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Diversity and habitat preferences of mangrove species in Demta Bay, Papua Province, Indonesia

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Tel./fax.: +62-22-2511575, ♥email: tati@sith.itb.ac.id
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Abstract. *Kalor JD, Sumarga E, Choesin DN, Syamsudin TS. 2026. Diversity and habitat preferences of mangrove species in Demta Bay, Papua Province, Indonesia. Biodiversitas 27 (3): d270338. https://doi.org/10.13057/biodiv/d270338.* Mangrove species diversity is shaped by complex interactions among environmental factors that influence species-specific habitat preferences. This study aims to assess mangrove species diversity and identify the key environmental factors affecting their habitat preferences in Demta Bay, Jayapura, Papua, Indonesia. Fieldwork was carried out from September 1 to 20, 2024, across 10 research stations covering a total area of 40,000 m². Data were collected using the line transect plot method. At each station, two transects (100 m × 20 m) were established perpendicular to the shoreline, with a spacing of 100 m apart. Along each transect, four plots measuring 10 m × 10 m were established two plots with two replications, resulting in a total of 20 transects and 80 plots. Soil sampling and analysis were performed both in situ and ex situ, with four replications per transect. Data analysis included the Shannon-Wiener, Simpson, Margalef, and Pielou indices, as well as the Important Value Index. Habitat relationships were examined using Principal Component Analysis and Pearson correlation. This study documented 14 mangrove species from 6 families in Demta Bay, indicating moderate diversity. The composition of mangrove vegetation was characterized by an average density of 146.3±14.84 individuals/station (800m^2), a diversity index of 1.36±0.25, a dominance index of 0.32±0.07, a species richness of 1.13±0.43, and an evenness index of 0.74±0.10, suggesting stable ecological interactions and functional redundancy among species. Key habitat variables, soil bulk density (0.63±0.21 g cm^{-3}), soil pH (6.80±0.32), soil salinity (24.79±2.98 PSU), soil temperature (29.21±1.54°C), and soil moisture (48.70±18.53%), were measured across sites. This study demonstrates that soil characteristics exert a significant influence on mangrove species diversity and endemism in Demta Bay, Jayapura. Elevated salinity was linked to reduced species richness and evenness. *Rhizophora apiculata* and *Rhizophora mucronata* were the most dominant and widely distributed species, thriving in saline, compacted soils alongside *Bruguiera sexangula*. In contrast, *Excoecaria agallocha* favored moist soils with moderate pH, while *Ceriops decandra* performed best under slightly alkaline conditions. Given the geomorphological and ecological heterogeneity that drives localized species zonation in Demta Bay, as well as its benefits to local coastal communities, conservation efforts should focus on habitat-specific planting.

Keywords: Demta Bay, habitat preferences, Jayapura, mangrove species diversity, Papua

INTRODUCTION

Mangrove ecosystems are unique and highly productive coastal environments that serve as vital interfaces between terrestrial and marine realms (Kathiresan and Bingham 2001; Hogarth 2015). They support rich biodiversity and provide essential ecosystem services, including habitats for diverse flora and fauna, shoreline stabilization, protection from storm surges, sediment retention, maintenance of water quality, pollutant filtration, blue carbon storage, and nutrient cycling (Duke and Schmitt 2015; Danielson et al. 2017; Strain et al. 2022; Dabalà et al. 2023; Cooray et al. 2024; Alongi 2025).

Habitat preference, defined by species' adaptation to local environmental conditions, is a key factor shaping mangrove persistence under changing environments (Beyer et al. 2010; Begon and Townsend 2021). Understanding these preferences is crucial for predicting how mangrove communities respond to environmental change and for developing site-specific conservation and restoration strategies (Rahadian et al. 2022). In the Indo-Pacific region, mangrove ecosystem resilience is strongly shaped by habitat-specific adaptations that govern species distribution, ecological stability, and responses to environmental change. These adaptations enable mangroves to persist across diverse salinity, sediment, and hydrological conditions, thereby sustaining ecosystem functioning under both natural variability and increasing environmental stressors (Lovelock et al. 2015; Buffington et al. 2024).

Papua Island, Indonesia, located at the core of the Indo-Pacific region, hosts the world's largest mangrove area and the highest recorded mangrove diversity (Sillanpää et al. 2024). The island contains approximately 1.75 million ha of mangroves, about 11.9% of the global total, making it the most extensive and diverse mangrove habitat in the Asia-Pacific (Setyadi et al. 2022; Sillanpää et al. 2024). Situated at the convergence of Asian, Pacific, and Australasian floristic zones, Papua supports unique species assemblages, with floristic surveys reporting between 28 and 66 mangrove species across regions such as Mimika, Bintuni, and Merauke (Setyadi et al. 2021; Yudha et al. 2021; Kasihiw et al. 2024).

Despite this global significance, Papua's mangrove ecosystems face increasing threats from both natural and human-induced pressures (Yudha et al. 2021; Sillanpää et al. 2024). Rapid expansion of aquaculture, agriculture, infrastructure development, and logging has been reported in the regions of Bintuni, Jayapura, Manokwari, Merauke, and Sorong (Amir et al. 2019; Hamuna and Wanimbo 2021; Yudha et al. 2021; Sillanpää et al. 2024). Weak regulatory enforcement and a lack of integrated management have exacerbated these threats, enabling unregulated land-use change and resource exploitation (Sillanpää et al. 2024). Additional pressures include extractive industries and climate-related hazards such as coastal erosion, altered hydrological regimes, and tsunamis (Lekatompessy et al. 2019; Dharmawan and Pramudji 2020; Setyadi et al. 2021).

The extensive, highly diverse, and relatively undisturbed mangrove ecosystems in Papua offer a rare opportunity to examine intact systems and establish robust ecological baselines for conservation planning and management (Sillanpää et al. 2024) before they are altered or degraded, as has happened in mangrove ecosystems worldwide. Effective site-specific conservation and restoration strategies require a clear understanding of the ecological factors that determine species composition and distribution. Environmental variables such as soil texture, salinity, moisture content, bulk density, pH, and temperature are known to influence habitat suitability (Ola et al. 2018; Dewiyanti et al. 2021). Because mangrove species differ in their tolerance limits and adaptive strategies, even small changes in these parameters can alter community structure and ecosystem functioning (Begon and Townsend 2021; Rahadian et al. 2022). Analyses of species-environment relationships are therefore essential for anticipating biodiversity responses to anthropogenic disturbances and climate variability (Sippo et al. 2018; Sannigrahi et al. 2020).

Although Papua is widely recognized as a mangrove biodiversity hotspot, fine-scale ecological studies remain scarce, particularly in relatively undisturbed ecosystems such as Demta Bay, Jayapura Regency (Kalor et al. 2019; Indrayani et al. 2021). This study aims to assess mangrove species diversity and identify the key environmental factors influencing habitat preferences in Demta Bay. Specifically, it examines the relationships between soil bulk density, salinity, pH, temperature, and moisture content with mangrove diversity indices. We hypothesize that mangrove species diversity and distribution in Demta Bay are significantly shaped by these habitat-specific environmental conditions. The findings are expected to contribute essential baseline data to support sustainable mangrove management and biodiversity conservation in Papua and across the wider Indo-Pacific region.

MATERIALS AND METHODS

Study area

This study was conducted in Demta Bay, located in the Demta District, Jayapura Regency, Papua, Indonesia (Figure 1). The mangrove forests, predominantly found in the coastal zones of Ambora, Yougapsa, and Tarfia Villages, are traditionally owned and managed by the indigenous communities of these three villages, reflecting the strong link between local customary ownership and mangrove ecosystem management (Kalor et al. 2019; Indrayani et al. 2021).

Fieldwork was carried out from 1 to 20 September 2024 at 10 designated research stations, encompassing a total area of 4 ha. The sampling sites were geographically positioned between 140°08'33.423"E, 2°21'07.096"S and 140°08'51.591"E, 2°20'01.944"S (Table 1). Station placement was based on geomorphological characteristics and salinity gradients: Stations 1-3 were in the inner bay (tidal river mangroves), Stations 4-5 in the riverine-basin transition zone, Stations 6-7 along the coastal margin (fringe mangroves), and Stations 8-10 in the outer bay (fringe mangroves), directly facing the Pacific Ocean.

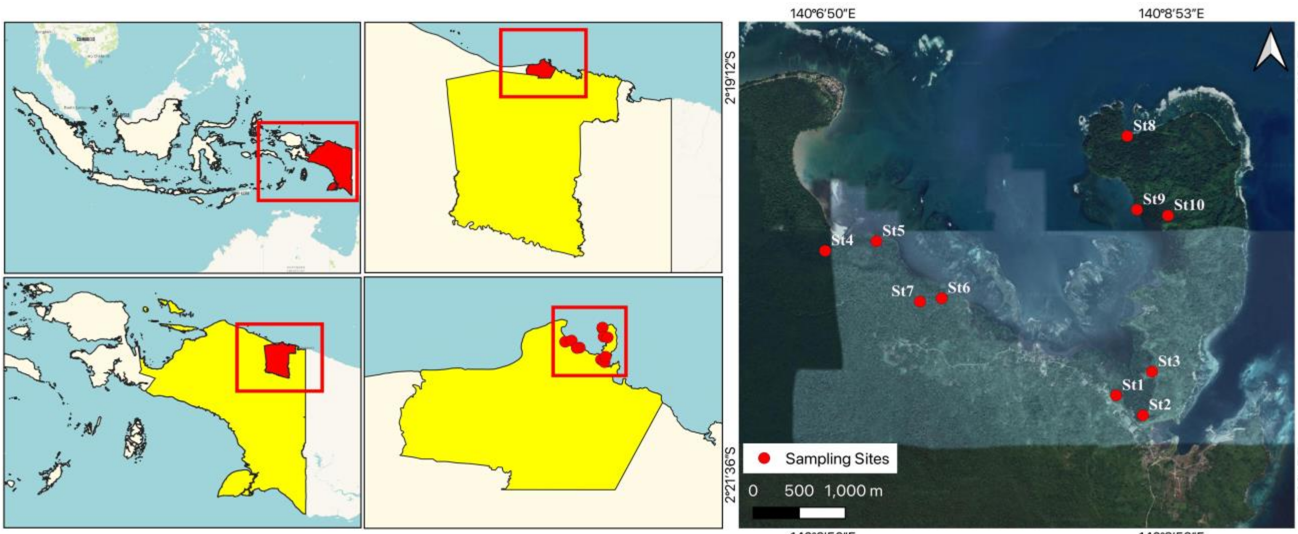

Figure 1. Map of the study area in mangrove ecosystem of Demta Bay, Jayapura, Papua, Indonesia, showing ten research stations

Table 1. Coordinates of mangrove sampling locations in Demta Bay, Jayapura, Papua, Indonesia

Stations	Locations	Latitude (S)	Longitude (E)
St1	Tidal river mangroves	2°21'07.1"	140°08'33.4"
St2	Tidal river mangroves	2°21'14.3"	140°08'42.8"
St3	Tidal river mangroves	2°20'58.5"	140°08'46.0"
St4	Riverine-basin mangroves	2°20'14.7"	140°06'51.2"
St5	Riverine-basin mangroves	2°20'11.2"	140°07'09.2"
St6	Fringe mangroves	2°20'31.9"	140°07'32.1"
St7	Fringe mangroves	2°20'33.1"	140°07'24.5"
St8	Fringe mangroves	2°19'33.1"	140°08'37.3"
St9	Fringe mangroves	2°19'59.8"	140°08'40.7"
St10	Fringe mangroves	2°20'01.9"	140°08'51.6"

Note: St1-St10: Station 1-Station 10

Data collection

To obtain accurate and representative data on mangrove vegetation, standardized field procedures were applied consistently across all research stations. Sampling was conducted during low tide to facilitate accessibility and improve visibility of the mangrove stands. Fieldwork was carried out for 6-8 hours per day, depending on tidal conditions and weather. Mangrove species composition, abundance, and structural attributes were assessed using the line transect plot method (Mueller-Dombois and Ellenberg 1974; Kauffman and Donato 2012).

At each station, two transects (100 m × 20 m) were established about 2 m inland from the forest edge and oriented perpendicular to the shoreline. The transects were spaced 100 m apart, giving a total sampled area of 40,000 m^2 across all ten stations. Within each transect, four plots measuring 10 m × 10 m were systematically positioned. This resulted in eight plots per station and 80 plots in total (or 8000 m^2). These plots were used for detailed vegetation and biotic observations, while the transects represented the overall sampling area at each station. Tree diameters were measured at breast height (DBH≥10 cm), taken 1.3 m above ground level for each stem. For multi-stemmed individuals, all stems ≥10 cm DBH were measured independently (Kauffman and Donato 2012; Setyadi et al. 2021). All mangrove species within each plot were identified, and the number of individuals per species was recorded. Species identification followed the taxonomic keys and morphological descriptions in Guide to the Introduction of Mangroves in Indonesia (Noor et al. 2006), Mangrove Guidebook for Southeast Asia (Giesen et al. 2007), and The Botany of Mangroves (Tomlinson 2016).

Soil sampling and analysis were performed both in situ and in the laboratory, with four replications per station. Soil pH, temperature, and moisture content were measured in situ using a 4-in-1 Digital Soil Tester (ISO 9001 certified), calibrated with distilled water before each use. The device provides indicative values suitable for rapid field assessment in saline or anoxic substrates. Soil porewater salinity was measured using a refractometer (ATAGO Master-S/Mill-E). Porewater was extracted from ~30 cm depth, and a few drops were placed directly onto the prism. The refractometer was calibrated with distilled water before each use, and values were reported in practical salinity units (PSU). Bulk density (BD) was measured using a cylindrical steel core (5 cm height, 73 mm internal diameter) inserted at 30 cm depth to obtain undisturbed samples. Cores were trimmed flush, oven-dried at 105°C for 48 h (Eyela SLI-400 Incubator), and BD was calculated as dry mass per core volume (g cm^{-3}). Soil texture was determined in the field using the hand-feel method, estimating the relative proportions of sand, silt, and clay by manipulating moist soil, and subsequently classified with the USDA soil texture triangle (Sartohadi and Suratman 2012).

Data analysis

The mangrove data were assessed using multiple ecological indices as detailed below.

Shannon-Wiener Index of Diversity (H′) was used to evaluate species diversity (Krebs 1978) and calculated as follows:

$$H' = -\sum_{i=1}^{s} pi \ln\ (pi)$$

Where, pi = ni/N; N: total number of individuals; ni: total of individual species; S: total number of species; and ln: natural logarithm (base *e*). Interpretation (Spellerberg and Fedor 2003): H'<1: low diversity, 1.0<H'<3: moderate, H'>3: high.

Simpson's Dominance Index (D) was calculated to assess species dominance (Krebs 1978) as follows:

$$D = \sum_{i=1}^{S} \left(\frac{ni}{N}\right)^2$$

Where, *ni* and N are as defined above, D: 0 indicates no dominance, while D: 1 indicates complete dominance by a single species.

Margalef's index equation (D_{mg}) was employed to assess species richness (Magurran 2003) with the formula as follows:

$$Dmg = \frac{S-1}{\ln{(N)}}$$

Where, S: number of species, N: Total number of individuals, ln: natural logarithm. Interpretation D_{mg} value, low: low species richness, high: high species richness.

Pielou index equation (J') was used to assess community evenness (Magurran 2003) using the equation below:

$$J' = \frac{H'}{lnS}$$

Where, H': Shannon Weiner index, S: number of species. Interpretation, if all species have the same number of individuals, J′: 1. If one species dominates, J′ is close to 0.

The Importance Value Index (IVI) was calculated as the sum of three ecological parameters: relative density (RD), relative frequency (RF), and relative dominance (RDo), following the standard ecological framework (Hogarth 2015; Dodo and Hidayat 2020; Jayadi et al. 2024).

IVI = Relative Density + Relative Frequency + Relative Dominance

$$\text{Density} = \frac{\textit{The number of species}}{\textit{Area measuring}}$$

$$\text{Relative Density} = \frac{\textit{Species density}}{\textit{Density of all species}} \; x\ 100\ \%$$

$$\text{Frequency} = \frac{\textit{The number of plots containing a species}}{\textit{The sum of all plots}}$$

$$\text{Relative Frequency} = \frac{\textit{Species frequency}}{\textit{Frequency of all species}} \; x\ 100\ \%$$

$$\text{Dominance} = \frac{\textit{Species dominance}}{\textit{Dominance of all species}}$$

$$\text{Relative Dominance} = \frac{\textit{Species Dominance}}{\textit{Dominance of all species}} \; x\ 100\ \%$$

The Importance Value Index (IVI) ranges from 0 to 300% for trees, with higher values indicating greater ecological importance of a species, reflecting their greater contribution to the mangrove community's structure, abundance, and spatial distribution. Soil bulk density (BD) (Tan 2005):

$$\text{BD } (gm^{-3}) = \frac{\text{oven-dried soil sample mass (g)}}{\textit{sample volume } (m^3)}$$

Principal Component Analysis (PCA) was employed to visualize multivariate patterns of species diversity in relation to environmental variables, reducing dimensionality and identifying key gradients driving mangrove community structure. Separately, Pearson's correlation analysis was conducted to assess pairwise relationships between soil physicochemical parameters (pH, salinity, moisture, bulk density, and temperature) and biodiversity indices (e.g., Shannon diversity, species richness). To quantify the influence of soil parameters on mangrove diversity, multiple linear regression models were fitted, with biodiversity indices as dependent variables and soil parameters as independent predictors. Final regression models are reported with coefficients (β), standard errors (SE), 95% confidence intervals (CI), and p-values for each predictor. All statistical analyses were performed using Microsoft Excel and XLSTAT version 2021.2.2, with PCA conducted in XLSTAT to ensure robust multivariate visualization.

RESULTS AND DISCUSSION

Mangrove species composition in Demta Bay

The mangrove community in Demta Bay, consisting of fourteen species from six botanical families across ten sampling stations, indicates a moderately high level of ecological complexity and biological integrity (Table 2). This study recorded an average of 146.3±14.84 individuals/station (800m^2). The diversity index (H') was 1.36±0.25, the dominance index (D) was 0.32±0.07, species richness (Dmg) averaged 1.13±0.43, and evenness (J') was 0.74±0.10, suggesting stable ecological interactions and functional redundancy among species. *Rhizophora apiculata* and *Rhizophora mucronata,* both highly salt-tolerant and structurally dominant species, were found consistently across all ten stations, from the tidal river zones (Stations 1-3) through transitional and coastal margins (Stations 6-7) to outer fringe areas (Stations 8-10). The presence of widespread species such as *Xylocarpus moluccensis*, *Bruguiera cylindrica*, *Bruguiera gymnorhiza*, and *Bruguiera sexangula*, alongside more localized species such as *Excoecaria agallocha* and *Ceriops decandra*, reflects the variety of habitats and differences in ecological niches across the bay.

When stations were grouped by geomorphological habitat types (Table 2 and Table 3), distinct patterns of diversity and structure emerged. Mangrove abundance (N) ranged from 127±11.53 individuals in the inner bay to 157.50±2.12 in riverine habitats. Species richness peaked in transitional and coastal fringe zones, reaching 11 species in areas likely characterized by moderate salinity, better drainage, and finer sediment textures conducive to species coexistence. These habitats also support complex ecological interactions, including mutualisms with pollinators and detritivores, which may further enhance diversity (Canty et al. 2022; Setyadi et al. 2022). The highest number of individuals occurred in riverine habitats (157.50±2.12), while the lowest was in the inner bay (127±11.53). Diversity index (H') ranged from 1.27 in the inner bay to 1.42 in coastal fringes, with dominance (D) generally low (0.28-0.36), indicating no single species overwhelmingly dominated. Species richness (Dmg) was highest in riverine and coastal habitats (~1.29) and lowest in the outer bay (0.86). Evenness (J') was relatively high across sites (0.68-0.84), suggesting balanced species distributions. Dominance was highest in the inner bay, primarily driven by the expansion of *Rhizophora* spp. This spatial pattern underscores the influence of environmental gradients on mangrove biodiversity across habitat types in Demta Bay: transition zones act as biodiversity hotspots, whereas ecotonal extremes tend to constrain biodiversity but enhance uniformity among well-adapted species (Duke and Schmitt 2015; Hogarth 2015).

Ecologically, this habitat distribution reveals Demta Bay's capacity to support both generalist and specialist mangrove taxa, structured by a mosaic of physicochemical and geomorphological variables (Table 2, Table 3, Table 4, and Table 5). Species with broader tolerances, such as *B. gymnorhiza*, *C. tagal*, *X. granatum*, were observed across multiple habitat types, while others like *Avicennia marina* and *Derris trifoliata* (restricted to Stations 6, 9 and 10) indicate localized habitat specificity, possibly driven by salinity thresholds, soil moisture, or tidal exposure. The species richness variability (Dmg: 0.79-1.90) and the presence of both dominant and subordinate species suggest a dynamic but resilient community structure (Table 2). The mangrove composition and spatial configuration of Demta Bay reflect a biologically adaptive and ecologically diverse coastal-riverine system. This system plays a crucial role in maintaining coastal resilience, biodiversity, and productivity in northern Papua (a region with fewer mangrove forests compared to Cenderawasih Bay and the Southern Coast of Papua), highlighting the importance of its conservation (Sillanpää et al. 2024).

The Importance Value Index (IVI) analysis highlights the ecological dominance of *R. apiculata* (IVI: 97.58) and *R. mucronata* (IVI: 64.28), these results are consistent with the species composition analysis presented in Table 2. Their high IVI scores are attributed to substantial relative density (RD: 36.02%, 28.10%, respectively), wide distribution (RF: 14.71%, 13.24%, respectively), and large contributions to stand structure (RDo: 46.86%, 22.94%; BA: 19.23 m² and 9.42 m², respectively), underscoring their critical role in shaping the mangrove community structure. Their broad spatial coverage and known physiological mechanisms (salt exclusion, stilt root anchoring) confirm their role as foundation species that enhance sediment retention, canopy cover, and ecosystem stability (Duke and Schmitt 2015). These keystone species likely thrive in the seaward or mid-zones of Demta Bay, where frequent tidal inundation and nutrient-rich sediments support their growth (Table 5). This aligns with Azwa et al. (2022) and Ashraf et al. (2023), who found that the roots of these species perform best in organic-rich, frequently inundated soils, conditions that enhance stability, attenuate waves, and support carbon sequestration vital for Papua's coastal resilience. Medium IVI species, such as *B. gymnorhiza* (IVI: 26.10), *B. sexangula* (IVI: 26.42), *X. granatum* (IVI: 18.74), *X. moluccensis* (IVI: 17.98), and *B. cylindrica* (IVI: 15.95), are co-dominant, occupying mid-to-landward zones of Demta Bay with moderate density (RD: 4.02-8.25%), distribution (RF: 5.88-11.76%), and biomass (RDo: 1.63-9.71%). These species enhance structural complexity, provide critical habitat for local fauna such as crabs and fish, and contribute significantly to nutrient cycling (Kalor et al. 2019). This is consistent with the findings of Sari et al. (2022), who reported high faunal diversity in the mangrove ecosystem of Youtefa Bay, highlighting the importance of structurally diverse mangrove habitats for sustaining rich and productive coastal biodiversity in Papua.

Low IVI species, including *C. tagal* (IVI: 9.61), *R. stylosa* (IVI: 9.56), *A. marina* (IVI: 3.69), *D. trifoliata* (IVI: 3.42), *H. littoralis* (IVI: 3.20), *C. decandra* (IVI: 1.87), and *E. agallocha* (IVI: 1.63), are rare or niche-specific in Demta Bay, with low density (RD: 0.07-4.02%), patchy distribution (RF: 1.47-7.35%), and minimal biomass (RDo: 0.05-1.12%). Species like *A. marina*, a pioneer in high-salinity seaward zones, and *E. agallocha*, a mangrove associate in landward zones, contribute to biodiversity and may indicate early succession or environmental stress, such as high salinity or disturbance in Papua's coastal conditions (Sillanpää et al. 2024). Management in Demta Bay should prioritize *Rhizophora* spp. for restoration in seaward zones to enhance coastal protection, include medium IVI species for zonation and diversity, and protect low IVI species to maintain biodiversity (Alongi and Zimmer 2024).

Table 2. Composition of mangrove species across Demta Bay, Jayapura, Papua, Indonesia

Species	St1	St2	St3	St4	St5	St6	St7	St8	St9	St10
Avicennia marina (Forssk.) Vierh.	-	-	-	-	-	+	-	-	-	-
Bruguiera cylindrica (L.) Blume.	+	+	-	-	+	+	+	-	+	+
Bruguiera gymnorhiza (L.) Lam.	-	+	+	+	-	+	+	-	+	+
Bruguiera sexangula (Lour.) Poir.	+	+	+	+	+	-	+	+	-	-
Ceriops decandra (Griff.) W.Theob.	-	-	-	-	+	-	-	-	-	-
Ceriops tagal (Perr.) C. B. Rob	+	+	+	-	+	+	-	-	-	-
Derris trifoliata Lour.	-	-	-	-	-	-	-	-	+	+
Excoecaria agallocha L.	-	+	-	-	-	-	-	-	-	-
Heritiera littoralis Aiton	-	+	-	-	+	-	-	-	-	-
Rhizophora apiculata Blume	+	+	+	+	+	+	+	+	+	+
Rhizophora mucronata Poir.	+	+	+	-	+	+	+	+	+	+
Rhizophora stylosa Griff.	-	+	-	-	+	-	+	-	-	-
Xylocarpus granatum J.Koenig	-	-	-	+	+	-	+	+	-	-
Xylocarpus moluccensis (Lam.) M.Roem.	-	+	-	+	+	+	+	+	+	+
Total number of individuals/station (800m^2)	131	114	136	156	159	147	159	157	153	151
Diversity Index (H')	1.16	1.67	0.97	1.09	1.66	1.54	1.30	1.19	1.43	1.57
Dominance Index (D)	0.38	0.26	0.43	0.39	0.23	0.26	0.35	0.35	0.27	0.23
Richness Index (Dmg)	0.82	1.90	0.81	0.79	1.78	1.20	1.38	0.79	0.99	0.80
Pielou's evenness Index (*J'*)	0.72	0.73	0.60	0.68	0.72	0.79	0.63	0.74	0.80	0.97

Note: St1-St10: Station 1-Station 10

Table 3. Diversity of mangrove species across habitat types in Demta Bay, Jayapura, Papua, Indonesia

Parameter	Inner Bay (tidal river)	Coastal (fringe)	River (basin-riverine)	Outer Bay (fringe)
Total number of individuals/ station (800 m^2)	127±11.53	153±8.49	157.50±2.12	153.67±3.06
Diversity index (H')	1.27±0.36	1.42±0.17	1.38±0.40	1.40±0.19
Dominance index (D)	0.36±0.9	0.31±0.6	0.31±0.11	0.28±0.6
Richness index (Dmg)	1.18±0.63	1.29±0.13	1.29±0.70	0.86±0.11
Pielou's evenness index (J')	0.68±0.07	0.71±0.11	0.70±0.03	0.84±0.12

Note: Stations 1-3: Tidal River mangroves, Stations 4-5: riverine-basin, Stations 6-7: fringe, Stations 8-10: fringe

Species-habitat associations of mangroves in Demta Bay

Habitat data from ten sampling stations in Demta Bay reveal significant spatial variability in soil conditions that influence the composition of mangrove species assemblages (Table 5 and Table 6). Soil bulk density ranged from 0.38-0.77 g/cm³, with the lowest values at riverine Station 5 and the highest at coastal and outer bay Stations 6 and 9, reflecting greater soil compaction in saline environments. Soil pH varied from 6.50 to 7.31, peaking at Station 5, while salinity ranged from 21.78 to 28.22 PSU, with the lowest at Station 4 due to freshwater input and the highest at Stations 3 and 9. Soil moisture (33.23%-60.59%) and clay loam-dominated soil types further influence aeration and water retention, critical for propagule settlement, seedling establishment, and root development (Dewiyanti et al. 2021; Sumani et al. 2021). Soil temperature remained relatively stable (26.02°C-30.12°C). This environmental heterogeneity across Inner Bay, River, Coast Line, and Outer Bay zones drives mangrove species distribution and zonation by creating distinct microhabitats. These findings highlight soil pH and bulk density as key determinants of species composition, providing critical insights for restoration planning and species selection in geomorphologically dynamic coastal ecosystems.

The spatial distribution and abundance of mangrove species in Demta Bay are closely linked to key environmental gradients, particularly soil bulk density, pH, and moisture content (Table 5 and Figure 2). These findings emphasize the importance of soil chemistry and physical structure in determining species-specific habitat suitability (Chowdhury et al. 2019; Dewiyanti et al. 2021). Data from Tables 2, 4, and 6 identify *R. apiculata* and *R. mucronata* as the most abundant and ecologically dominant species, functioning as keystone taxa within the Demta Bay mangrove ecosystem, a finding further corroborated by the regression analyses in Figure 2, which demonstrate their strong association with higher salinity and compacted soil conditions. These species were predominantly distributed in sites with moderately compacted soils (bulk density: 0.59-0.63 g/cm³) and near-neutral pH values (6.76-6.81), which are characteristic of riverine-basin and fringe mangrove zones (Figure 2 and Table 6). However, Setyadi et al. (2021) reported that both species were dominant in four estuaries in Mimika District, Papua, namely, the Kamora, Tipuka, Ajkwa, and Minajerwi estuaries.

Table 4. Important Value Index of mangrove species in Demta Bay, Jayapura, Papua, Indonesia

Species	N	DBH (Cm)	BA (%)	RD (%)	RF (%)	RDo (%)	IVI (%)
Avicennia marina (Forssk.) Vierh.	9	10.67±0.52	0.05	0.61	2.94	0.13	3.69
Bruguiera cylindrica (L.) Blume.	59	11.38±1.94	0.67	4.02	10.29	1.63	15.95
Bruguiera gymnorhiza (L.) Lam.	121	16.80±6.66	3.10	8.25	10.29	7.55	26.10
Bruguiera sexangula (Lour.) Poir.	94	20.82±10.39	3.99	6.41	10.29	9.71	26.42
Ceriops decandra (Griff.) W.Theob.	5	9.45±2.47	0.02	0.34	1.47	0.05	1.87
Ceriops tagal (Perr.) C. B. Rob	26	9.69±2.06	0.20	1.77	7.35	0.49	9.61
Derris trifoliata Lour.	5	12.04±0.57	0.06	0.34	2.94	0.14	3.42
Excoecaria agallocha L.	1	21.34±0	0.04	0.07	1.47	0.09	1.63
Heritiera littoralis Aiton	2	17.04±6.53	0.05	0.14	2.94	0.12	3.20
Rhizophora apiculata Blume	528	19.52±9.12	19.23	36.02	14.71	46.86	97.58
Rhizophora mucronata Poir.	412	15.47±7.25	9.42	28.10	13.24	22.94	64.28
Rhizophora stylosa Griff.	59	9.81±2.60	0.46	4.02	4.41	1.12	9.56
Xylocarpus granatum J.Koenig	86	18.50±9.14	2.87	5.87	5.88	6.99	18.74
Xylocarpus moluccensis (Lam.) M.Roem.	59	12.90±5.30	0.90	4.02	11.76	2.19	17.98

Note: N: Total number of individuals, DBH: Diameter at breast height, BA: Basal area, RD: Relative density, RF: Relative frequency, RDo: Relative dominance, IVI: Importance value index

Table 5. Environmental characteristics of mangrove habitats in Demta Bay, Jayapura, Papua, Indonesia

Stations	Habitat	Soil	BD (gcm⁻³)	pH	S (PSU)	T (°C)	SM (%)
St 1	Tidal river (IB)	CL, L	0.49±0.49	6.63±0.24	25.01±2.81	29.69±0.70	43.2±8.27
St 2	Tidal river (IB)	CL, L, SCL	0.43±0.18	6.83±0.19	24.35±3.28	30.00±0.00	58.09±20.98
St 3	Tidal river (IB)	CL, SCL	0.62±0.13	6.86±0.07	28.22±1.15	29.41±1.00	44.24±5.11
St 4	Basin-riverine (R)	CL	0.65±0.14	6.94±0.14	21.78±1.43	26.02±2.35	55.53±5.35
St 5	Basin-riverine (R)	CL, SCL	0.46±0.20	7.31±0.36	23.54±2.51	30.12±0.27	48.74±8.36
St 6	Fringe (Cs)	CL, L	0.77±0.11	7.01±0.16	24.65±1.63	29.26±0.43	56.67±3.25
St 7	Fringe (Cs)	CL, L	0.62±0.29	6.5±0.22	26.33±2.07	29.95±0.37	56.09±9.64
St 8	Fringe (OB)	L	0.60±0.14	6.89±0.07	22.95±3.17	28.28±1.10	32.83±2.40
St 9	Fringe (OB)	CL	0.73±0.20	6.57±0.34	28.08±1.36	29.53±0.50	48.11±28.83
St 10	Fringe (OB)	CL	0.75±0.22	6.64±0.24	22.78±1.54	30±0.00	49.35±36.98

Note: St1-St10: Station 1-Station 10, IB: Inner Bay, R: River, Cs: Coastal, OB: Outer Bay, CL: Clay loam, L: Loam, SCL: Silty clay loam, BD: bulk density, pH: potential of hydrogen, S: salinity, T: temperature, SM: Soil Moisture

Rhizophora apiculata and *R. mucronata* exhibit broad ecological adaptability, enabling their widespread occurrence across varied habitat types. In Demta Bay (Table 6), these species are commonly associated with clay, loam, and silty clay loam soils that offer both aeration and water retention, conditions favorable for the establishment of stilt-rooted mangroves. Their distribution underscores a tolerance for diverse physical and chemical settings, including moderately brackish waters and semi-compacted substrates with stable sediments. This resilience and ecological versatility highlight their value as priority species for mangrove conservation and restoration initiatives across heterogeneous coastal landscapes of Papua and beyond.

In contrast, less common species such as *E. agallocha, H. littoralis*, and *D. trifoliata* were associated with habitats that have distinct physicochemical profiles. *E. agallocha* was found in the most humid microhabitats (soil moisture >60%), while *D. trifoliata* occurred in compacted substrates with the highest recorded bulk density (0.87 g/cm³). *H. littoralis* was recorded in soils with the lowest bulk density (0.28 g/cm³), indicating a preference for loose substrates that may offer lower mechanical resistance for root penetration (Table 4, Table 6, Figure 2). *E. agallocha*, *H. littoralis*, and *D. trifoliata* are relatively uncommon in mangrove ecosystems and are often classified as mangrove associate species because of their preference for landward or transitional zones, limited salinity tolerance, susceptibility to anthropogenic pressures, and relatively lower competitive and reproductive capacities (Kaliamurthi and Selvaraj 2016; Wu et al. 2025). These factors contribute to their lower abundance compared to dominant species like *Rhizophora*. Conversely, several core mangrove species exhibited broader ecological adaptability. For example, *B. gymnorhiza*, *B. sexangula*, and *B. cylindrica* showed intermediate abundance and were commonly found in slightly acidic soils (pH 6.7-6.8) with moderate bulk density (Figure 5), indicating their tolerance of a wider range of habitat conditions. Similarly, *X. granatum* and *X. moluccensis*, occurred across multiple sites, suggesting generalist ecological strategies in relation to salinity, temperature, and soil texture (Duke and Schmitt 2015).

The linear regression analyses presented in Figure 2 provide insights into the relationships between mangrove species distribution and key environmental parameters, serving as indicators of habitat preferences. The coefficient of determination (R^2) values suggests that salinity (R^2: 0.1378) exerts the strongest influence on species distribution, followed by soil moisture (R^2: 0.0888) and temperature (R^2: 0.051). Bulk density (R^2: 0.031) and pH (R^2: 0.045) showed only weak associations with species distribution. This suggests that other ecological drivers, such as tidal inundation regimes, hydrological connectivity, propagule dispersal, and interspecific competition, may exert stronger influences on the spatial structuring of mangrove species in this region.

Increase in mangrove species diversity in Demta Bay

The diversity of mangrove species across 10 research sites within the mangrove ecosystem area of Demta Bay exhibits considerable variation (Table 2, Table 3, Table 4). The diversity index ranges from 0.97 to 1.67 (1.36±0.25), indicating a moderate to high level of species diversity. These findings align with previous research, which identified nine mangrove species across five families, indicating a moderate level of species diversity with an H index ranging from 1.45 to 1.62 (Kalor et al. 2019; Indrayani et al. 2021). However, these studies did not account for the presence of *Sonneratia caseolaris* (Kalor et al. 2019; Indrayani et al. 2021). When this species is included, the cumulative total increases to fifteen mangrove species from seven families in Demta Bay.

The relatively moderate diversity and high evenness observed in this study suggest that the mangrove ecosystem in Demta Bay is both healthy and balanced. Comparable biodiversity patterns have been reported in other mangrove ecosystems with similar ecological conditions and limited anthropogenic disturbance. For instance, the coastal mangroves of Bintuni Bay in Papua, Indonesia, support 30 species, reflecting a rich and diverse ecosystem (Sasmito et al. 2020). In Youtefa Bay, the estuarine-coastal setting sustains nine mangrove species (Kalor et al. 2018; Sari et al. 2022). Likewise, the mangroves of Takalar Beach in South Sulawesi, Indonesia, host eleven species from eight families (Setiawan and Mursidin 2018), while the Sundarbans coast in India harbors as many as 30 species (Sreelekshmi et al. 2020). These comparisons underscore the role of stable environmental conditions in sustaining biodiversity across different mangrove ecosystems.

Correlation between mangrove species diversity and habitat characteristics

The results of Pearson correlation analysis for mangrove diversity and habitat characteristics across 10 research sites revealed several inter-variable relationships (Figure 3 and Table 7). Soil bulk density (BD) showed a weak and non-significant negative correlation with species diversity (r: -0.179, p: 0.62) and dominance (r: -0.005, p: 0.989). By contrast, BD exhibited a strong and significant negative correlation with species richness (r: -0.661, R^2: 0.437, p: 0.037), indicating that compacted soils may constrain the establishment of new taxa. A moderate positive, though non-significant, correlation was also observed between BD and species evenness (r: 0.44, p: 0.204), suggesting that while soil compaction reduces richness, it may promote a more balanced distribution among the remaining species. The dynamics of BD in mangrove ecosystems are influenced by ecological conditions and disturbances (Nengi-Benwari et al. 2022). High levels of disturbance can reduce tree density, potentially leading to an increase in BD, and conversely, low disturbance levels may result in a decrease in BD (Weiss et al. 2016; Gani et al. 2021; Wiesebron et al. 2021; Ayu et al. 2023). Likewise, Sumani et al. (2021) reported that natural mangrove forests in Merauke exhibit moderate bulk density, depending on the degree of anthropogenic disturbance.

Soil BD plays a fundamental role in shaping mangrove ecosystem structure by regulating sediment compaction, aeration, and root penetrability, which directly determine species establishment and zonation (Ola et al. 2024). In this study (Figure 3 and Table 7), the observed BD range (0.38-

0.77 g/cm³; mean: 0.60 g/cm³) reflects moderate compaction, generally favorable for root development (Hossain and Nuruddin 2016; Ola et al. 2018). Low-BD zones (0.5-1.0 g/cm³), often located in frequently inundated mudflats, supported flood-tolerant species such as *Rhizophora* spp. whereas moderate-BD zones (0.8-1.2 g/cm³) sustained the highest richness (Farahisah and Siregar 2024). Conversely, higher BD values (>1.5 g/cm³), typically occurring landward, favored stress-tolerant mangrove associates such as *D. trifoliata*, *E. agallocha* and *H. littoralis*. These BD gradients reflect the interaction of sediment heterogeneity, tidal regimes, and hydrological processes, which collectively shape species zonation, influence endemism, and drive biogeographic distribution patterns within Demta Bay, Jayapura.

Table 6. Habitat preferences of mangrove species in Demta Bay, Jayapura, Papua, Indonesia

Species	BD (gcm⁻³)	pH	S (PSU)	T (°C)	SM (%)	L	CL	SCL
Am	0.72±0.01	7.00±0.11	24.33±1.50	29.17±0.40	55.05±3.75	+	-	-
Bc	0.54±0.02	6.73±0.29	24.65±2.73	29.88±0.46	57.55±30.19	+	+	+
Bg	0.71±0.22	6.67±0.31	25.34±2.68	29.73±0.44	51.87±26.35	+	+	-
Bs	0.56±0.15	6.86±0.14	23.40±3.09	28.52±1.83	38.57±12.21	+	+	+
Cd	0.32±0.00	8.00±0.00	22.00±0.00	30.00±0.00	37.54±0.00	-	+	-
Ct	0.47±0.17	7.13±0.11	24.33±1.53	29.33±0.57	49.91±4.70	+	+	+
Dt	0.90±0.18	6.70±0.11	24.60±3.28	29.50±0.55	59.91±41.58	-	+	-
Ea	0.49±0.00	6.50±0.00	24.00±0.00	30.00±0.00	75.70±0.00	-	+	-
Hl	0.28±0.09	6.95±0.07	25.00±5.66	30.50±0.71	57.49±0.87	-	+	-
Ra	0.61±0.22	6.81±0.35	24.88±2.99	29.19±1.63	48.97±17.17	+	+	+
Rm	0.62±0.21	6.76±0.28	25.71±2.74	29.58±0.80	45.89±17.08	+	+	+
Rs	0.56±0.19	7.06±0.08	23.35±2.18	30.00±0.00	54.00±10.37	+	-	+
Xg	0.66±0.16	6.91±0.26	22.17±1.99	26.55±2.31	54.50±6.43	+	+	-
Xm	0.56±0.21	6.95±0.41	23.88±2.49	29.34±1.63	51.98±21.32	+	+	+

Note: Am: *Avicennia marina*, Bc: *Bruguiera cylindrica*, Bg: *Bruguiera gymnorhiza*, Bs: *Bruguiera sexangular*, Cd: *Ceriops decandra*, Ct: *Ceriops tagal*, Dt: *Derris trifoliata*, Ea: *Excoecaria agallocha*, Hl: *Heritiera littoralis*, Ra: *Rhizophora apiculata*, Rm: *Rhizophora mucronata*, Rs: *Rhizophora stylosa*, Xg: *Xylocarpus granatum*, Xm: *Xylocarpus moluccensis*. N: number of species, BD: Bulk density, pH: Potential of hydrogen, S: Salinity, T: Temperature, SM: Soil Moisture, L: Loam Soil, CL: Clay loam, SCL: Silty Clay Loam

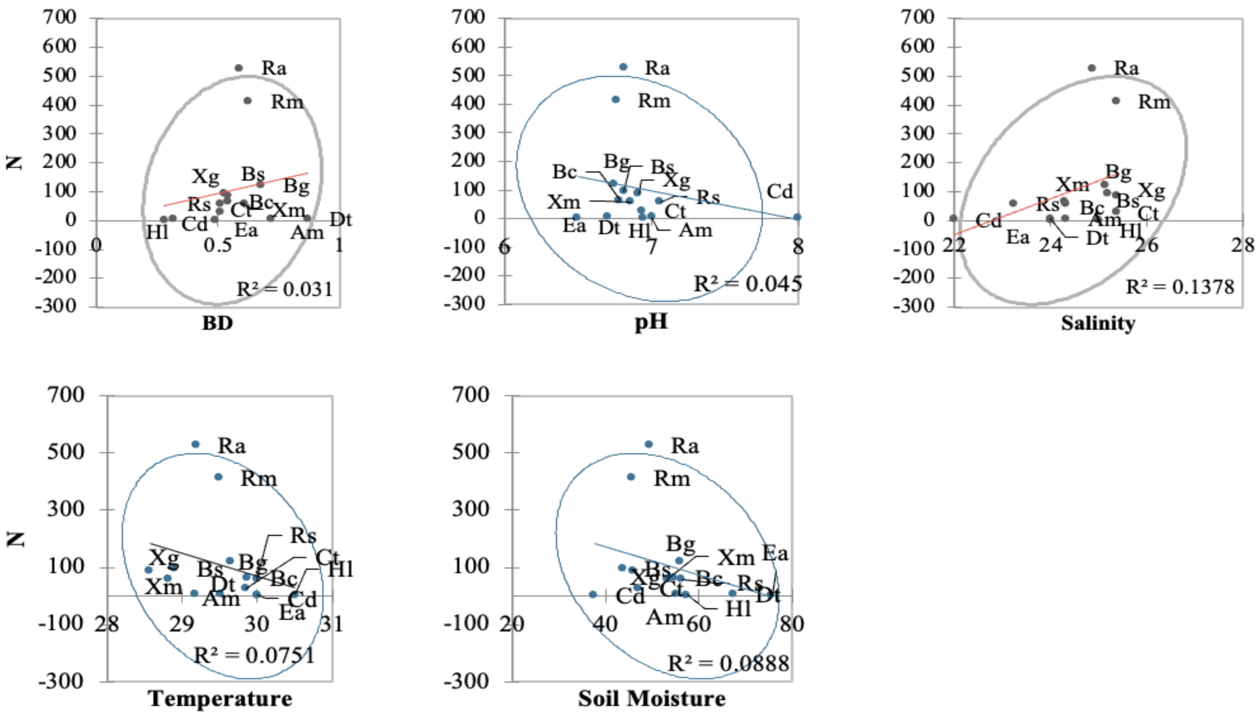

Figure 2. Species-habitat relationships in mangrove ecosystems of Demta Bay, Jayapura. Am: *Avicennia marina*, Bc: *Bruguiera cylindrica*, Bg: *Bruguiera gymnorhiza*, Bs: *Bruguiera sexangula*, Cd: *Ceriops decandra*, Ct: *Ceriops tagal*, Dt: *Derris trifoliata*, Ea: *Excoecaria agallocha*, Hl: *Heritiera littoralis*, Ra: *Rhizophora apiculata*, Rm: *Rhizophora mucronata*, Rs: *Rhizophora stylosa*, Xg: *Xylocarpus granatum*, Xm: *Xylocarpus moluccensis*

As shown in Figure 3 and Table 7, pH showed a weak positive correlation with species diversity (r: 0.219, p: 0.543) and richness (r: 0.351, p: 0.320), while weak negative correlations were observed with dominance (r: -0.197, p: 0.586) and evenness (r: -0.141, p: 0.697). Although none of these relationships were statistically significant, the trends suggest that slightly higher pH (less acidic soils) may be associated with greater diversity and richness, whereas lower pH conditions could marginally favor species dominance (Hossain and Nuruddin 2016; Weiss et al. 2016; Wiesebron et al. 2021). These patterns highlight that soil pH exerts a relatively minor influence on mangrove community structure in Demta Bay compared to other edaphic factors such as bulk density. Unlike the unstable pH conditions reported from polluted mangrove ecosystems such as Youtefa Bay, Jayapura (Sari et al. 2020; Hamuna and Wanimbo 2021), the relatively stable pH values observed in Demta Bay (6.50-7.31) indicate neutral to slightly acidic soils, which are optimal for mangrove growth and nutrient cycling (Hossain and Nuruddin 2016; Dewiyanti et al. 2021).

Salinity (S) exhibited variable correlations with mangrove community attributes across the 10 study sites (Figure 3 and Table 7). A weak negative relationship was observed with species diversity (r: -0.244, p: 0.496) and species richness (r: -0.037, p: 0.920), while a weak positive association was detected with species dominance (r: 0.261, p: 0.466). Notably, species evenness showed a moderate negative correlation with salinity (r: -0.356, p: 0.313), suggesting that increased salinity may reduce the uniformity of species distribution within stands. Although none of these relationships were statistically significant, the overall trend supports the well-established role of salinity as a key driver of mangrove community structure and distribution (Lovelock et al. 2016; Alongi 2018). Average salinity levels of 24.84 PSU (Table 5 and Table 6), typical mangrove habitats influenced by seawater, reflect the adaptability of mangrove species to saline environments (Hossain and Nuruddin 2016; Nasrin et al. 2019). Pronounced salinity fluctuations driven by human activities and pollution can substantially alter mangrove species composition by favoring salt-tolerant taxa while suppressing less tolerant species, as documented in Youtefa Bay, Jayapura (Hamuna and Wanimbo 2021). These changes often lead to shifts in forest composition, reduced biodiversity, and diminished structural complexity, highlighting the critical role of salinity in shaping mangrove ecosystem health and zonation patterns (Chowdhury et al. 2019; Wang et al. 2024). Therefore, restoration strategies should incorporate salinity gradients as a key criterion in selecting planting sites and species, aligning restoration efforts with species-specific salinity tolerance and adaptive capacity (Hossain et al. 2014).

Temperature (T) showed moderate positive correlations with species diversity (r: 0.543, R^2: 0.295, p: 0.105) and species richness (r: 0.477, R^2: 0.228, p: 0.163), alongside a weak positive relationship with species evenness (r: 0.217, R^2: 0.047, p: 0.546) (Figure 3 and Table 7). In contrast, species dominance exhibited a moderate negative association with temperature (r: -0.488, R^2: 0.238, p: 0.153), suggesting that higher temperatures may reduce the prevalence of dominant taxa, thereby favoring more balanced community structures. Stable temperature regimes support higher species abundance and diversity, contributing to a more balanced community structure (Azwa et al. 2022). In contrast, temperature shows a significant negative correlation with species dominance (r: -0.51), suggesting that elevated temperatures reduce the dominance of particular species, thereby enhancing ecological evenness. Furthermore, temperature fluctuations significantly influence mangrove species distribution, with elevated temperatures posing constraints on mangrove dispersal and recruitment (Lovelock et al. 2016; Sippo et al. 2018).

Soil moisture (SM) exhibited a moderate positive correlation with species diversity (r: 0.511, R^2: 0.261, p: 0.131), suggesting that higher soil water content tends to support more diverse mangrove communities, although the relationship was not statistically significant (Figure 3 and Table 7). Species dominance showed a moderate negative correlation with SM (r: -0.460, R^2: 0.211, p: 0.181), indicating that wetter soils may reduce the competitive advantage of dominant taxa and promote greater community balance. Meanwhile, weaker positive correlations with species richness (r: 0.320, p: 0.367) and evenness (r: 0.362, p: 0.304) imply that while soil moisture contributes to diversity patterns, its influence on species abundance and distribution uniformity is less pronounced. The observed soil moisture range (33.23%-60.59%; mean: 50.16%) reflects stable hydrological conditions in Demta Bay; however, anthropogenic disturbances such as mangrove clearance, aquaculture expansion, and pollution may disrupt these regimes, reducing soil water availability and threatening habitat stability and biodiversity (Lovelock et al. 2016; Sippo et al. 2018). To safeguard mangrove diversity, conservation strategies should prioritize protecting freshwater inputs, restoring natural hydrological flows, establishing buffer zones to mitigate pollution, and regulating aquaculture practices to sustain optimal soil moisture and overall ecosystem stability (Reef et al. 2010; Hossain and Nuruddin 2016; Azwa et al. 2022).

Neutral soil bulk density and pH are crucial for promoting species richness, while acidic conditions and compacted soils tend to reduce diversity (Hossain and Nuruddin 2016; Ola et al. 2024). Moderate salinity levels support diverse, mixed-species stands, but extreme salinity restricts communities to highly salt-tolerant genera such as *Avicennia* and *Rhizophora* (Sippo et al. 2018; Nasrin et al. 2019). High soil moisture content is beneficial for enhancing seedling survival and the development of below-ground biomass (Lovelock et al. 2016; Constance et al. 2022). Furthermore, stable temperatures (26-32°C) are essential for maintaining the physiological functioning of mangroves and their characteristic zonation patterns (Azwa et al. 2022). These interconnected environmental gradients collectively shape regional endemism and the adaptive distributions of species within Indo-Pacific mangrove ecosystems. High species richness and endemism in the Indo-West Pacific are partly attributable to environmental heterogeneity across coastal landscapes, shaped by the interaction of tectonic uplift, riverine sediment delivery, monsoonal rainfall, and oceanic connectivity (Duke 2017; Alongi and Zimmer 2024). Consequently, maintaining the stability of these abiotic factors is critical for sustaining mangrove biodiversity, supporting endemic species, and preserving the ecological functions of these forests in a rapidly changing climate.

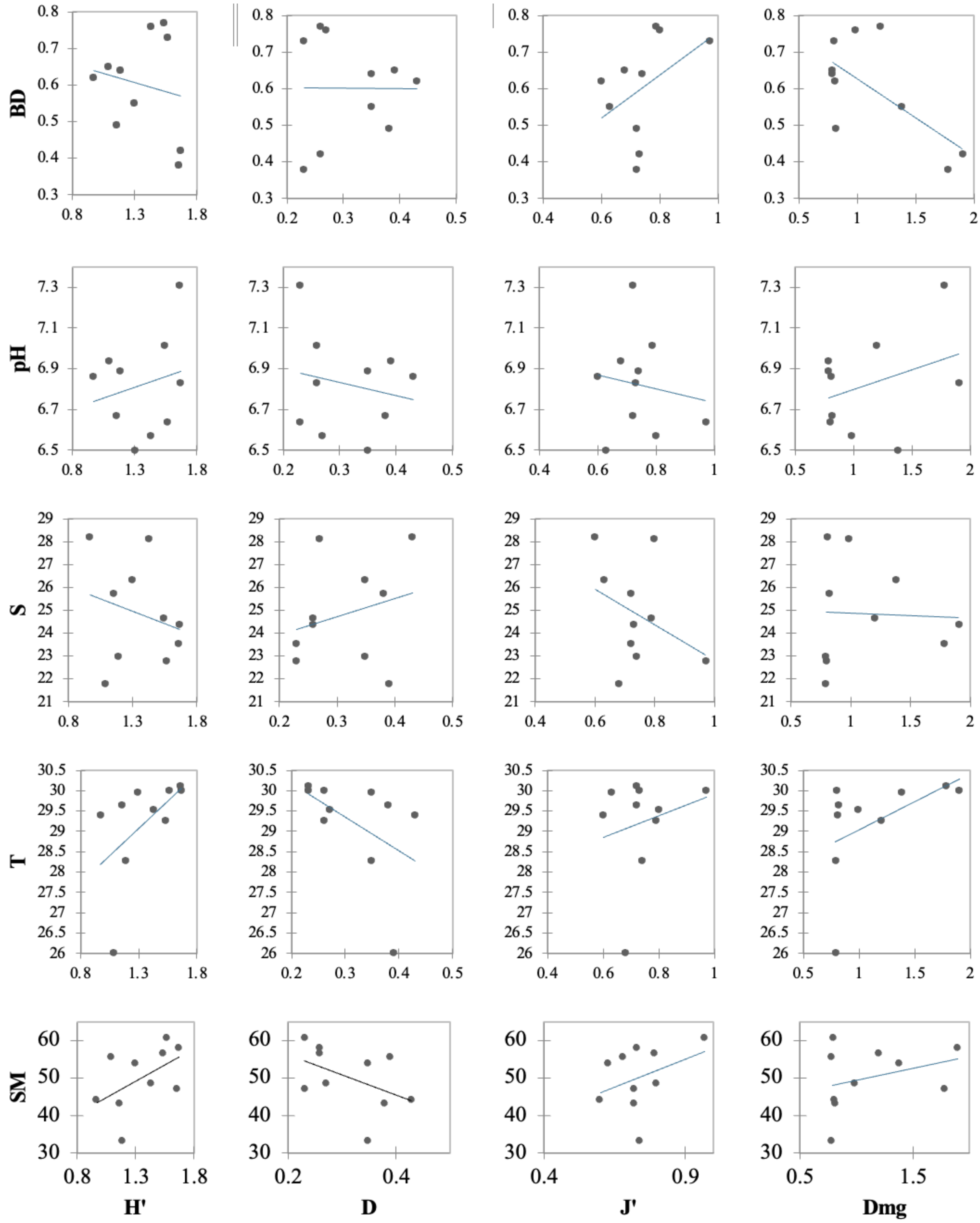

Figure 3. The correlations between mangroves and habitat characteristics in Demta Bay, Jayapura, Papua, Indonesia. H': Species diversity, D: Dominance, Dmg: Richness, J': Evenness, BD: Bulk Density, S: Salinity, T: Temperature, SM: Soil Moisture

Table 7. Pearson's correlation analysis of biodiversity indices and soil parameters

Soil parameter	Biodiversity index	r	R²	p-value
BD	H'	-0.179	0.032	0.62
BD	D	-0.005	0.000	0.989
BD	Dmg	-0.661	0.437	0.037
BD	J'	0.44	0.193	0.204
PH	H'	0.219	0.048	0.543
PH	D	-0.197	0.039	0.586
PH	Dmg	0.351	0.123	0.320
PH	J'	-0.141	0.020	0.697
S	H'	-0.244	0.06	0.496
S	D	0.261	0.068	0.466
S	Dmg	-0.037	0.001	0.92
S	J'	-0.356	0.127	0.313
T	H'	0.543	0.295	0.105
T	D	-0.488	0.238	0.153
T	Dmg	0.477	0.228	0.163
T	J'	0.217	0.047	0.546
SM	H'	0.511	0.261	0.131
SM	D	-0.46	0.211	0.181
SM	Dmg	0.32	0.102	0.367
SM	J'	0.362	0.131	0.304

Note: H': Species diversity, D: Dominance, Dmg: Richness, and J': Evenness, BD: Bulk Density, S: Salinity, T: Temperature, SM: Soil Moisture

Multivariate analysis of habitat characteristics and mangrove species diversity

Habitat characteristics as an ecological preference for mangrove diversity were analyzed using Principal Component Analysis (PCA) to evaluate the influence of habitat characteristics on mangrove diversity in Demta Bay, Jayapura. The analysis identified two principal components: F1 (35.58%) and F2 (22.62%), together accounting for approximately 58.20% of the total data variability (Figure 4). F1 was strongly associated with pH (factor loading: 0.22), temperature (0.58), and soil moisture (0.56), which showed positive correlations with species diversity (factor loading: 0.99), richness (0.74), and evenness (0.54). Stations, St2 (factor score 2.73), St5 (2.47), St6 (1.19), and St10 (1.89), with high F1 scores, displayed favorable environmental conditions and higher biodiversity.

In contrast, St3 (-2.71) and St4 (-2.12) had negative F1 scores and lower diversity, likely due to suboptimal soil or microclimatic conditions. Similar patterns have been observed in Bintuni Bay and Merauke (Sasmito et al. 2020; Sumani et al. 2021), where altered pH or moisture regimes reduce mangrove resilience. However, external pressures such as coastal erosion, aquaculture expansion, and industrial pollution continue to degrade mangrove habitat quality. These stressors alter soil properties and disrupt hydrological balance, ultimately reducing biodiversity. Similar patterns have been reported in other mangrove ecosystems across Papua and Southeast Asia (Hossain and Nuruddin 2016; Nasrin et al. 2019; Sumani et al. 2021; Ola et al. 2024). Effective conservation strategies should prioritize habitat restoration, enforce sustainable aquaculture practices, and enhance monitoring to protect biodiversity and ecosystem function.

Principal Component F2 is primarily influenced by bulk density and salinity (factor loadings: 0.82 and 0.21, respectively). Bulk density shows a positive correlation with F2, while salinity exhibits a negative correlation. This pattern is reflected in the distribution of sampling stations: St8 (factor score: 0.60), St9 (1.04), and St10 (2.81) are more closely associated with high bulk density, whereas St3 is more strongly linked to elevated salinity levels. Ecologically, high bulk density can affect soil structure and nutrient availability, ultimately impacting the number of individuals and the dominance of specific species (Diana et al. 2023; Yan et al. 2024). In contrast, high salinity tends to limit species diversity, as only salt-tolerant species can thrive under such conditions (Hossain and Nuruddin 2016; Nasrin et al. 2019). High bulk density and salinity levels limit mangrove diversity by favoring halophytic species such as *A. marina*, *R. apiculata*, and *R. mucronata*, which can outcompete less salt-tolerant species and exhibit contrasting responses to variations in soil bulk density, resulting in monospecific stands and decreased structural complexity (Chowdhury et al. 2019; Nasrin et al. 2019; Ashraf et al. 2023).

The analysis indicates that environmental variables such as pH, temperature, and soil moisture play a more substantial role in supporting mangrove species diversity compared to bulk density and salinity, which are more closely associated with species dominance and abundance. These environmental gradients contribute to distinct species distribution patterns across observation stations. For instance, St2, St5, and St10 demonstrate more favorable conditions for sustaining diverse mangrove communities, while St1 and St3 exhibit signs of environmental stress, marked by increased salinity and species dominance. Similar patterns have been observed in mangrove ecosystems of Youtefa Bay, Jayapura, where soil chemistry and hydrological balance are key determinants of species composition and community structure (Sari et al. 2020; Hamuna and Wanimbo 2021). These findings align with observations from Demta Bay, where environmental variables such as pH, temperature, and soil moisture play a dominant role in shaping mangrove diversity. In Youtefa Bay and Demta Bay, alterations in hydrological conditions and soil properties have been associated with declines in biodiversity and ecosystem functioning. Our findings suggest that the ecological and biological condition of mangroves in Demta Bay is comparatively better than in Youtefa Bay. Furthermore, growing human pressures such as coastal erosion, aquaculture expansion, and pollution worsen salinity and soil degradation, leading to simpler forest structures and reduced ecological complexity. These threats highlight the urgent need for targeted conservation strategies in Demta Bay, Jayapura.

Habitat preferences reveal that bulk density, pH, salinity, temperature, and soil moisture significantly influence mangrove diversity. Low bulk density supports higher biodiversity, while elevated salinity tends to limit species variation. Conversely, neutral pH, stable temperature, and consistent soil moisture enhance species diversity and reduce dominance, underscoring the importance of favorable environmental conditions for maintaining mangrove ecosystem equilibrium. Mangrove zonation in Demta Bay reflects broader Indo-Pacific patterns, where species distribution is shaped by edaphic and hydrological gradients. Seaward zones with higher salinity and lower pH favor stress-tolerant species such as *Avicennia* and *Rhizophora*, while mid-zones with moderate bulk density and soil moisture support greater diversity (Nengi-Benwari et al. 2022b; Ola et al. 2024). Environmental variability across Demta Bay, influenced by riverine inputs and tidal regimes, mirrors regional endemism trends in the Indo-West Pacific (Alongi 2018; Friess et al. 2020).

Multivariate analysis of mangrove species-specific preference to habitat characteristics

Principal Component Analysis (PCA) to investigate mangrove species-specific preference to habitat characteristics revealed two main components (F1 and F2) that together accounted for 69.60% of the total variance (Figure 5). The first axis (F1), explaining 42.15% of the variance, was most strongly associated with salinity (loading: 0.76) and bulk density (loading: 0.34), reflecting gradients in species tolerance to saline and compacted soils. The second axis (F2), which explained 27.45% of the variance, was primarily correlated with salinity (loading: 0.54), soil moisture (loading: 0.79), and temperature (loading: 0.34). Several species exhibited strong positive loadings on salinity and bulk density, including *R. apiculata* (2.53), *R. mucronata* (2.28), *B. sexangula* (1.367), and *B. gymnorhiza* (1.100).

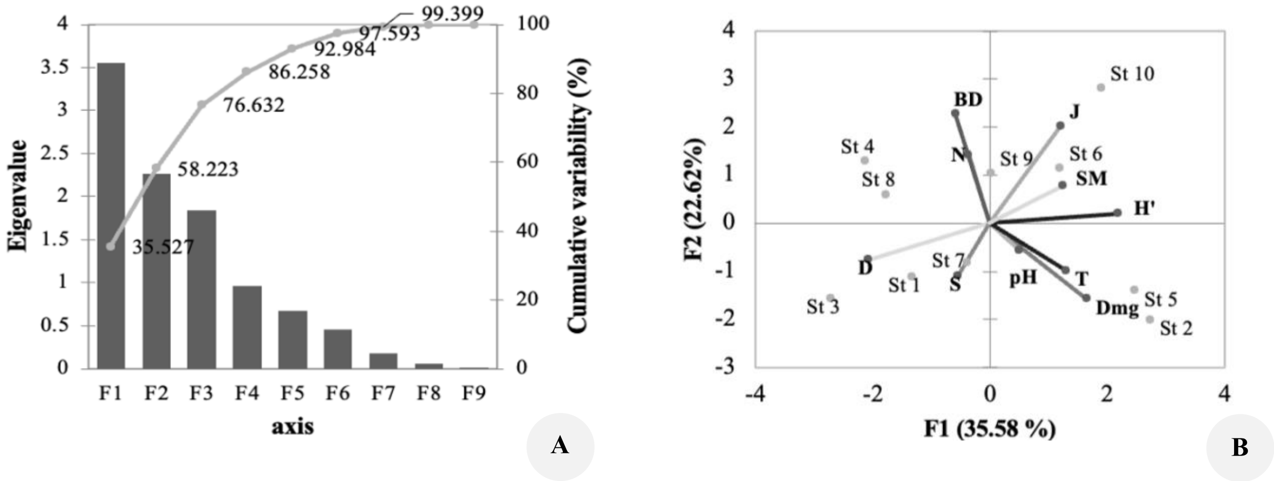

Figure 4. A. Scree plot of eigenvalues for habitat preference components related to mangrove species diversity, B. PCA diagram of habitat preferences and mangrove species diversity across sampling stations. St 1-St 10: Station, H': Species diversity, D: Dominance, Dmg: Richness, and J': Evenness, BD: Bulk Density, S: Salinity, T: Temperature, SM: Soil Moisture

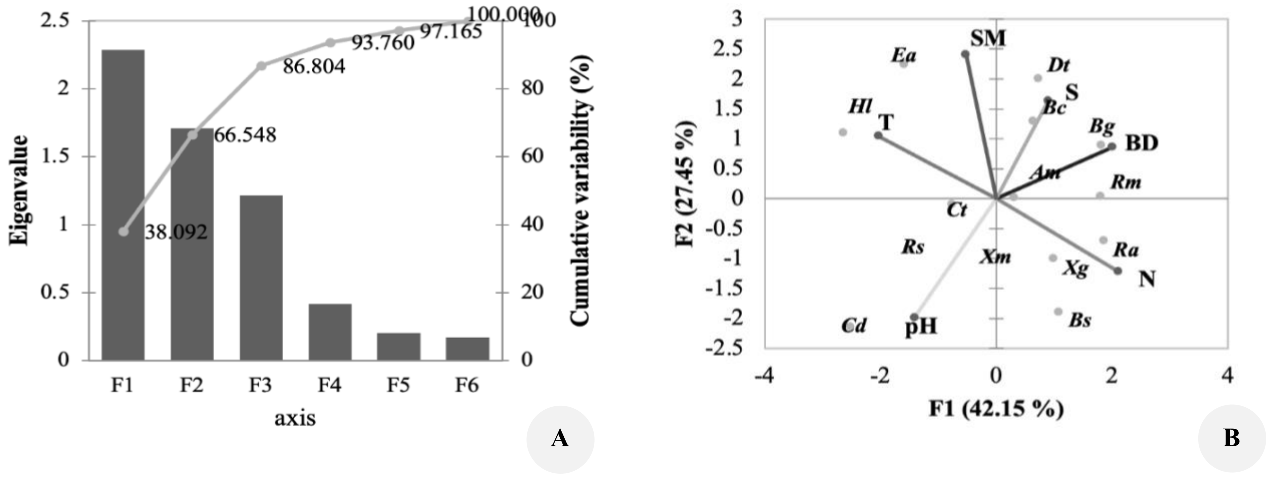

Figure 5. A. Scree plot of eigenvalues of mangrove species-specific preferences to habitat characteristics, B. PCA diagram of mangrove species-specific preferences to habitat characteristics. Am: *Avicennia marina*, Bc: *Bruguiera cylindrica*, Bg: *Bruguiera gymnorhiza*, Bs: *Bruguiera sexangula*, Cd: *Ceriops decandra*, Ct: *Ceriops tagal*, Dt: *Derris trifoliata*, Ea: *Excoecaria agallocha*, Hl: *Heritiera littoralis*, Ra: *Rhizophora apiculata*, Rm: *Rhizophora mucronata*, Rs: *Rhizophora stylosa*, Xg: *Xylocarpus granatum*, Xm: *Xylocarpus moluccensis*. BD: Bulk Density, S: Salinity, T: Temperature, SM: Soil Moisture

Rhizophora species display contrasting responses to soil bulk density due to differences in root morphology, oxygen transport capacity, nutrient acquisition strategies, and phenotypic plasticity (Analuddin et al. 2020; Ashraf et al. 2023). These traits enable some species to thrive in compact, low-oxygen soils, while others perform better in looser, more aerated substrates. In Demta Bay, these patterns are shaped by the bay's local ecological conditions (characterized by variable salinity regimes, periodic freshwater input from riverine systems, and heterogeneous soil textures), resulting in distinct species zonation and diversity patterns. Such site-specific edaphic influences highlight the adaptive strategies of mangrove species to local environmental gradients found in other parts of Papua's coastal ecosystems, including Bintuni, Merauke, Mimika, and Waropen (Setyadi et al. 2021; Sumani et al. 2021; Kasihiw et al. 2024; Sillanpää et al. 2024).

Mangrove species in Demta Bay Jayapura show distinct adaptations to soil salinity and bulk density (BD), influencing their zonation. *A. marina* thrives in high salinity (24.33±1.50) and low BD soils (0.72±0.01 %), using salt glands and pneumatophores for salt excretion and aeration. *R. apiculata* and *R. mucronata* tolerate salinity and prefer high-BD substrates, relying on prop roots for stability and gas exchange. *C. tagal* adapts to moderate salinity (24.33±1.53 PSU) and compact soils by shedding salt-laden leaves (0.47±0.17%). In contrast, *X. granatum* Koenig and *X. moluccensis* prefer lower salinity (22.17±1.99 PSU) and looser soils, with pneumatophores and buttress roots aiding survival (Hossain and Nuruddin 2016; Alongi 2018; Ola et al. 2018; Madhavan et al. 2025).

The correlations indicate strong associations between species distribution and tolerance to salinity and bulk density, reflecting broad ecological adaptability across the ten stations in Demta Bay. Fluctuations in salinity and BD significantly influence both the distribution and population dynamics of mangrove species (Hossain et al. 2014; Nengi-Benwari et al. 2022; Wang et al. 2024). Spatially, the salinity was highest at the outer part, intermediate at the middle part, and lowest at the inner part of the bay. Seasonal variation in water salinity is primarily driven by rainfall, with higher salinity levels during the dry season and lower levels during the wet season.

In the lowland and coastal regions of Papua, Indonesia, the climate is tropical, characterized by high humidity and relatively stable temperatures ranging from 26°C to 30°C. Annual rainfall varies between 2,000 and 5,000 mm, with the northern coast experiencing wetter conditions from November to April and the southern coast from April to October (Sarvina 2023). According to Ola et al. (2018), variations in bulk density significantly influence root growth and biomass of various mangrove species, including *Rhizophora* spp. and *Bruguiera* spp. While both groups demonstrate high adaptive capacity to BD fluctuations, their responses are species-specific, influenced by differences in growth rates, soil conditions, and ecosystem status. Similarly, Ayu et al. (2023) found that *R. apiculata* and *R. mucronata* can adapt to mangrove areas with both low and high anthropogenic disturbances, as observed in Bone Bay, Palopo, South Sulawesi, Indonesia. Farahisah and Siregar (2024) reported that *R. apiculata* shows greater adaptability to higher bulk densities along the Ruyung coast, Aceh Besar, Indonesia.

In the second principal component (F2), temperature and soil moisture vectors were prominent, indicating strong positive correlations with F2, while pH showed a negative correlation. High positive scores for *E. agallocha* (2.714) and *D. trifoliata* (2.455) on F2 indicated their preference for conditions with high soil moisture and specific pH levels. Conversely, species such as *C. decandra* (-2.812) and *B. sexangula* (-0.969) showed significant negative scores, reflecting their preference for low pH and reduced tolerance to high soil moisture. Species such as *C. tagal*, *D. trifoliata* and *E. agallocha* are predominantly found in transitional zones, which are characterized by low salinity and near-neutral pH levels. This pattern is consistent with the findings of Hossain and Nuruddin (2016). These areas receive significant freshwater input from surrounding rivers and experience reduced tidal influence, resulting in diluted saline conditions and stable edaphic parameters. The presence of these species in such habitats reflects their physiological adaptations to lower salinity stress and moderate soil pH (6.5-7.5), which support optimal nutrient uptake and microbial activity (Lovelock et al. 2016; Sippo et al. 2018; Azwa et al. 2022). For instance, *D. trifoliata*, a nitrogen-fixing semi-mangrove, thrives in organic-rich, low bulk density soils due to its symbiotic root associations and tolerance to waterlogged conditions. Similarly, *E. agallocha* and *C. decandra* are frequently associated with high soil moisture environments and exhibit broad tolerance to fluctuating edaphic conditions. These ecological traits enable them to colonize landward of Demta Bay, where reduced salinity and high freshwater availability create favorable microhabitats. The distribution of these species corresponds with zonation patterns observed across Indo-Pacific mangrove systems, where freshwater inflow, sedimentation processes, and soil chemistry significantly influence species composition and spatial structure. Salinity and bulk density show a positive correlation with the distribution of species such as *R. apiculata*, *R. mucronata* and *B. sexangula*, reflecting their adaptation to high salinity and dense soils. On the other hand, *E. agallocha* demonstrates a preference for high soil moisture and specific pH ranges, while *C. decandra* is associated with lower pH conditions. The variation in species adaptation to environmental factors provides valuable insights for mangrove ecosystem management, highlighting the need for species-specific studies with significant ecological roles. This underscores the importance of considering the unique ecological preferences of each species in conservation efforts to ensure the sustainability and resilience of these critical ecosystems.

In conclusion, this study documented 14 mangrove species from 6 families in Demta Bay, reflecting moderate diversity within the coastal ecosystems of northern Papua. Vegetation structure was characterized by an average density of 146.3±14.84 individuals/station (800m^2), Shannon-Wiener diversity index (H′) of 1.36±0.25, a dominance index (D) of 0.32±0.07, a species richness index (Dmg) of 1.13±0.43, and an evenness index (J′) of 0.74±0.10, indicating relatively stable community interactions. Key soil variables influenced species distribution and ecological patterns. Bulk density (0.63±0.21 g cm^{-3}) showed a negative relationship with diversity, while pH (6.80±0.32), salinity (24.79±2.98 PSU), temperature (29.21±1.54°C), and soil moisture (48.70±18.53%) exhibited significant positive correlations with diversity and evenness. Elevated salinity, however, reduced species richness and evenness, underscoring its role as a limiting factor. Species-specific responses were evident: *R. apiculata* and *R. mucronata* dominated saline, compacted soils, while *E. agallocha* favored moist, moderately acidic conditions, and *C. decandra* thrived in slightly alkaline soils. These findings emphasize that geomorphological and ecological heterogeneity drive localized zonation in Demta Bay. Accordingly, site-specific conservation and restoration strategies are recommended. Salt-tolerant taxa such as *Rhizophora* spp. should be prioritized for high-salinity, compacted zones, whereas *Bruguiera*, *Ceriops*, and *Excoecaria* species are better suited for transitional and low-salinity habitats. By aligning conservation interventions with environmental gradients, this study provides a baseline framework for biodiversity management and climate-resilient restoration in Papua's mangrove ecosystems. Protecting these habitats will safeguard biodiversity, enhance carbon storage, and sustain coastal livelihoods in eastern Indonesia.

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