i>p</i> -value
Dry season vs Transition season 1	0.067	0.400
Dry season vs Transition season 2	0.000	0.002
Dry season vs Rainy season	0.000	0.000
Transition season 1 vs Transition season 2	0.085	0.510
Transition season 1 vs Rainy season	<0.001	<0.001
Transition season 2 vs Rainy season	0.003	0.015

Statistical significance was determined based on adjusted *p*-values (Adj. Sig.), with $p < 0.05$ considered significant. Adjusted *p*-value = *p*-value adjusted based on Bonferroni correction for multiple tests.

Based on the current results SOC concentrations in the Segara Anakan mangrove forest fluctuated seasonally, tending to be higher during the wet season and decreasing significantly during the dry season. This pattern was closely related to rainfall. During the wet season, lower temperatures and increased input of organic matter from litterfall and organic-rich water or sediment deposition contributed to the higher SOC levels. Rainfall transports organic material from the land to the mangrove forest through erosion and surface runoff. The moist, waterlogged and low oxygen soil conditions create an anaerobic environment, slowing down the activity of decomposer microorganisms. However, excessive rainfall can lead to SOC and litter loss in the upper sediment layers

due to runoff or leaching. During the transition from the wet to the dry season, saturated soils begin to dry out, increasing soil oxygenation, which may activate aerobic decomposer microorganisms. Under optimal moisture conditions, this accelerates organic matter decomposition and carbon release as CO₂. However, during extreme drought conditions (dry season), increased salinity causes microbial activity to decline due to water stress, resulting in many microbes entering dormancy or dying (Davidson and Janssens 2006). Conversely, during the wet season, low salinity may cause cell lysis due to excessive water uptake (He et al., 2025) affecting not only microbial processes but also mangrove vegetation conditions. Mangrove plants tend to experience physiological stress during extreme dry seasons due to increased temperature, salinity and drought, leading to reduced leaf production and root growth, directly decreasing litter input to the soil (Kresnasari et al., 2025). During transitional periods (pre-dry and pre-wet seasons), there were no significant differences in the SOC concentrations. The microbial activity gradually increased or decreased, depending on rainfall fluctuations, explaining the SOC dynamics within the biogeochemical cycle. Similar patterns have been observed in the Sundarban mangrove forest, India, where SOC peaks during the wet season due to runoff, sediment deposition and increased litterfall (Mitra et al., 2024). Furthermore, mangrove vegetation generally undergoes active growth phases during the wet season, producing more biomass and litter, which serve as primary carbon inputs into the soil (Twilley et al., 1992).

The phenomenon of increased SOC during the wet season has been reported not only in Segara Anakan, Indonesia. Studies on the SOC content in several other mangrove forests are presented in Table 4. The distribution of SOC in Laguna Segara Anakan reflects seasonal shifts in mangrove carbon dynamics, with values reaching 3.98% during the rainy season and decreasing to 1.20% during the dry season. The increase in SOC levels during months with high rainfall could be attributed to increased litterfall, the influx of sediment rich in organic matter and optimal moisture conditions that promote microbial activity and decomposition. A comparable phenomenon was documented in Brazilian mangroves, where total organic carbon levels escalated to 5.9–6.0% during the rainy season, attributable to heightened organic input and the presence of low-oxygen sediment environments (Ramos et al., 2023). However notably, these seasonal trends are not uniform across all regions. For example, in the Sundarbans, India, SOC levels reached a peak after the rainy season (2.71 $\pm$ 0.03%) but underwent a substantial decrease during periods of peak rainfall, with the decline likely attributable to processes,

Table 4 Comparison of soil organic carbon (SOC) concentrations in mangrove ecosystems across different regions and seasons.

SOC concentration	Vegetation	Location
Highest SOC concentration in February 2024 (3.98%, rainy season), while lowest in August 2023 (1.20%, dry season).	<i>S. caseolaris</i> , <i>A. alba</i> , <i>A. marina</i> , <i>N. frutican</i> , <i>R. mucronata</i> , <i>A. corniculatum</i> , <i>A. ilicifolius</i> , <i>D. trifoliata</i>	Mangrove forest of Laguna Segara Anakan, Cilacap (current study)
Highest SOC concentration after rainy season ($2.71 \pm 0.03\%$) and lowest during rainy season ($0.31 \pm 0.04\%$).	<i>A. marina</i> , <i>Avicennia officinalis</i> L., <i>Excoecaria agallocha</i> L., <i>R. mucronata</i> , <i>Xylocarpus granatum</i> J.Koenig	Mangrove ecosystem in the western Bay of Bengal, India (Banerjee et al., 2021)
Highest SOC concentration in Kelantan Delta during transition season ($50.17 \pm 9.47\%$), while in Johor Park it was during dry season ($53.55 \pm 6.27\%$).	Mangrove species in Kelantan Delta were <i>A. marina</i> and <i>Rhizophora apiculata</i> Blume, whereas dominant species in Johor Park were <i>R. mucronata</i> and <i>Bruguiera cylindrica</i> (L.) Blume,	Mangrove forests in Peninsular Malaysia (Rozainah et al., 2018)
Highest SOC during dry season (12.58%) and lowest during rainy season (3.70%).	<i>Avicennia germinans</i> (L.) L., <i>Laguncularia racemosa</i> (L.) C.F.Gaertn, <i>Rhizophora mangle</i> L.	El Salado Mangrove Estuary, Jalisco, Mexico (González-Farias et al., 2024)
Highest total organic carbon content during rainy season (5.9–6.0%).	<i>R. mangle</i> , <i>L. racemosa</i>	Mangrove forest of Baía de Todos os Santos, Brazil (Ramos et al., 2023)

such as leaching and flushing, resulting from elevated water flow (Banerjee et al., 2021). A comparable phenomenon was evident in the El Salado Mangrove Estuary, where there was a decline in SOC during the rainy season, followed by an increase during the dry season (González-Farias et al., 2024). Conversely, mangrove sites in the Malaysian Peninsula had notably elevated levels of SOC, even during the dry season, with concentrations reaching up to $53.55 \pm 6.27\%$, which might be due to variations in the species composition, sediment characteristics or the analytical methods applied (Rozainah et al., 2018).

In the current study, the vegetation type appeared to be the primary determinant of SOC levels. Dominant species, such as *S. caseolaris*, *R. mucronata* and *Laguncularia racemosa*, exhibit different patterns of organic matter production and root decay, contributing unevenly to soil carbon accumulation.

Conversely, degraded habitats dominated by understory plant species, such as *A. ilicifolius* and *D. trifoliata*, often show a decrease in SOC, consistent with the study results on deforested or disturbed mangrove landscapes reported by Nordhaus et al. (2019).

Relationship between soil organic content and environmental variables

The rotated component plot from the Principal Component Analysis (PCA) illustrates how environmental variables in the mangrove ecosystem are grouped according to their influence on the two main components (Fig. 2). The first principal component (PC1) represents factors associated with soil and water quality, with strong positive loadings from soil salinity,

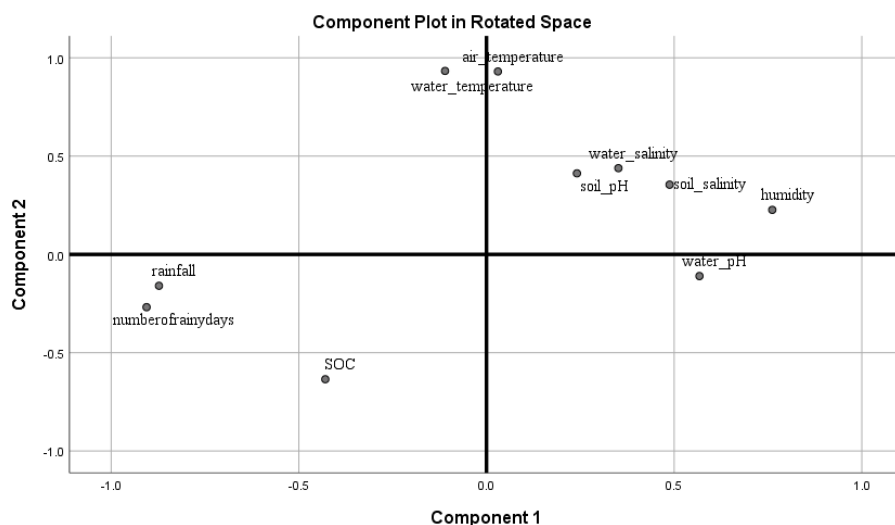


Fig. 2 Principal component analysis, showing the association of soil organic content (SOC) with rainfall-related variables, while the other variables were positioned in different quadrants.

water salinity, soil pH, water pH and humidity. These variables are highly interrelated with positive correlations, suggesting that areas with higher salinity and pH also tend to have higher humidity levels. This pattern reflects typical conditions in mangrove soils during the dry season (Rivera-Monroy et al., 2017). Conversely, rainfall, the number of rainy days and soil organic carbon (SOC) exhibit negative loadings on PC1. This suggests that higher rainfall can dilute salinity and lower pH through freshwater input. In addition, high rainfall may physically remove litter and slow decomposition rates via increased water saturation (Vinh et al., 2020; Simpson et al., 2023), thereby influencing carbon accumulation.

The second component (PC2) shows the primary influence of temperature-related variables. Air temperature and water temperature both have strong positive loadings, indicating a co-varying thermal gradient. However, SOC and rainfall have negative loadings on PC2, suggesting that higher temperatures do not necessarily enhance SOC levels in mangrove soils, possibly due to limited microbial activity under waterlogged conditions (Davidson and Janssens, 2006; Fang et al., 2022). Notably, both soil and water pH were inversely related to SOC. During the decomposition process, microbial breakdown of organic matter generates a range of organic acids, such as humic, fulvic and carbonic acids, that can reduce the pH in both the soil and surrounding water (Liu et al., 2025), resulting in pH patterns that are inversely correlated with SOC levels.

Overall, the PCA identified two major environmental gradients: 1) a physicochemical gradient (salinity, pH and moisture); and 2) a thermal gradient. SOC appeared in an opposite position relative to these variables, suggesting its variation was more closely linked to hydrological processes, such as precipitation, rather than to abiotic stressors such as temperature or salinity. These findings supported other research indicating that carbon storage in mangrove ecosystems is strongly governed by water input, tidal frequency and litter dynamics.

Conclusion

This study revealed that the spatial and temporal distribution of SOC in the Segara Anakan Lagoon mangrove forest was significantly influenced by the vegetation structure and seasonal variation. SOC concentrations were higher in areas dominated by dense mangrove stands, such as *S. caseolaris*, which produced more litter and supported

better decomposition dynamics. In contrast, degraded sites, dominated by understory vegetation such as *A. ilicifolius* and *D. trifoliata*, had significantly lower SOC levels. Seasonally, SOC was highest during the rainy season due to increased litterfall, favorable moisture conditions and the input of carbon-rich sediments through runoff, while the dry season was marked by reduced microbial activity and lower organic inputs.

These findings underscore the critical role of vegetation diversity and hydrometeorological dynamics in maintaining carbon storage functions in mangrove ecosystems. From a management perspective, maintaining vegetation structure and preventing deforestation are essential for sustaining SOC and the ecosystem services provided by mangroves.

However, the study had certain limitations, including the lack of in-depth microbial analysis, sedimentation rate measurements and long-term monitoring data. Future research should incorporate microbial community profiling, soil respiration assessments and isotopic tracing of carbon sources to better understand the complex biogeochemical processes driving SOC dynamics. In addition, long-term studies are needed to evaluate the resilience of SOC under projected climate change scenarios and extreme weather events.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Funding support was received from: Our gratitude goes to Beasiswa Pendidikan Indonesia, BPI (The Indonesian Education Scholarship); Pusat Pelayanan Pembiayaan dan Asesmen Pendidikan Tinggi, PPAPT (Centre for Higher Education Funding and Assessment), Ministry of Higher Education, Science and Technology of the Republic of Indonesia; Lembaga Pengelola Dana Pendidikan, LPDP (Endowment Fund for Education Agency), Ministry of Finance of Republic Indonesia (contract number 010880/PPAPT.1.2/BPI.06/02/2025). Academic support was provided by staff in the Faculty of Fisheries and Marine Science, Diponegoro University and in Nahdlatul Ulama Purwokerto University.

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