EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(9), 92–108
https://doi.org/10.12912/27197050/209460
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.29.07
Accepted: 2025.08.15
Published: 2025.09.01

Vertical profiles of physicochemical properties and nutrients in mangrove and non-mangrove sediments of the small islands of Bali, Indonesia

Anak Agung Eka Andiani[1], Tri Prartono[2*], Rastina[2], Adriani Sunuddin[2]

[1] Graduate Program of Marine Science, Faculty of Fisheries and Marine Sciences, IPB University. Campus IPB Dramaga, Bogor 16680, West Java, Indonesia
[2] Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University. Campus IPB Dramaga, Bogor 16680, West Java, Indonesia
* Corresponding author's e-mail: tripr@apps.ipb.ac.id

ABSTRACT

Coastal sediments play a dual role in biogeochemical processes, both as a medium for substance storage and transformation, and as a natural archive, recording the historical traces of environmental change, including possible changes in mangrove coverage and species composition. This study is to disclose the mangrove zone in modifying the biogeochemical characteristics of sediments. The 50 cm sediment cores were collected at three stations representing variations in mangrove and non-mangrove stand structure and analyzed in various layers. Grain size, color, pH, salinity, oxidation-reduction potential (ORP), organic carbon (C-organic), total nitrogen (TN), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and total phosphorus (TP) were measured from the concerned layers of sediments. The results revealed that gradual decreases in pH, ORP, C-organic, and nutrient concentrations in mangrove sediment profiles were observed, suggesting chemical processes associated with increasing anoxic/reducing conditions in deeper layers. In contrast, those in the non-mangrove sediments apparently varied. Principal component analysis (PCA) demonstrated clear spatial segregation among stations. Mangrove sediments were characterized by fine-grained sediments, higher C-organic, and enriched nutrient profiles, whereas coarser textures, alkaline conditions, and low nutrient concentrations were observed in the non-mangrove sediments. Different profiles of sediment properties across these distinctive zones were also identified. These weaker associations with any dominant parameter were probably related to the influence of sparse stand structure, simple mangrove morphology, and dynamics of site hydrology. These findings highlight the critical role of mangrove in biogeochemical processes to form and modify properties of the physico-chemical sediment, and possibly the ecological function of coastal environments.

Keyword: biogeochemistry, mangrove, nutrient, physicochemical properties, sediment.

INTRODUCTION

Coastal sediments play an essential role as a medium of storage, conversion, and the cycle of substances, including organic matter and nutrients. In addition to functioning as a site for key biogeochemical processes such as decomposition, mineralization, and nutrient retention, sediment also reflects the prevailing physicochemical conditions of the environment (Castro-Rodríguez et al., 2018; Kalev and Toor, 2018; Sarker et al., 2020). Furthermore, sediments preserve historical records of temporal changes, thereby reflecting the long-term dynamics of an ecosystem (Sarker et al., 2020). Parameters such as pH, salinity, ORP, texture, color, and C-organic are essential indicators for assessing the functional status and stability of sediments, spatially and vertically. One of the key drivers forming these sediment characteristics is the presence of vegetation cover, particularly mangrove ecosystems (Alongi, 2021; Gijsman et al., 2023).

The presence of mangroves significantly influences and modifies sediment characteristics through litter accumulation, root structural complexity, and the alterations of biogeochemical processes (Gijsman et al., 2023). Mangrove roots trap fine particles and organic matter, enrich sediments with nutrients, and create redox microzones that facilitate biogeochemical processes (Kristensen et al., 2017; Castro-Rodríguez et al., 2018). The zonation of mangrove species along the intertidal gradient influences patterns of sediment accumulation and the distribution of organic matter beneath the canopy, as different species exhibit varying tolerances to environmental conditions (Bourgeois et al., 2019). Conversely, non-mangrove coastal areas are typically characterized by coarse sediment texture, low organic matter content, and homogeneous and limited nutrient distribution (Castro - Rodríguez et al., 2018).

Nutrient dynamics, particularly those involving nitrogen (N) and phosphorus (P), are closely regulated by the presence of vegetation, sediment physicochemical conditions, and microbial activity (Alongi, 2020). In sediments, nutrients such as ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}) are closely linked to organic matter input, redox conditions, and biogeochemical processes, including ammonification, nitrification, and denitrification (Chowdhury et al., 2019; Alongi, 2020). Mangrove vegetation contributes significantly to these processes through litterfall input and complex root structures, which enhance organic matter availability and facilitate microbial activity that drives sediment biogeochemical transformations. Consequently, vertical nutrient stratification is commonly observed in vegetated sediments, reflecting progressive sedimentary succession and increasing biogeochemical complexity with depth (Aprilia et al., 2020). In contrast, non-mangrove areas, lacking substantial organic inputs, exhibit more homogeneous and stagnant vertical distribution of nutrients. These contrasting patterns emphasize sedimentary dynamics across ecosystems and highlight the importance of location-specific studies to reveal nutrient distributions within ecological variability.

Previous studies have highlighted the role of mangrove in sediment biogeochemical processes in various regions. These studies indicate that mangrove sediments possess finer textures, higher organic matter content, and more complex nutrient stratification than their non-mangrove counterparts (Castro-Rodríguez et al., 2018). However, most studies have been conducted in major terrestrial ecosystems or areas with extensive and homogeneous mangrove coverage. Detailed knowledge of the vertical variation in sediment physicochemical properties and nutrient distribution on small islands, particularly those exhibiting pronounced differences in mangrove density and species composition, remains limited. This knowledge gap is particularly relevant in areas such as Nusa Lembongan and Nusa Penida, which have distinct differences in mangrove composition. Nusa Lembongan is surrounded by mangrove areas dominated by *Rhizophora*, *Ceriops*, and *Xylocarpus* species (Wijaya et al., 2024). In Nusa Penida, mangroves are confined to limited areas and are primarily composed of *Lumnitzera racemosa*. Until now, no research output has comprehensively examined the presence of mangroves in Nusa Penida and their implications for sediment characteristics and nutrient distribution. These conditions may lead to pronounced differences in sediment structure and nutrient distribution, yet they have not been comprehensively investigated.

A vertical profile-based approach to assessing the physicochemical properties of sediments and nutrient dynamics is expected to provide deeper insights into spatial variability and the role of mangrove vegetation in shaping sediment characteristics. This study aims to reveal the influence of differences in mangrove vegetation structure on the physicochemical properties and nutrient stratification of sediments, thereby filling data gaps in small island ecosystems and supporting sustainable coastal conservation strategies (Veitayaki et al., 2017; Wijaya et al., 2024). The hypothesis is that differences in mangrove vegetation structure will result in significant variations in sediment texture, organic matter content, and nutrient stratification, with vegetated sediments exhibiting higher organic accumulation and greater biogeochemical complexity.

METHOD

Study site and sampling design

This research was observed at three stations representing variations in mangrove and non-mangrove stand structure on two small islands in Bali Province, specifically the mangrove area of Nusa Lembongan (NL) and the less dense

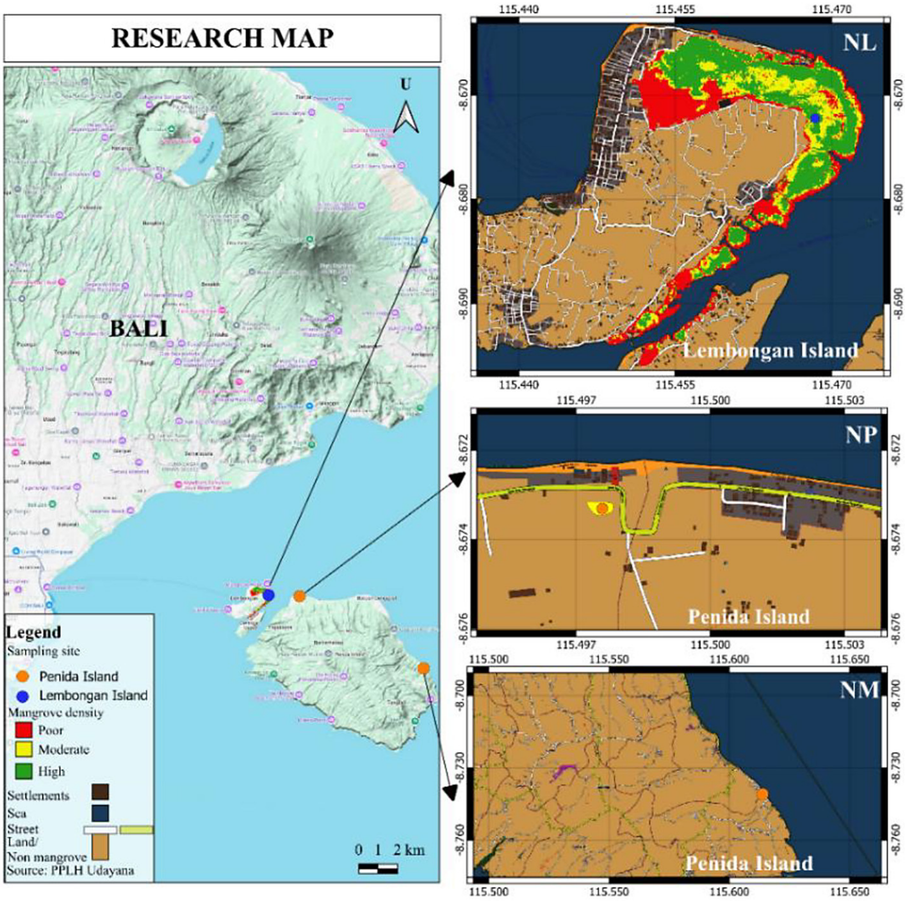

Figure 1. Sampling stations at both research locations

mangrove (NP) and non-mangrove areas (NM) of Nusa Penida (Figure 1). In other words, purposive sampling was used to represent those distinctive vegetation types, i.e., the presence of mangrove vegetation and variations in stand structure, to assess the impact of mangrove vegetation and structural complexity on sediment characteristics. Representative field conditions across the sampling stations are shown in Figure 2. Data collection was carried out in September 2024.

Mangrove structure

Mangrove stand structure was observed within 10×10 m plots by measuring tree density, canopy cover, and morphometric characteristics, including diameter and height. Each individual was identified to the species level (As-syakur et al., 2023). Diameter at breast height (DBH) was measured and categorized into two groups: trees (DBH ≥ 5 cm) and saplings (DBH < 5 cm). Canopy cover was assessed using hemispherical photography, taken from five positions in each plot (each corner and center) using a smartphone camera with a resolution exceeding 3 megapixels. ImageJ software was used to analyze the canopy photos and calculate canopy cover percentage. The mangrove stand height was estimated using trigonometric calculations based on a measurement of horizontal distance (10 m), the observer's eye height (H_0), and the angle of elevation to the canopy apex (θ), measured using a protractor application (Dharmawan et al., 2020). The MonMang 2.0 application was used to record field measurement data efficiently.

Soil physicochemical and nutrient analysis

Methodology for soil sampling and preparation

Sediment cores were collected using a russian corer from the surface to a depth of 50 cm, representing a 10×10 m research plot. Cores were carefully retrieved to preserve stratification. During sample transport to the laboratory, the cores were maintained in a vertical position to prevent mixing between layers and preserve their natural vertical structure. Each core was stratified

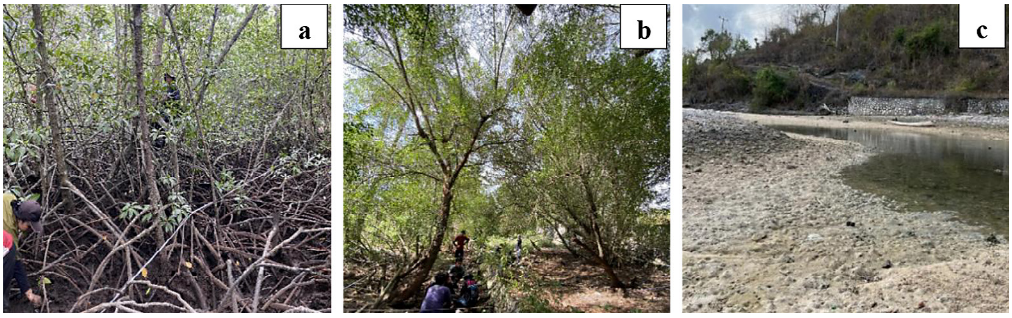

Figure 2. Field conditions at the three sampling stations, (a) NL Station (b) NP Station, (c) NM Station

Figure 3. Analysis of sediment physicochemical parameters, (a) Grain size distribution, (b) C-organic content analysis using the Walkley and Black method, (c) Measurement of oxidation-reduction potential (ORP) and pH

into sublayers considering the diagenetic change of sediment color: i.e., NL (0–5, 10–15, 20–25, 30–35, 35–40, 45–50 cm), NP (0–5, 5–10, 10–15, 15–20, 25–30, 40–45 cm), and NM (0–5, 5–10, 10–15, 15–20, 25–30, 40–45 cm). All physicochemical and nutrient analyses were performed as single measurements for each sediment layer at each sampling station, without replication. Thus, the reported data represent individual values rather than statistical averages. The analyzed data was assessed for accuracy and precision using quality assurance and quality control (QA/QC) measures, with accuracy reaching ~93% and recovery percentages ranging from 93–111%.

Physicochemical analysis of sediment parameters

Physicochemical parameters of sediment samples were analyzed to determine vertical variations in sediment texture, sediment color, organic carbon (C-organic) content, oxidation-reduction potential (ORP), pH, and salinity along the sediment core. Grain size of the sediment was determined using the dry sieving method and classified according to the Wentworth scale (1922), categorizing sediment into sand (2–0.063 mm), silt (0.063–0.0039 mm), and clay (< 0.0039 mm) (Figure 3a). Sediment color was visually assessed before core sectioning and qualitatively described based on observable vertical color transitions that guided the stratification of each core. Organic carbon content in the sediment was determined using the Walkley and Black method (Figure 3b) (Okalebo et al., 2002). Sediment samples were dried, ground, and weighed (0.5 g), followed by the addition of $K_2Cr_2O_7$ solution and concentrated H_2SO_4. The mixture was heated for 30 minutes, cooled, diluted with distilled water, homogenized, and left to stand for approximately 24 hours. Absorbance was then measured using a spectrophotometer at a wavelength of 561 nm. Sediment pH and oxidation–reduction potential (ORP) were measured using a EUTECH Instruments PC 700 with a sediment-to-distilled water ratio of 1:5 (w/v) (Figure 3c). Salinity of the sediment was measured using a refractometer on a 1:5 (w/v) suspension of sediment in distilled water, which was thoroughly shaken and left unfiltered before analysis (Behera et al., 2019; Das et al., 2021; Semanti et al., 2021).

Analysis of nutrient concentrations

Total nitrogen (TN) was determined using the Kjeldahl method according to AOAC (2012; 955.04). Sediment (0.1 g) was added with selenium and concentrated H_2SO_4, then heated until the solution turned transparent green. After that, distilled water and 40% NaOH solution were added, followed by distillation. The distillate was collected in 2% boric acid solution and subsequently titrated with standard HCl (Figure 4a). Total phosphorus (TP) was analyzed using a spectrophotometric method adapted from Sudjadi et al. (1971). Sediment (2 g) was extracted with 25% HCl by shaking for 5 hours, followed by overnight incubation. The clear filtrate was diluted, reacted with a phosphorus color reagent, and incubated for 30 minutes. Absorbance was measured at 693 nm using a UV-Vis spectrophotometer (Figure 4b).

Inorganic nutrients, including ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}), were initially extracted using a 2 M KCl solution, followed by 5 hours of shaking and overnight settling before filtration and analysis (Thanh et al., 2016; Wang et al., 2016; Semanti et al., 2021). Ammonium (NH_4^+) concentrations were determined using a modified APHA (2023; 4500-NH_3) method. The 25 ml filtrate was reacted with EDTA, sodium nitroprusside, phenolate solution (a mixture of NaOH and phenol), and an oxidizing reagent composed of alkaline citrate and hypochlorite. After incubation for approximately one hour, absorbance was measured at 640 nm (Figure 5a). Results were expressed as NH_4^+, as calibration was conducted using ammonium standards. Nitrite (NO_2^-) was analyzed following the AOAC (2006; 973.31) method by reacting the 50 ml filtrate with sulfanilamide and N-(1-naphthyl)ethylenediamine, followed by spectrophotometric measurement at 543 nm (Figure 5b). Nitrate (NO_3^-) determination followed the EPA 352.1 method. The 5 ml filtrate was acidified with H_2SO_4, reacted with NaCl and brucine–sulfanilic reagent, then heated at 90 °C for one hour before absorbance was measured at 410 nm (Figure 5c). Phosphate (PO_4^{3-}) analysis followed the APHA (2023; 4500-P) method, in which the 2 ml filtrate was reacted with a color reagent containing ascorbic acid. After a 30-minute incubation, absorbance was measured at 693nm (Figure 5d). All nutrient concentrations were measured using a UV-Vis spectrophotometer, with absorbance readings taken at nutrient-specific wavelengths as indicated.

Statistical analysis

Sediment physicochemical and nutrient data were visualized using *OriginPro*. The distribution patterns among stations and the contribution of each parameter in different sedimentary environments were analyzed using principal component analysis (PCA) with XLStat software version 2019.2.2. This multivariate analysis was to correlate among variables and to identify the dominant parameters characterizing each station.

RESULT AND DISCUSSION

Mangrove stand structure

The ecological characteristics of mangroves between stations show differences in those observed locations (Table 1). Station NL is dominated by *Rhizophora stylosa* with tree and sapling densities of 36 stands/100 m² and 46 stands/100 m², respectively. These values are considerably higher than those observed in the other locations, such as Middleburg-Miossu Island (11 stands/100 m² and 16 stands/100 m²) (Nurdiansah and Dharmawan, 2021) and Padaidori Island, Padaido Islands (6 stands/100 m² and 15 stands/100 m²) (Siahaan et al., 2022).

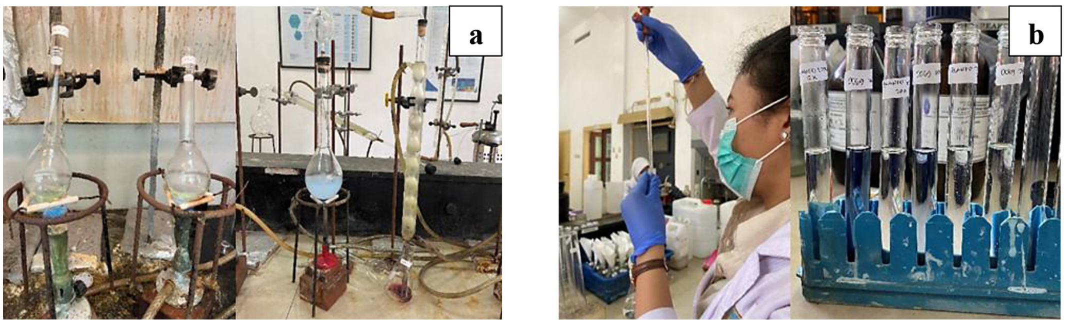

Figure 4. Nutrient analysis procedures in sediment samples, (a) Total nitrogen, (b) Total phosphorus

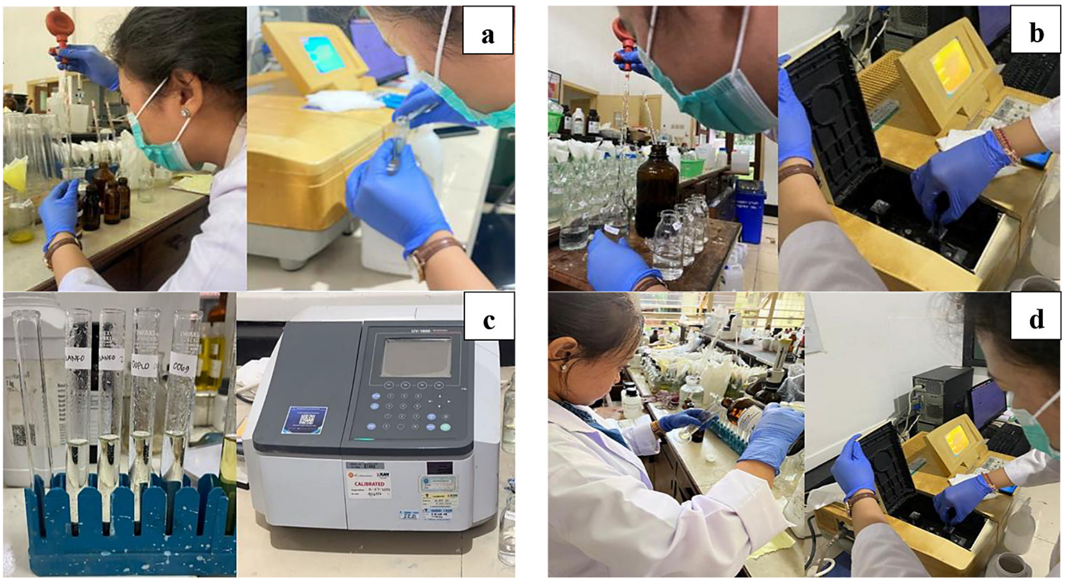

Figure 5. Laboratory procedures for inorganic nutrient analysis in sediment samples, with absorbance measured using a spectrophotometer at the respective wavelengths, (a) Ammonium (NH_4^+), (b) Nitrite (NO_2^-), (c) Nitrate (NO_3^-), and (d) Phosphate (PO_4^{3-})

Table 1. Structure of mangrove stands at the research stations

Parameter	Sampling site		
	NL	NP	NM
Dominance of mangrove	*Rhizophora stylosa*	*Lumnitzera racemosa*	-
Number of spp.	2 *Rhizophora stylosa* *Rhizophora apiculata*	2 *Lumnitzera racemosa* *Excoecaria agallocha*	-
Tree density (stands/100 m^2)	36	22	-
Sapling density (stands/100 m^2)	46	16	-
Diameter (cm) Mean Min Max	6.20 2.55 27.36	6.82 1.91 20.36	- - -
Canopy coverage (%)	80.36	74.89	-
Height (m)	8.55	6.41	-

Note: NL: mangrove Nusa Lembongan; NP: mangrove Nusa Penida; NM: non-mangrove Nusa Penida

The average stem diameter (6.20 cm) in NL Station was relatively small compared to those of NP, indicating the influence of high stand density, leading to light and nutrients competition, which may constrain radial growth (Xiong et al., 2019). The average stand height of 8.55 m reflects a vertical growth strategy to optimize light capture in densely vegetated conditions (Mustika et al., 2014; Dharmawan et al., 2020). The high canopy cover (80.36%) is consistent with the dense stand structure and the typical conical crown form of *Rhizophora* species (Dharmawan, 2020; Ernawati et al., 2024). Furthermore, the high proportion of saplings indicates active regeneration, supported by the viviparous reproductive strategy of *Rhizophora* (Wijaya et al., 2024).

Mangrove in the NP Station is dominated by *Lumnitzera racemosa*, with *Excoecaria agallocha* as a companion species. The tree and sapling densities are 22 stands/100 m² and 16 stands/100 m², respectively, considerably higher than those in Middleburg-Miossu Island and Padaidori Island (Nurdiansah and Dharmawan, 2021; Siahaan et al., 2022), although still lower compared to those in NL. This pattern aligns with the finding of Ernawati et al. (2024), suggesting that areas dominated by *Rhizophora* generally exhibit higher stand densities than those dominated by *Lumnitzera*, both at the tree category (2,040 ± 1,053 stands/ha vs. 900 ± 596 stands/ha) and at the sapling category (2,880 ± 1,773 stands/ha vs. 2,120 ± 502 stands/ha). The average diameter of stems in NP is slightly larger (6.82 cm) than those in NL, indicating low competitive pressure between stands, thus allowing for more optimal stem growth (Dharmawan et al., 2020; Cuc and Hien, 2021). The average height of stands in NP is 6.41 m with a canopy cover of 74.89%, influenced by the horizontally spreading crown of *Lumnitzera*, which contributes to broader lateral coverage despite lower vertical growth and stand density (Ernawati et al., 2024).

No mangrove vegetation in Station NM was observed, and it was deliberately chosen for comparison purposes. This sandy-beach area probably receives less organic matter input from litterfall or roots. Therefore, the physicochemical characteristics of the sediment tend to be influenced by abiotic factors rather than biotic processes, such as decomposition, and are discussed.

Vertical profile of sedimentary physicochemical parameters

Physicochemical parameter data, including proportions of sand, silt, and clay fractions, pH, salinity, ORP, and C-organic per station and depth, are presented in Table 2. Being dominated by dense and complex root systems of *Rhizophora* species, the NL Station exhibits low hydrodynamic energy, facilitating the efficiency of trapping fine particles and litter (Syahminan, 2015; Kusuma et al., 2022; Yuniar et al., 2023). Although the sand fraction remains predominantly (59.21–65.29%), the composition of silt (21.03–25.02%) and clay (13.68–15.76%) are higher than those of NP and NM Stations (Figure 6a). The decrease in the vertical profile of sand fraction and a concurrent increase in finer particles with depth reflects the increased deposition of fine fraction that may be caused by entrapment of mangrove root systems. At the NP Station, the sediment profile is predominantly composed of sand (76.68–80.27%), higher than those observed in the NL Station, and lower proportions of silt (12.84–14.96%) and clay (6.89–8.36%) (Figure 6c). These sediment characteristics are possibly related to the relatively sparse mangrove

Table 2. Comparative physicochemical parameters of sediments at the research stations

Station	Depth (cm)	Physical parameters			Chemical parameters			
		Grain size (%)			pH	ORP (mV)	Salinity (ppt)	C-organic (%)
		Sand	Silt	Clay				
NL	0–5	65.29	21.03	13.68	6.28	-3.2	25	2.73
	10–15	63.62	21.92	14.46	6.20	-3.7	25	2.63
	20–25	62.08	23.36	14.56	6.18	-12.4	26	2.67
	30–35	60.56	23.74	15.70	6.18	-28.4	25	2.68
	35–40	60.23	24.16	15.61	6.14	-33.6	26	2.55
	45–50	59.21	25.02	15.76	6.04	-37.2	27	2.17
NP	0–5	80.27	12.84	6.89	6.15	-53.6	16	0.94
	5–10	79.46	13.78	6.76	6.13	-76.9	17	0.72
	10–15	78.56	13.07	8.36	6.11	-86.9	17	0.69
	15–20	78.13	13.63	8.24	5.98	-114.9	18	0.50
	25–30	77.32	14.69	7.99	6.05	-112.6	19	0.48
	40–45	76.68	14.96	8.36	5.72	-137.1	20	0.41
NM	0–5	98.79	0.39	0.82	8.86	32.5	30	0.09
	5–10	98.05	0.60	1.35	8.74	30.5	29	0.11
	10–15	97.73	0.96	1.31	8.64	16.3	30	0.17
	15–20	97.54	0.89	1.57	8.40	7.5	31	0.15
	25–30	97.03	1.36	1.61	8.48	-14.8	33	0.16
	40–45	95.87	2.27	1.87	8.12	-26.8	33	0.10

Note: NL: mangrove Nusa Lembongan; NP: mangrove Nusa Penida; NM: non-mangrove Nusa Penida.

density. This zone is characterised by *Lumnitzera* vegetation, which lacks pneumatophores and exhibits a simpler root structure, reducing its effectiveness in trapping fine sediments and litter (Costa et al., 2019; Wulandari et al., 2024). The NM Station has no mangrove cover, and the sediment characteristics typical of an unvegetated coastal area are overwhelmingly dominated by sand fractions, ranging from 95.87% to 98.79%, with a slight decrease in the fine fraction in the very recent deposition (Figure 6e). Water disturbances efficiently mobilize fine materials in this area, and hence develop a macro-textured and highly porous sediment structure (Dewi, 2020). In addition, this composition aligns with the geological characteristics of Nusa Penida, in which carbonate rocks and biogenic sediments are the structure (Astjario, 2008).

The effect of mangrove habitat is probably crucial for organic matter deposition, as shown in Figure 7a. The highest C-organic content, ranging from 2.17% to 2.73% is found in the NL Station. The high stand density and canopy cover, producing detritus and the development of benthic microalgae, are probably responsible for enhancing organic matter deposition (Chowdhury et al., 2019). However, the NP Station, located in the backshore and away from tidal influence, resulting in limited periodic flooding and reduced supply of fine sediments from the sea (Cinco-Castro et al., 2022), is characterized by the low accumulation of C-organic contents

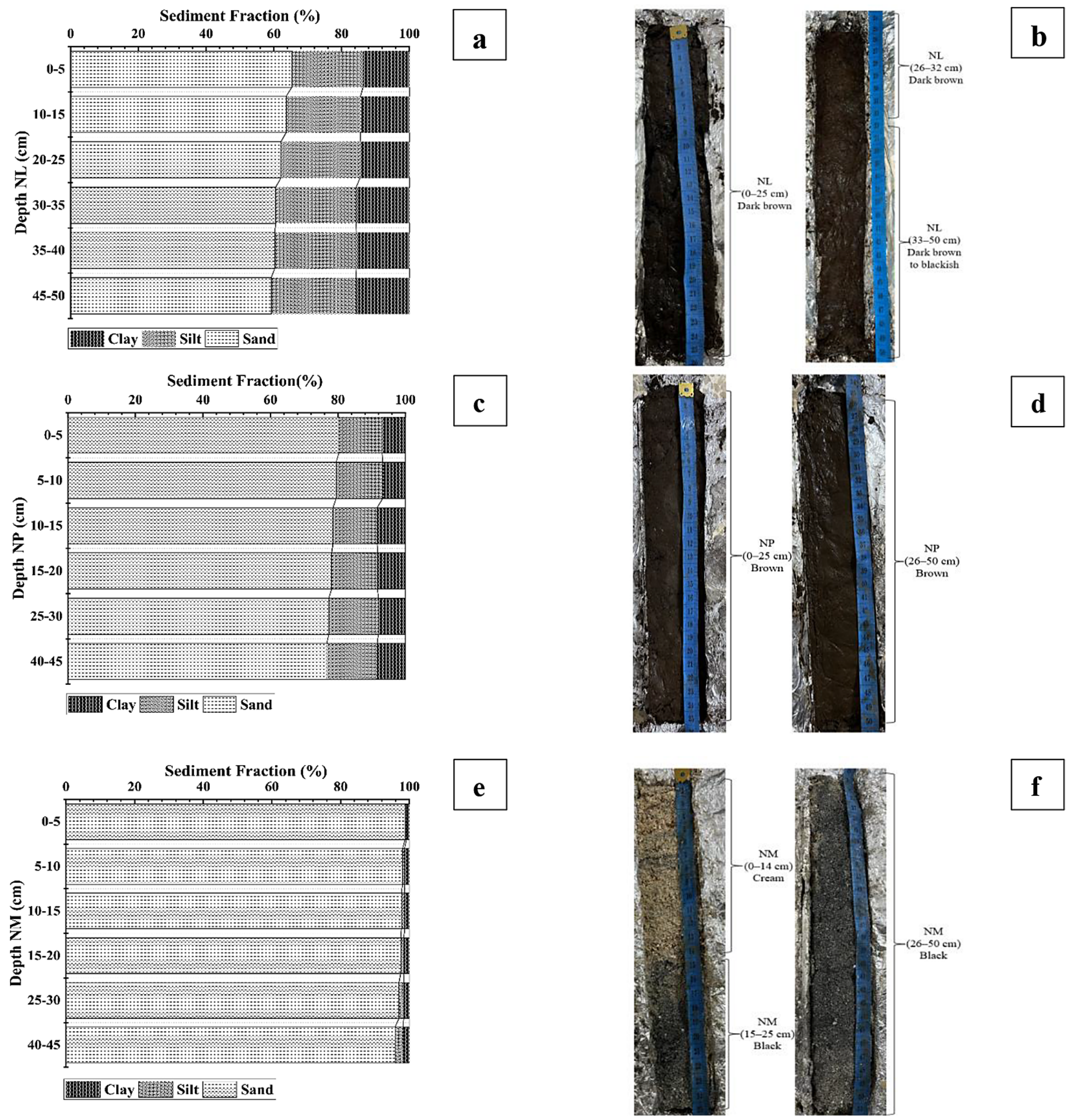

Figure 6. Vertical profile of physical characteristics at the sediment core, (a) Grain size of NL Station, (b) Sediment color of NL Station, (c) Grain size of NP Station, (d) Sediment color of NP Station, (e) Grain size of NM Station, (f) Sediment color of NM Station

ranging from 0.41% to 0.94%. This occurrence is consistent with the lower litterfall and organic matter input typically found in *Lumnitzera* dominated mangrove forests compared to those dominated by *Rhizophora,* leading to a correspondingly lower organic carbon content in sediments under *Lumnitzera* stands (Ernawati et al., 2024). This may explain the lower C-organic input compared to those observed in the NL Station, regardless of the increase in organic inputs, which is still observed in recent sediment of the NP Station. The lowest input of organic detritus contributes to the extremely low C-organic content in the NM Station, ranging from 0.09% to 0.17% in which no vegetation and a sandy beach is a type of area. Overall, the limited organic matter input and high sediment porosity promote rapid leaching and prevent organic matter accumulation, resulting in consistently low C-organic levels throughout the sediment column (Castro - Rodríguez et al., 2018; Perera and Amarasinghe, 2019; Matos et al., 2020).

The extent to which the organic content is available in the sediment can drive the sedimentary-chemical modification. Decomposition of C-organic accumulation may consume oxygen, and its depletion contributes to anaerobic conditions in the sediment (Noël et al., 2014; Kristensen et al., 2017; Castro – Rodríguez et al., 2018). The negative of ORP indicates an anaerobic/reducing condition within sediment, and most of the ORP profiles show a gradual increase from the older layer towards the surface layer. This suggests that decomposition occurred in some periods in the old sediment compared to the new deposition surface layer. In addition, the negative of ORP is probably due to more intensive degradation of organic matter. Oxygen is progressively consumed as the primary electron acceptor during organic matter decomposition with increasing depth, leading to more reducing conditions in the deeper layer. This decline is not solely driven by microbial activity, but also associated with limited oxygen diffusion into deeper sediment, as the fine-grained sediment is increasingly compacted (Noël et al., 2014; Alongi, 2020). The anaerobic decomposition processes further generate reduced compounds such as sulfides, which react with metals to form iron sulfide (FeS) (Castro - Rodríguez et al., 2018; Rohmawati, 2019), leading to a visual transition in sediment color from dark brown (0–32 cm) to blackish at depths greater than 32 cm in NL Station (Figure 6b). In contrast, NP Station displays a more homogeneous brown coloration throughout the profile, indicating a lower degree of organic matter degradation than NL (Figure 6d). Meanwhile, NM Station shows a distinct two-layered color pattern, with a cream tone at the surface (0–14 cm), indicating carbonate sand dominance and marine biota remnants, transitioning to black at deeper layers (14–50 cm) (Figure 6f), due to the weathering of volcanic rocks or the accumulation of heavy minerals such as magnetite and ilmenite, rather than due to the decomposition of organic matter such as mangrove sediments (Noviadi and Setiady, 2020).

The ORP values in the NP Station are apparently most negative (−53.6 to −137.1 mV) compared to the others (i.e., −3.2 to −37.2 mV in NL Station and 32.5 mV to −26.8 mV in NM Station) (Figure 7b). However, the highest organic content occurs in the NL Station. The type of deposited organic matter and oxygen supply is responsible for this inconsistency, and more degradable material in the NP sediment is possibly available compared to that observed in the NL area. The high ORP in the NM Station is clearly due to minimum organic matter input because of the unvegetated area (Table 1). Noël et al. (2014) similarly reported that unvegetated area (350 to 87 mV) exhibit more oxidative than *Avicennia* (150 to −110 mV) and *Rhizophora* (250 to −50 mV), all showing decreasing ORP with depth. It is necessary to note that the ORP profile shifting from negative to positive indicates a possible change of environmental deposition to be more inorganic input. The decomposition of organic matter can also release H^+ ions, reducing the sediment pH (Taylor et al., 2015; Rahman et al., 2021). The profiles of pH in this study area apparently support the phenomena, indicating that the low pH is characterized in both NL (pH 6.04 to 6.28) and NP (pH 5.72 to 6.15) Stations compared to the NM Station (pH 8.12 to 8.86) (Figure 7c). This pattern is further supported by Noël et al. (2014), that unvegetated area have relatively high pH values (7.6–6.8), whereas mangrove zones dominated by *Avicennia* and *Rhizophora* exhibit lower pH levels, namely 6.5–7 and 5–6, respectively. In addition, the salinity profile in which the salinity is more saline successively from NP (16–20 ppt), NL (25–27 ppt) towards NM stations (29–33 ppt) is apparently more convincing that the occurrence of diffusion is more readily in the sandy beach of NM Station (Figure 7d). It is crucial to diffuse and transport oxygen and buffer capacity within sediments, and

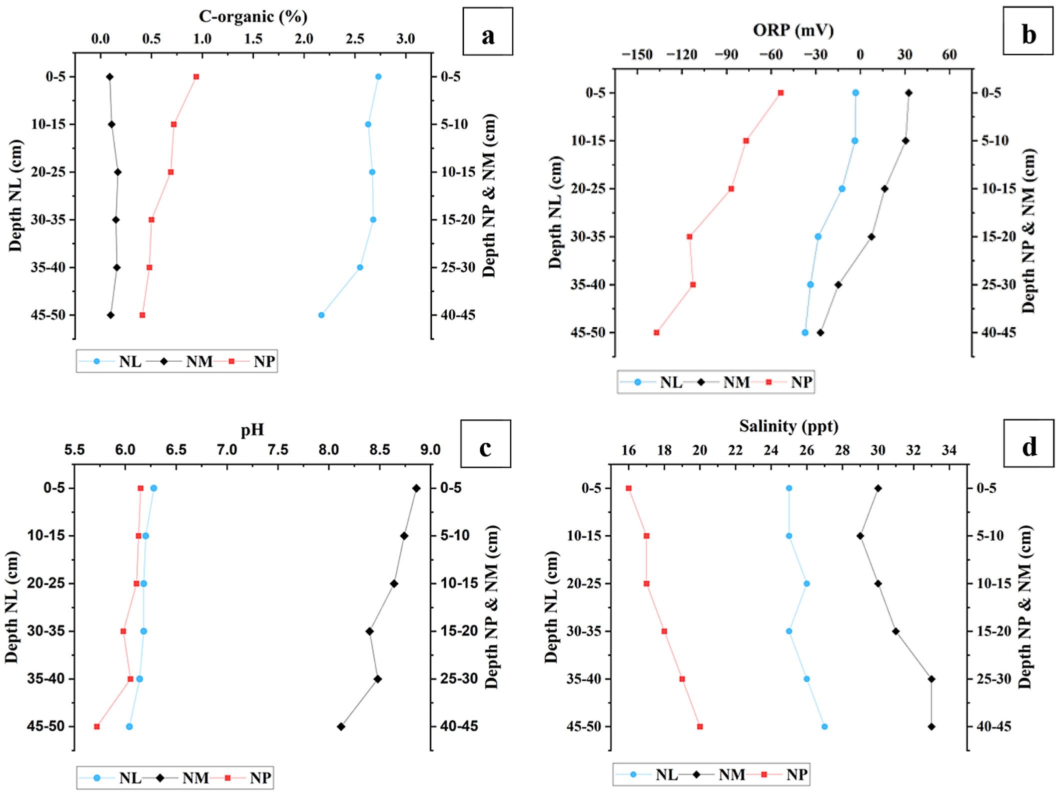

Figure 7. Vertical profile of physicochemical parameters of the sediment core, (a) C-organic, (b) ORP, (c) pH, (d) Salinity

consequently influence the geochemical profile of the sediments (Singh and Rangarajan, 2023). The lower salinity in *Lumnitzera* dominated zones is also attributable to their location in the landward mangrove zone, in contrast to *Rhizophora* dominated zones typically situated in the middle mangrove zone, closer to marine influence. This finding aligns with Ernawati et al. (2024), reporting that mangrove zones dominated by *Lumnitzera* exhibit lower salinity levels (± 20.8 ppt) compared to zones dominated by *Rhizophora* (± 29.4 ppt).

Vertical profile of nutrient concentration

The vertical distribution of nutrients (nitrogen and phosphorus) in particular NL and NP Stations generally exhibits an increasing profile from deeper layers towards the surface layer (Table 3; Figure 8). Most nitrogen concentrations (total nitrogen and species) appear to correlate with the presence of dense mangrove stands and organic matter; i.e., the highest in NL Station and the lowest in NM Station. Therefore, concentrations of nitrogen are probably derived from the decomposition of organic matter, regardless of other sources such as anthropogenic. The microbial decomposition of organic matter trapped by mangrove roots releases ammonium (NH_4^+), which is subsequently converted through geochemical processes into nitrite (NO_2^-) and subsequently nitrate (NO_3^-), as important steps in the nitrogen cycle (Ray et al., 2014). The highest concentration of ammonium (NH_4^+) compared to its counterparts (NO_2^- and NO_3^-) in these sites indicates insufficient oxygen availability (as shown by negative ORP in the sediment) to proceed completely these nitrification.

In NL Station, total nitrogen (TN) exhibits a pronounced upward trend, increasing from 0.32% in the deepest layer (45–50 cm) to 0.47% at the surface layer (0–5 cm). A similar upward trend is observed at NP Station from 0.10% to 0.23%. In contrast, TN concentrations at NM Station remain relatively stable, fluctuating only slightly between 0.05% and 0.08%, with the highest value recorded at 5–10 cm, indicating minimal temporal variation in organic matter deposition. For ammonium (NH_4^+), concentrations at NL Station increase from 20.87 mg/kg (45–50 cm) to 32.8 mg/kg (0–5 cm), while NO_2^- and NO_3^- also increase from 0.07 mg/kg to 0.25 mg/kg and from 1.10 mg/kg to 1.60 mg/kg, respectively. A similar pattern is evident at NP Station, with NH_4^+

Table 3. Comparative nutrient concentration of sediments at the research stations

Station	Depth (cm)	Nutrient concentration					
		NH_4^+ (mg/kg)	NO_2^- (mg/kg)	NO_3^- (mg/kg)	Total nitrogen (%)	PO_4^{3-} (mg/kg)	Total phosphorus (%)
NL	0–5	32.80	0.25	1.60	0.47	1.60	0.015
	10–15	29.12	0.20	1.43	0.41	1.53	0.014
	20–25	26.72	0.14	1.31	0.43	1.55	0.015
	30–35	26.98	0.17	1.35	0.40	1.49	0.011
	35–40	24.85	0.10	1.27	0.37	1.21	0.014
	45–50	20.87	0.07	1.10	0.32	1.10	0.010
NP	0–5	13.38	0.21	0.60	0.23	0.73	0.004
	5–10	10.62	0.19	0.52	0.16	0.64	0.006
	10–15	7.64	0.20	0.42	0.14	0.61	0.005
	15–20	8.77	0.17	0.29	0.12	0.57	0.004
	25–30	6.46	0.16	0.34	0.12	0.43	0.004
	40–45	4.59	0.09	0.21	0.10	0.37	0.002
NM	0–5	3.02	0.05	0.15	0.05	0.27	0.001
	5–10	3.32	0.08	0.19	0.08	0.31	0.002
	10–15	3.85	0.07	0.22	0.07	0.29	0.004
	15–20	2.95	0.05	0.20	0.05	0.27	0.002
	25–30	2.46	0.04	0.14	0.06	0.28	0.001
	40–45	1.98	0.02	0.08	0.05	0.26	0.001

Note: NL: mangrove Nusa Lembongan; NP: mangrove Nusa Penida; NM: non-mangrove Nusa Penida.

increasing from 4.59 mg/kg in the deeper layer to 13.38 mg/kg at the surface, NO_2^- increasing from 0.09 mg/kg to 0.21 mg/kg, and NO_3^- from 0.21 mg/kg to 0.60 mg/kg. In these two stations, the profiles of NO_2^- and NO_3^- show significant increases toward the surface layer. This aligns with previous studies indicating that ammonium (NH_4^+) concentrations are 4–18 times higher than NO_2^- and NO_3^- in mangrove environments (Ray et al., 2014; Semanti et al., 2021). At NM Station, ammonium still dominates among nitrogen species, but at much lower concentrations. NH_4^+ increases from 1.98 mg/kg in the deeper layer to 3.85 mg/kg at 10–15 cm. NO_2^- also increases from 0.02 mg/kg to 0.08 mg/kg (5–10 cm), and NO_3^- from 0.08 mg/kg to 0.22 mg/kg (10–15 cm). However, the peak concentrations of these nitrogen species occur in the middle layers rather than at the surface, suggesting limited mangrove litter input and poor nutrient retention due to the sandy, highly porous substrate (Ray et al., 2014; Castro-Rodríguez et al., 2018; Matos et al., 2020). This pattern is consistent with Zhang et al. (2018), reporting that nitrogen and its species tend to increase from deeper layers to the surface due to higher fresh organic matter inputs and intensified biological activity in upper sediments.

During microbial decomposition of the deposited organic material, phosphate is also released in addition to its contributions from anthropogenic sources. The concentrations gradually increase from the deeper layer to the more recent deposition, for instance, from 1.10 mg/kg to 1.60 mg/kg and 0.37 mg/kg to 0.73 mg/kg in the NL and NP Stations, respectively. However, it is relatively unchanged in NM, ranging from 0.26 to mg/kg to 0.31 mg/kg (5–10 cm). The profile of phosphate concentrations is also similar to those observed in organic material and nitrogen. This is also probably related to the extent to which the deposited organic material is remineralized. Similarly, at the NM Station, total phosphorus (TP) increases from 0.001% in the deepest layer and reaches its highest concentration (0.004%) at a depth of 10–15 cm, with a distribution pattern that tends to be fluctuating. In comparison, NL Station exhibits a higher range, from 0.010% at 45–50 cm to 0.015% at the surface (0-5 cm), while NP Station shows intermediate values, increasing from 0.002% in the deepest layer to a peak of 0.006%. This vertical pattern aligns with the distribution of organic matter, where higher TP and phosphate concentrations are linked to

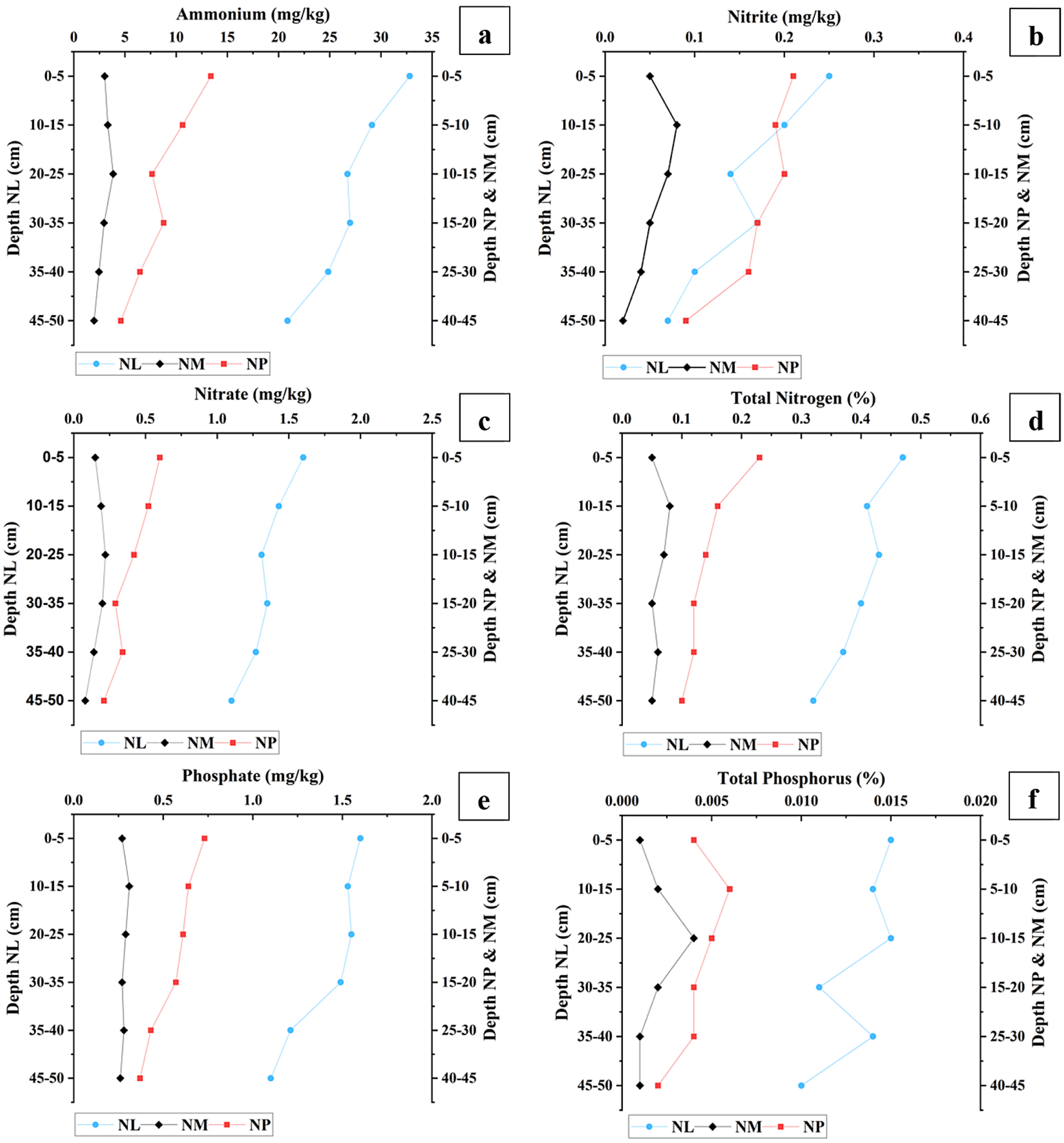

Figure 8. Vertical profile of nutrient concentration at the sediment core, (a) NH_4^+, (b) NO_2^-, (c) NO_3^-, (d) Total nitrogen, (e) PO_4^{3-}, (f) Total phosphorus

mangrove litter input and finer sediments in NL and NP, whereas NM exhibits minimal TP and phosphate due to sandy texture and limited organic contributions. In addition to remineralisation of organic matter, the contribution of phosphate concentrations may derive from mineral rocks weathered through reduction processes of Fe^{3+} to Fe^{2+} in anoxic conditions that lead to phosphates into pore water (Singh et al., 2015; Perera et al., 2024). The upward increase in TP concentrations is likely attributable to the accumulation of fresh litter, enhanced microbial activity in the upper layers, and greater phosphate retention in fine sediments. Similar vertical patterns have been reported by Matos et al. (2020) and Perez et al. (2020).

Relationship between sediment physicochemical characteristics and nutrient concentration

Principal component analysis (PCA) of physicochemical and nutrient parameters resulted in two main axes (F1 and F2) that cumulatively explain 93.72% of the total variation in the data, with 73.38% (F1) and 20.34% (F2), respectively (Figure 9). NL Station is characterized by a high C-organic content, elevated nutrient concentrations, and a predominance of fine sediment fractions (silt and clay) throughout the vertical profile. In contrast, NM Station exhibits the dominance of sand fractions and high pH levels. No indication of the measured parameters is predominant in the NP Station.

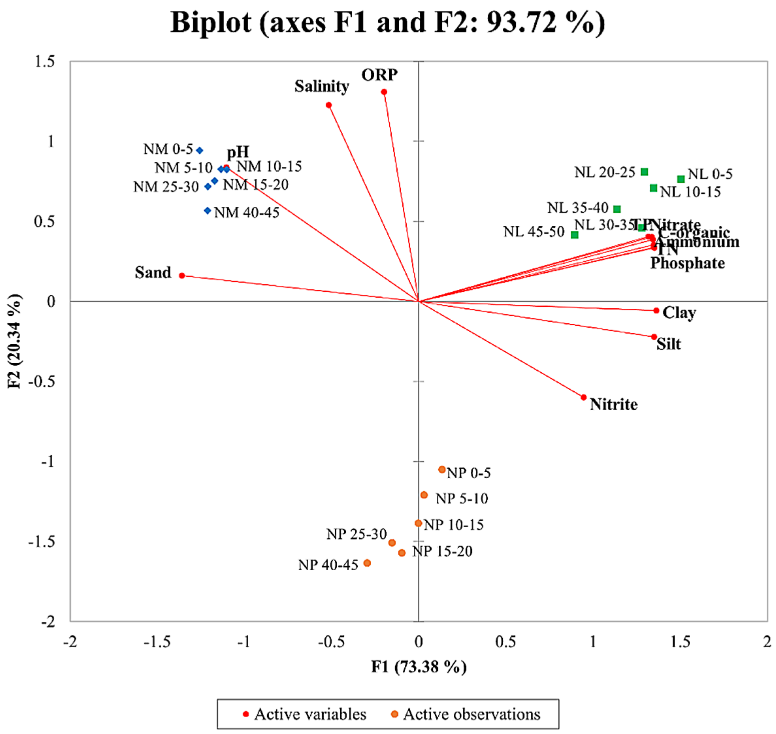

Figure 9. PCA analysis results show clear differences in the physicochemical characteristics of the sediments

Differences in physical, chemical, and nutrient profiles appear to illustrate the important role of biogeochemical sediment formation, and the existence of mangroves stimulates material accumulation, clearly influencing that process. Mangrove structures, with their strong and complex root systems, are able to reduce current velocity, and hence trapping and depositing fine particles and litter (Grallier et al., 2017; Kusuma et al., 2022; Yuniar et al., 2023), as in the Nusa Lembongan sediments (NL). This may not occur in non-mangrove areas in which coarser particles (sand) are more abundant because the absence of root structures prevents the natural mechanism from the deposition of fine particles (Fernandes et al., 2016). Differences in grain size composition will further affect porewater circulation and substance diffusion, including dissolved oxygen and salinity. The supplies of oxygen and salinity from overlaying water into the sandy sediment layer (NM) will diffuse compared to those observed in the fine sediment (NL).

The decomposition of organic matter in mangrove areas primarily determines the chemical characteristics of the sediment. Decomposition of sedimentary organic matter consumes oxygen and produces nutrients such as NH_4^+, NO_2^-, NO_3^-, TN, PO_4^{3-}, and TP. C-organic serves as an energy source for microorganisms, stimulating biogeochemical processes such as mineralization, ammonification, and nitrification in sediment (Srisunont et al., 2017; Aprilia et al., 2020). Limited water circulation and excessive oxygen consumption in fine sediment (NL Station) create a more anaerobic environment, indicated by the negative ORP parameter. The predominance of fine fractions increases the sediment adsorption capacity, allowing longer nutrient retention and reducing leaching losses (Aprilia et al. 2020; Matos et al. 2020), but reduces oxygen penetration from water overlaying sediment. In contrast, the dominance of sand fractions with high porosity and permeability accelerates nutrient loss through leaching (Castro-Rodríguez et al., 2018; Matos et al., 2020; Tang et al., 2023). The decomposition of organic matter also produces CO_2, leading to decreased pH in the sediment because of the disturbance of the buffer capacity within the sediment. The pH value in the NM Station is relatively high, reflecting alkaline conditions caused by low decomposition activity and high seawater intrusion. Under these circumstances, the release of H^+ ions as a result of decomposition is insignificant and may not be able to disturb the buffer system as observed in organic-rich sediments (Noël et al. 2014; Ho et al. 2017; Rahman et al., 2021).

Differences in vegetation composition are important contribution to modifying physical and chemical characteristics, clearly shown in the observed sites. The NL and NM are examples of significantly opposite conditions (shown in Table1). The NP Station is apparently intermediate in characteristics, with sparse mangrove density dominated by *Lumnitzera*, which has a simpler root structure than *Rhizophora* (Costa et al., 2019; Wulandari et al., 2024). Therefore, the input of litter and the physical structure for retaining fine particles are limited, resulting in relatively low organic matter and nutrient accumulation within the sediment profile. The sediment texture, comprising a mixture of sand and fine fractions, further supports this transitional nature of NP Station between those NL and NM regarding sedimentary and biogeochemical attributes. This sedimentary characteristic of NP Station indicates the role of mangrove vegetation, which is not dominant but still has a limited influence on sediment dynamics compared to the denser vegetation observed in the NL.

The species of mangrove and the density of the stands are the main controlling factors in forming the spatial differences in sediment characteristics by influencing litter input, root system complexity, and the ability to retain fine particles and organic matter. Layer distribution across all stations accentuates this pattern, demonstrating that the accumulation and dynamics of physicochemical parameters and nutrients are not only confined to the surface layer but also propagate to the deeper layers. The vertical gradients formed at each station reflect the long-term contribution of mangroves to sediment characteristics. Conversely, in non-mangrove areas, the limited input of organic matter weakens biogeochemical processes, including the storage of nutrients within sediment. Although vertical distribution remains apparent, the pattern in non-mangrove areas tends to be more homogeneous and consistently has low nutrient content. Thus, the presence of mangroves strengthens the physical stability of sediments and supports long-term ecological functions in coastal areas.

CONCLUSIONS

The study met its objective of revealing the vertical profile of sediment physicochemical characteristics and nutrient distribution in the mangrove and non-mangrove areas. Mangrove vegetation plays a crucial role in establishing sediment characteristics and nutrient dynamics through litter input, root system complexity, and enhancement of fine particle retention. Species composition and stand density emerge as primary drivers of spatial variation, as evidenced by vertical gradients that reflect sustained organic matter accumulation and biogeochemical modification. In contrast, non-mangrove areas exhibit lower nutrient content and limited vertical differentiation, emphasizing the role of mangrove vegetation as a major regulator of nutrient retention in isolated coastal environments. This study provides empirical evidence that in small-island mangrove ecosystems without major riverine inputs, nutrient accumulation and stratification processes can still occur similarly to those in large estuarine or mainland ecosystems. Thus, the research fills a knowledge gap on sediment dynamics in small-island mangroves and offers opportunities for applying vegetation-based restoration conservation strategies to maintain nutrient stocks and enhance the resilience of coastal ecosystems to environmental changes, supporting the long-term resilience and functionality of coastal ecosystems.

Acknowledgements

We express our gratitude to the Lembaga Pengelola Dana Pendidikan (LPDP), Ministry of Finance, Republic of Indonesia, for providing financial support for this research project under the master's thesis research plan. Sincere appreciation is also extended to the field team for their invaluable assistance, dedication, and support during data collection. The authors declare no conflict of interest in preparing this paper.

REFERENCES

1. Alongi, D. M. (2020). Carbon cycling in the world's mangrove ecosystems revisited: Significance of non-steady state diagenesis and subsurface linkages between the forest floor and the coastal ocean. *Forests*, *11*(9). https://doi.org/10.3390/f11090977
2. Alongi, D. M. (2021). Macro-and micronutrient cycling and crucial linkages to geochemical processes in mangrove ecosystems. *Journal of Marine Science and Engineering*, *9*. https://doi.org/10.3390/jmse9050456
3. Aprilia, D., Dianti, Arifiani, K. N., Cahyaningsih, A. P., Kusumaningrum, L., Sarno, Rahim, K. A. B. A., Setyawan, A. D. (2020). Review: Biogeochemical process in mangrove ecosystem. *International*

Journal of Bonorowo Wetlands, *10*(2). https://doi.org/10.13057/bonorowo/w100205

4. As-syakur, Abd. R., Wijaya, I. M. S., Andiani, A. A. E., Dewi, I. G. A. I. P., Sugiana, I. P., Faiqoh, E., Wiyanto, D. B., Rachman, H. A. (2023). *Mangrove identification guidelines in Bali (First)* (in Indonesia). PT. Arti Visual Intermedia.
5. Astjario, P. (2008). Natural resources in the coastal area of Nusa Penida Island and its surroundings, Klungkung Regency, West Nusa Tenggara (in Indonesia). *Geo-Resources*, *18*(6).
6. Behera, P., Mohapatra, M., Kim, J. Y., Adhya, T. K., Pattnaik, A. K., Rastogi, G. (2019). Spatial and temporal heterogeneity in the structure and function of sediment bacterial communities of a tropical mangrove forest. *Environmental Science and Pollution Research*, *26*(4), 3893–3908. https://doi.org/10.1007/s11356-018-3927-5
7. Bourgeois, C., Alfaro, A. C., Leopold, A., Andreoli, R., Bisson, E., Desnues, A., Duprey, J. L., & Marchand, C. (2019). Sedimentary and elemental dynamics as a function of the elevation profile in a semi-arid mangrove toposequence. *Catena*, *173*, 289–301. https://doi.org/10.1016/j.catena.2018.10.025
8. Castro - Rodríguez, E., León - Luna, I., Pinedo - Hernández, J. (2018). Biogeochemistry of mangrove sediments in the Swamp of Mallorquin, Colombia. *Regional Studies in Marine Science*, *17*, 38–46. https://doi.org/10.1016/j.rsma.2017.11.005
9. Chowdhury, R., Sutradhar, T., Begam, M. M., Mukherjee, C., Chatterjee, K., Basak, S. K., Ray, K. (2019). Effects of nutrient limitation, salinity increase, and associated stressors on mangrove forest cover, structure, and zonation across Indian Sundarbans. *Hydrobiologia*, *842*(1), 191–217. https://doi.org/10.1007/s10750-019-04036-9
10. Cinco-Castro, S., Herrera-Silveira, J., Comín, F. (2022). Sedimentation as a support ecosystem service in different ecological types of mangroves. *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.733820
11. Costa, L. D., Budiastuti, M. T. H. S., Sutrisno, J., Sunarto. (2019). The diversity of plant species in a mangrove forest in the coast of Metinaro, Timor-Leste. *IOP Conference Series: Earth and Environmental Science*, *256*(1). https://doi.org/10.1088/1755-1315/256/1/012026
12. Cuc, N. T. K., Hien, H. T. (2021). Stand structure and above ground biomass of *Kandelia obovata* Sheue, H.Y. Liu, J. Yong mangrove plantations in Northern, Viet Nam. *Forest Ecology and Management*, *483*. https://doi.org/10.1016/j.foreco.2020.118720
13. Das, S., Ganguly, D., De, T. K. (2021). Microbial methane production-oxidation profile in the soil of mangrove and paddy fields of West Bengal, India. *Geomicrobiology Journal*, *38*(3), 220–230. https://doi.org/10.1080/01490451.2020.1829207
14. Dewi, I. S. (2020). *Study of mangrove organic carbon stock in Tanjung Batu, Derawan Islands District, Berau, East Kalimantan* [Master's thesis, IPB University] (in Indonesia). IPB University.
15. Dharmawan, I. W. E. (2020). *Hemispherical photography: analysis of the percentage of canopy cover of mangrove communities* (in Indonesia). CV. Nas Media Pustaka. https://www.researchgate.net/publication/350671870
16. Dharmawan, I. W. E., Suyarso, Ulumuddin, Y. I., Prayudha, B., Pramudji. (2020). *Mangrove community structure monitoring guide in Indonesia (First)* (in Indonesia). PT Media Sains Nasional. https://www.researchgate.net/publication/344000335
17. Ernawati, N. M., Dewi, A. P. W. K., Sugiana, I. P., Dharmawan, I. W. E., Ma'ruf, M. S., Galgani, G. A. (2024). Mangrove gastropod distribution based on dominant vegetation classes and their relationship with physicochemical characteristics on fringe mangroves of Lembongan Island, Bali, Indonesia. *Biodiversitas*, *25*(1), 142–152. https://doi.org/10.13057/biodiv/d250116
18. Fernandes, S. O., Dutta, P., Gonsalves, M. J., Bonin, P. C., LokaBharathi, P. A. (2016). Denitrification activity in mangrove sediments varies with associated vegetation. *Ecological Engineering*, *95*, 671–681. https://doi.org/10.1016/j.ecoleng.2016.06.102
19. Gijsman, R., Horstman, E. M., Swales, A., MacDonald, I. T., Bouma, T. J., van der Wal, D., Wijnberg, K. M. (2023). Mangrove forest drag and bed stabilisation effects on intertidal flat morphology. *Earth Surface Processes and Landforms*, *49*(3), 1117–1134. https://doi.org/10.1002/esp.5758
20. Grellier, S., Janeau, J. L., Nhon, D. H., Cuc, N. T. K., Quynh, L. T. P., Thao, P. T. T., Nhu-Trang, T.-T., Marchand, C. (2017). Changes in soil characteristics and C dynamics after mangrove clearing (Vietnam). *Science of the Total Environment*, 593–594, 654–663. https://doi.org/10.1016/j.scitotenv.2017.03.204
21. Ho, D. T., Ferrón, S., Engel, V. C., Anderson, W. T., Swart, P. K., Price, R. M., Barbero, L. (2017). Dissolved carbon biogeochemistry and export in mangrove-dominated rivers of the Florida Everglades. *Biogeosciences*, 14(9), 2543–2559. https://doi.org/10.5194/bg-14-2543-2017
22. Kalev, S. D., Toor, G. S. (2018). *The composition of soils and sediments.* In Green Chemistry: An Inclusive Approach 339–357. Elsevier Inc. https://doi.org/10.1016/B978-0-12-809270-5.00014-5
23. Kristensen, E., Connolly, R. M., Otero, X. L., Marchand, C., Ferreira, T. O., Rivera-Monroy, V. H. (2017). Biogeochemical cycles: Global approaches and perspectives. In *Mangrove* Ecosystems: A Global Biogeographic Perspective: Structure, Function, and Services 163–209.

Springer International Publishing. https://doi.org/10.1007/978-3-319-62206-4_6

24. Kusuma, A. H., Effendi, E., Hidayatullah, M. S., Susanti, O. (2022). Estimation of carbon absorption in mangrove vegetation Register 15, Pasir Sakti District, East Lampung Regency, Lampung Province (in Indonesia). *Journal of Marine Research*, *11*(4), 768–778. https://doi.org/10.14710/jmr.v11i4.35605
25. Matos, C. R. L., Berrêdo, J. F., Machado, W., Sanders, C. J., Metzger, E., Cohen, M. C. L. (2020). Carbon and nutrient accumulation in tropical mangrove creeks, Amazon region. *Marine Geology*, *429*. https://doi.org/10.1016/j.margeo.2020.106317
26. Mustika, D. I., Rusdiana, O., Sukendro, A. (2014). The development of *Rhizophora apiculata* at mangrove nursery of Muara Teluk Naga Village, Tangerang District, Banten. *International Journal of Bonorowo Wetlands*, *4*(2), 108–116. https://doi.org/10.13057/bonorowo/w040204
27. Noël, V., Marchand, C., Juillot, F., Ona-Nguema, G., Viollier, E., Marakovic, G., Olivi, L., Delbes, L., Morin, G., Gelebart, F., Gelebart, F., Morin, G. (2014). EXAFS analysis of iron cycling in mangrove sediments downstream a lateritized ultramafic watershed (Vavouto Bay, New Caledonia). *Geochimica et Cosmochimica Acta*, *136*, 211–228. https://doi.org/10.1016/j.gca.2014.03.019
28. Noviadi, Y., Setiady, D. D. (2020). Sand sedimentation along the coast of Kulon Progo, special region of Yogyakarta. *Geologi Kelautan*, *18*(1).
29. Nurdiansah, D., Dharmawan, I. W. E. (2021). Community structure and healthiness of mangrove in Middleburg-Miossu Island, West Papua. *Jurnal Ilmu Dan Teknologi Kelautan Tropis*, *13*(1), 81–96. https://doi.org/10.29244/jitkt.v13i1.34484
30. Okalebo, J. R., Gathua, K. W., Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis: a working manual second edition*. Sacred Africa Nairobi Office, Nairobi.
31. Perera, G. L. E. P., Maeda, M., Akao, S., Somura, H., Nakano, C., Nishina, Y. (2024). Phosphorus release from agricultural drainage sediments with iron-added sediment microbial fuel cells. *Journal of Water and Environment Technology*, *22*(2), 75–91. https://doi.org/10.2965/JWET.23-071
32. Perera, K. A. R. S., Amarasinghe, M. D. (2019). Carbon sequestration capacity of mangrove soils in micro tidal estuaries and lagoons: a case study from Sri Lanka. *Geoderma*, *347*, 80–89. https://doi.org/10.1016/j.geoderma.2019.03.041
33. Pérez, A., Machado, W., Gutierrez, D., Smoak, J. M., Breithaupt, J. L., Saldarriaga, M. S., Sanders, L., Marotta, H., Sanders, C. J. (2020). Carbon and nutrient accumulation in mangrove sediments affected by multiple environmental changes. *Journal of Soils and Sediments*, *20*(5), 2504–2509. https://doi.org/10.1007/s11368-020-02612-4
34. Rahman, M. S., Saha, N., Ahmed, A. S. S., Babu, S. M. O. F., Islam, A. R. M. T., Begum, B. A., Jolly, Y. N., Akhter, S., Choudhury, T. R. (2021). Depth-related dynamics of physicochemical characteristics and heavy metal accumulation in mangrove sediment and plant: *Acanthus ilicifolius* as a potential phytoextractor. *Marine Pollution Bulletin*, *173*. https://doi.org/10.1016/j.marpolbul.2021.113160
35. Ray, R., Majumder, N., Das, S., Chowdhury, C., Jana, T. K. (2014). Biogeochemical cycle of nitrogen in a tropical mangrove ecosystem, east coast of India. *Marine Chemistry*, *167*, 33–43. https://doi.org/10.1016/j.marchem.2014.04.007
36. Rohmawati, A. M. S. (2019). *The relationship between physico-chemical characteristics of sediment with the morphology of Avicennia alba mangrove in Segara Anakan, Cilacap Regency* [Master's thesis, IPB University] (in Indonesia). IPB University.
37. Sarker, S., Masud-Ul-Alam, M., Hossain, M. S., Rahman Chowdhury, S., Sharifuzzaman, S. M. (2020). A review of bioturbation and sediment organic geochemistry in mangroves. *Geological Journal*, *56*(5), 1–12. https://doi.org/10.1002/gj.3808
38. Semanti, P., Robin, R. S., Purvaja, R., Ramesh, R. (2021). Fatty acid signatures of sediment microbial community in the chronically polluted mangrove ecosystem. *Marine Pollution Bulletin*, *172*. https://doi.org/10.1016/j.marpolbul.2021.112885
39. Siahaan, T. R. F., Manalu, E., Mangando, S., Dan, F. C. E., Demena, Y. E., Rumbino, F. N. Y., Leatemia, S. P. O., Saleh, F. I. E., Tebaiy, S., Widiastuti, N., Manangkalangi, E. (2022). Gastropod community in the mangrove ecosystem on Padaidori Island, Biak Numfor Regency, Papua (in Indonesia). *Journal of Marine Research*, *11*(4), 598–608. https://doi.org/10.14710/jmr.v11i4.33933
40. Singh, G., Chauhan, R., Ranjan, R. K., Ramanathan, A. (2015). Phosphorus dynamics in mangroves of India. *Current Science*, *108*(10). https://www.researchgate.net/publication/277359026
41. Singh, S., Rangarajan, S. (2023). Seasonal and spatial variability of sediment characteristics of Pichavaram Mangrove Forest, India. *Environment and Ecology Research*, *11*(1), 195–205. https://doi.org/10.13189/eer.2023.110114
42. Srisunont, C., Jaiyen, T., Tenrung, M., Likitchaikul, M., Srisunont, T. (2017). Nutrient accumulation by litterfall in mangrove forest at Klong Khone, Thailand. *Thammasat International Journal of Science and Technology*, *22*(1). https://doi.org/10.14456/tijsat.2017.2
43. Sulaeman, Suparto, Eviati. (2005). Chemical analysis of soil, plants, water, and fertilizer (in Indonesia). Balai Penelitian Tanah.

44. Syahminan. (2015). *Status of Heavy Metal Pollution of Lead (Pb) and Cadmium (Cd) in Sediments in the Waters of West Dumai, Riau* [Master Thesis, IPB University] (in Indonesia). IPB University.
45. Tang, D., Liu, X., Xia, Z., Hou, J., Yang, X., Li, P., Yuan, X. (2023). Sources of organic matter and carbon stocks in two mangrove sediment cores and surface sediment samples from Qinglan Bay, China. *Science of the Total Environment*, *893*. https://doi.org/10.1016/j.scitotenv.2023.164897
46. Taylor, P., Lichtschlag, A., Toberman, M., Sayer, M. D. J., Reynolds, A., Sato, T., Stahl, H. (2015). Impact and recovery of pH in marine sediments subject to a temporary carbon dioxide leak. *International Journal of Greenhouse Gas Control*, *38*, 93–101. https://doi.org/10.1016/j.ijggc.2014.09.006
47. Thanh, T. K., Maeda, M., Anh, T. N. (2016). Nitrous oxide emission from sediment of a tropical mangrove forest in central Vietnam implications of short-term laboratory experiments. *Journal of Environmental Science for Sustainable Society*, *7*, 1–8.
48. Veitayaki, J., Waqalevu, V., Varea, R., Rollings, N. (2017). *Mangroves in small island development states in the Pacific: An overview of a highly important and seriously threatened resource*. In DasGupta R, Shaw R (eds). (pp. 303–327). Springer. https://doi.org/10.1007/978-4-431-56481-2_19
49. Wang, L., Huang, X., Zheng, T. L. (2016). Responses of bacterial and archaeal communities to nitrate stimulation after oil pollution in mangrove sediment revealed by illumina sequencing. *Marine Pollution Bulletin*, *109*(1), 281–289. https://doi.org/10.1016/j.marpolbul.2016.05.068
50. Wijaya, I. M. S., Sugiana, I. P., Astarini, I. A., Ginantra, I. K., Rahim, K. A. A. (2024). Floristic composition of mangrove community in Ngurah Rai Forest Park and Nusa Lembongan, Bali, Indonesia. *Biodiversitas*, *25*(1), 300–309. https://doi.org/10.13057/biodiv/d250134
51. Wulandari, N. K. P., Ernawati, N. M., Saraswati, N. L. G. R. A. S. (2024). Estimated total carbon storage in Gilimanuk Bay Mangrove Forest, Bali. *Buletin Oseanografi Marina Oktober*, *13*(3), 424–436. https://doi.org/10.14710/buloma.v13i3.63104
52. Xiong, Y., Cakir, R., Phan, S. M., Ola, A., Krauss, K. W., Lovelock, C. E. (2019). Global patterns of tree stem growth and stand aboveground wood production in mangrove forests. *Forest Ecology and Management*, *444*, 382–392. https://doi.org/10.1016/j.foreco.2019.04.045
53. Yuniar, S. T., Virizki, A. N., Sahilla, D., Jumari, Fajri, M., Praditya, M. H., Febriansyah, P., Manalu, R., Kurniadi, Z. K., Sanjaya, I. M. Y., Nugraha, B. A., Hidayat, R., Kurniawan, D., Zamalludin, Saputra, D., Nugraha, H. A., Veronisa, Irawan, H. (2023). Analysis of marine garbage catches in mangrove roots of rhizophora sp in senggarang besar, tanjungpinang, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1148*(1). https://doi.org/10.1088/1755-1315/1148/1/012029
54. Zhang, M., Luo, Y., Lin, L., Lin, X., Hetharua, B., Zhao, W., Zhou, M., Zhan, Q., Xu, H., Zheng, T., Tian, Y. (2018). Molecular and stable isotopic evidence for the occurrence of nitrite-dependent anaerobic methane-oxidizing bacteria in the mangrove sediment of Zhangjiang Estuary, China. *Applied Microbiology and Biotechnology*, *102*(5), 2441–2454. https://doi.org/10.1007/s00253-017-8718-2