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Floristic and structural characterization of the mangrove formations of the Tachina and Camarones parishes, Esmeraldas – Ecuador

Caracterización florística y estructural de las formaciones de manglar de las parroquias Tachina y Camarones, Esmeraldas – Ecuador

Laura Suarez[1], Edison Velasco[1], Gabriel Suarez[2]

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[1] Universidad Técnica Luis Vargas Torres. Facultad de Ciencias Agropecuarias, Carrera de Ingeniería Forestal. Tachina. 080150. Esmeraldas, Esmeraldas, Ecuador.

[2] Universidad Técnica Luis Vargas Torres. Facultad de Ingenierías, Carrera de Tecnologías de la información. Tachina. 080150. Esmeraldas, Esmeraldas, Ecuador.

Correspondencia: lauritasuarezsoto@gmail.com

Abstract

Mangroves are coastal ecosystems that provide multiple goods and services and depend on salinity, temperature, and nutrients. The study was carried out in the coastal area of Esmeraldas Canton, with the objective of floristically and structurally characterizing the mangrove formations of the Tachina and Camarones parishes, analyzing the physicochemical parameters of soil and water. Four permanent monitoring blocks [PMBs] were established, with the first (B1) located in the Achilube sector, the second and third (B2 and B3) in the Colope sector, and the fourth (B4) in the El Edén sector. Three circular plots of 500 m² were established in each PMB to record the data, and soil and water samples were collected. A total of 2,360 mangrove individuals were recorded, comprising four species: *Rhizophora harrisonii*, *Laguncularia racemosa*, *Avicennia germinans*, and *Conocarpus erectus*. B2 showed greater floristic richness, recording four species. The species with the greatest distribution was *Avicennia germinans*, present in three study blocks. The findings classified B1 as primary succession with predominance of seedlings, B2 and B3 as secondary succession with predominance of juvenile trees, and B4 as being in a high state of vulnerability. Soil analysis showed low levels of organic matter, nitrogen, and phosphorus in most PMBs. The correlations revealed the relationship of *Laguncularia racemosa* with zinc and the relationship of *Rhizophora harrisonii* with N, Ca, Mn, and organic matter. Electrical conductivity indicated the influence of salinity on species distribution.

Keywords: mangrove ecology, mangrove structure, spatial distribution, tree diversity

Resumen

Los manglares son ecosistemas costeros que proporcionan múltiples bienes y servicios, dependen de la salinidad, temperatura y nutrientes. El estudio se llevó a cabo en la zona costera del cantón Esmeraldas, con el objetivo de caracterizar florística y estructuralmente las formaciones de manglar de las parroquias Tachina y Camarones, analizando parámetros físicos-químicos del suelo y agua. Se estableció cuatro bloques permanentes de monitoreo [PMBS], ubicándose el primero (B1) en el sector de Achilube, el segundo y tercero (B2 y B3) en el sector Colope y el cuarto (B4) en el sector El Edén. Se estableció tres parcelas circulares de 500 m² en cada PMBS para registrar los datos, y se tomaron muestras de suelo y agua. Se registró un total de 2360 individuos de mangle, abarcando cuatro especies; *Rhizophora harrisonii, Laguncularia racemosa, Avicennia*

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germinans y Conocarpus erectus. El B2 mostró una mayor riqueza florística, registrando cuatro tipos de especies. La especie con mayor distribución es *Avicennia germinans,* presente en tres bloques de estudio. Los hallazgos de la investigación clasifican el B1 como sucesión primaria con predominancia de brinzal, los B2 y B3 representan sucesión secundaria con predominancia de árboles juveniles y el B4 se encuentra en un alto estado de vulnerabilidad. El análisis de suelo mostró niveles bajos de materia orgánica, nitrógeno y fósforo en la mayoría de los PMBS. Las correlaciones revelaron la relación de *Laguncularia racemosa* con el zinc y la relación de *Rhizophora harrisonii* con N, Ca, Mn y materia orgánica. La conductividad eléctrica indicó la influencia de la salinidad en la distribución de las especies.

Palabras clave: distribución espacial, diversidad arbórea, ecología del manglar, estructura del manglar

1. Introduction

Mangroves are located in tropical coastal zones and depend on key factors such as salinity, temperature, tides, and soil nutrients. They are highly productive forested wetlands that absorb large amounts of CO_2 (Alongi, 2021). They exhibit a high tolerance to seawater salinity and perform important ecological, economic, and chemical functions (Amel et al., 2023).They are found at sea level, commonly in intertidal zones of estuaries and in areas where rivers flow into the sea (Ministerio del Ambiente, Agua y Transición Ecológica [MAATE] & Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO], 2014). Their distribution varies according to salinity preferences and soil type (Mejía et al., 2014). Mangrove ecosystems interact to different degrees with oceanic, climatic, geomorphological, and edaphic conditions, which in turn influence water and nutrient availability (Mira et al., 2019).

They are mainly composed of mangrove trees that provide shelter and food to various organisms, in addition to filtering water, releasing oxygen, and protecting the coasts from degradation and erosion (Limmon et al., 2023). According to MAATE & FAO (2014), the following mangrove species are found in Ecuador: *Rhizophora mangle*, *R. racemosa*, *R. harrisonii*, *Laguncularia racemosa* var. *racemosa*, *L. racemosa* var. *glabriflora*, and *Avicennia germinans*.

Mangrove productivity is related to micro- and macronutrients, which are, in turn, closely related. When there is an increase in the primary productivity of mangroves, there is greater nutrient uptake and rapid nutrient cycling (Alongi, 2021). According to Mira et al. (2019), mangrove forest richness is maximized under brackish soil conditions where nutrients are available, and soil pH is high.

Mangroves obtain the essential nutrients required for their development from the soil and interstitial water; therefore, the soil is key to evaluating nutrient availability. The required macronutrients are nitrogen [N], phosphorus [P], sulfur [S], magnesium [Mg], calcium [Ca], and potassium [K]. The micronutrients are iron [Fe], manganese [Mn], copper [Cu], zinc [Zn], nickel [Ni], molybdenum [Mo], boron [B], chloride [Cl^-], sodium [Na], silicon [Si], cobalt [Co], selenium [Se], and aluminum [Al] (Alongi, 2021). Mangroves are complex systems that exhibit high primary productivity and facilitate an exchange of energy (nutrients) with surrounding areas and the aquatic environment. This exchange is mainly driven by decomposition processes (Torres et al., 2018).

There are three types of mangrove ecosystems according to forest structure, productivity, mangrove species, and ecological processes: riverine, basin, and fringe mangroves (Bodero & Robadue, 1995). As spawning grounds and nursery areas for many species, mangroves have become a source of livelihood for many coastal communities (Beitl et al., 2020) through fishing, crustacean harvesting, agriculture, and tourism (Quispe et al., 2021). More than 10,000 families on the Ecuadorian coast depend on mangroves as their primary source of livelihood (Rodríguez, 2022).

Pollution and the overexploitation of mangrove ecosystem resources generate significant problems that seriously affect the human communities that depend on these ecosystems (Carrera et al., 2017; Yépez Rendón, 2021). The main cause of mangrove forest destruction is their conversion to other land uses (Kusmana, 2014). In addition, the conversion of swampy soils to sandy soils, driven by natural and anthropogenic factors, destroys the vegetation and promotes weed growth, which attracts species not associated with mangroves and depletes soil nutrients and organisms (Numbere & Obanye, 2023).

According to Carrera and Vicente da Silva (2019), the environmental problems affecting mangroves are also related to the degradation process caused by the establishment of shrimp farms in mangrove areas. The loss of these ecosystems is mainly due to the cutting of mangrove trees for the construction of shrimp ponds (Centro de Levantamientos Integrados de Recursos por Sensores Remotos [CLIRSEN], 1990; Malik et al., 2017), as well as agriculture, livestock farming, urban expansion, and timber extraction in these vulnerable areas (Díaz, 2011).

In Ecuador, mangroves are protected by a legal framework that seeks to conserve these ecosystems and guarantee the rights of the communities that depend on them (López Rodríguez, 2020; MAATE & FAO, 2014). Their conservation, management, and sustainable use depend on the intrinsic knowledge of these ecosystems and the valuation of their functions or environmental services (Rodríguez Villón, 2015). The assessment of mangroves for their protection, recovery, and restoration makes it possible to ensure the continuity of the environmental services they provide (Suárez, 2016).

In Esmeraldas Canton, studies on biodiversity and forest structure have been conducted exclusively in the Esmeraldas River Estuary Mangrove Wildlife Refuge [RVSMERE], as evidenced by the assessments carried out by Bruno Waibel (2019), Drouet Yánez (2019), and Andrade Chica (2019), which focused solely on this protected area. The lack of research on the mangrove formations along the coastal profile limits the implementation of conservation measures and contributes to the deterioration of the ecosystem. This is consistent with the evidence presented by Morocho et al. (2022), who state that in Ecuador the greatest effectiveness in mangrove conservation and restoration is associated with their location within protected areas and under use and stewardship agreements.

Although mangrove formations are present in the Tachina and Camarones parishes, studies on their forest structural diagnosis, floristic composition, and development factors are scarce or nonexistent. This research is the first initiative to study the mangrove formations of Esmeraldas Canton, excluding the Esmeraldas River Estuary Mangrove Wildlife Refuge. It therefore provides information to support the recovery of these areas under sustainability criteria. Accordingly, the objective of this study was to characterize the floristic composition and forest structure of the mangrove formations in the Tachina and Camarones parishes by analyzing the physicochemical parameters of the soil and water.

2. Materials and Methods

2.1. Study area

The coastal zone of Esmeraldas Canton comprises the urban parishes of Esmeraldas, Luis Tello, and Bartolomé Ruiz, as well as the rural parishes of Tachina and Camarones. The mangrove formations selected in Tachina and Camarones, based on the preliminary exploration, were defined according to the environmental problems identified in the study area.

Tachina has mangrove areas that are distributed mainly in the estuarine zones associated with the Esmeraldas River and the Tachina Estuary. Soft silty-clay soils influenced by tidal dynamics predominate in these areas. The parish also contains fragmented mangrove cover resulting from deforestation and anthropogenic activities, with remaining mangrove stands intermixed with secondary vegetation (Gobierno Autónomo Descentralizado Parroquial Rural Tachina, 2019).

In Camarones Parish, mangroves are located along the estuarine zone of the Camarones Estuary and in low-lying areas associated with the Colope River basin. These mangrove formations grow on saturated soils and fine alluvial deposits, which are characteristic of coastal plains. Their vegetation cover consists of mangrove patches surrounded by agricultural areas and forest plantations (Gobierno Autónomo Descentralizado Parroquial Rural Camarones, 2020).

2.2. Sample size

Mangrove typology was used as a reference for the distribution of the study areas. Two areas were selected in the Colope sector to obtain a broader range of information, since the mangrove formations in this area are located at two significant river mouths: the Colope River and the Colope Estuary.

Four study blocks, referred to as Permanent Monitoring Blocks [PMBs], were established. The first block (B1) was located in the Achilube sector of Tachina Parish; the second (B2) and third (B3) blocks were established in the Colope sector of Camarones Parish; and the fourth block (B4) was located in the El Edén sector, also in Camarones Parish (Table 1).

Three circular plots of 500 m² were established in each PMB for the collection of dasometric data, as recommended by Melo & Vargas (2003). The location of the PMBs is shown in Figure 1.

In each plot, all mangrove individuals with a minimum height of 30 cm were identified and measured. The stem diameter of seedlings ranging from 30 cm to 130 cm in height was measured above the first node of the seedling. However, seedlings between 130 cm and 150 cm in height were measured at half of their total height. For saplings (150–300 cm in height) and trees (>3 m in height), the circumference at breast height [CBH] was measured at 1.30 m above the ground, except for *Rhizophora harrisonii*, which was measured 30 cm above the last aerial root.

2.3. Soil sample collection

Cavities were excavated to a depth of 30 cm, and the soil samples were mixed thoroughly to obtain a

Table 1. UTM Coordinates (Zone 17S, WGS84 Datum) of the Permanent Monitoring Block Plots.

PMB	Plots	X	Y
B1	1	654752	10108992
	2	654383	10109027
	3	654520	10109000
B2	1	665844	10112795
	2	665674	10112530
	3	665562	10112354
B3	1	668102	10114023
	2	668058	10113961
	3	668140	10113924
B4	1	669104	10114501
	2	669023	10114447
	3	668941	10114513

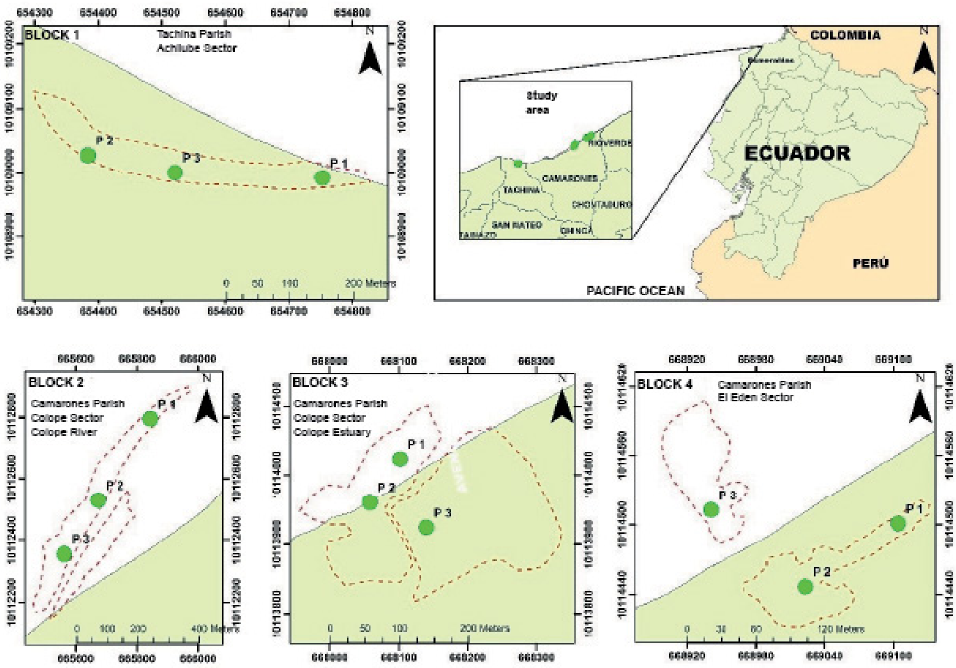

Figure 1. Permanent monitoring blocks.

representative sample for each block. A 0.5 kg soil sample was placed in Ziploc bags, following the methodology of Torán Figueroa (2020), to determine the physicochemical properties of the soil, including macronutrients such as N, P, and K; micronutrients such as Ca, Mg, Zn, Cu, Fe, and Mn; soil pH; and organic matter [OM]. Interstitial water was collected from the soil sampling points and placed in a one-liter container to measure the electrical conductivity of the water, as suggested by Andrade Chica (2019).

For the calculation of basal area [BA, m²] in the study area, Equation [1] was used, where D is the diameter at breast height [DBH]. The basal area for each species was obtained by summing the basal area of all individuals of that species within each PMB.

$$AB = \pi \times \left(\frac{D}{2}\right)^2 \quad [1]$$

To calculate the Importance Value Index [IVI] of the mangrove species, Equation [2] was used.

$$IVI = Ar\% + Fr\% + Dr\% \quad [2]$$

Each component of the Importance Value Index [IVI] was determined as follows:

- The relative abundance [RA%] was calculated according to Equation [3], where *ni* is the number of individuals of the *i*th species, and *N* is the total number of individuals in the sample.

$$\text{Ar\%} = \left(\frac{ni}{N}\right) \text{x } 100 \quad [3]$$

- The relative frequency [RF%] was calculated according to Equation [4], where *Af* is the absolute frequency of the species and ∑*Af* is the sum of the absolute frequencies. *Af* was calculated using Equation [5], where *Ne* is the number of plots in which the species occurs, and *Tp* is the total number of sampled plots.

$$\text{Fr\%} = \left(\frac{Fa}{\sum Fa}\right) \text{x } 100 \quad [4]$$

$$\text{Af} = \left(\frac{Ne}{Tp}\right) \quad [5]$$

- Relative dominance [RDo%] was calculated using Equation [6], where *Da* is the absolute dominance (BA/ha-SP is the basal area per hectare of each species), and ∑*Da* is the sum of the absolute dominance.

$$\text{RDo\%} = \left(\frac{Da}{\sum Da}\right) \text{x } 100 \quad [6]$$

The IVI obtained by summing the three components provides the result of the different size categories in the PMBs for the ecological analysis of mangrove formations.

2.4. Statistical analysis

For data processing, Microsoft Excel 2021 and the Statistical Package for the Social Sciences version 29 (IBM SPSS) were used. To evaluate the correlation of the data, Spearman's proposed model was applied.

3. Results

3.1. Dendrometric analysis

In the four PMBs of the study area, 2,360 individuals were recorded, distributed across the 12 established plots, encompassing four species: *Rhizophora harrisonii*, *Laguncularia racemosa*, *Avicennia germinans*, and *Conocarpus erectus*. *Laguncularia racemosa* was the species with the highest number of individuals, with 1,395 (Figure 2).

Figure 3 shows the distribution of individuals of the PMBs in the sampling plots. In B1, plot 3 recorded the highest abundance with 422 individuals. In B2, plot 2 stood out with 532 individuals. In B3, plots 1 and 3 showed the highest number, both with 160 individuals.

B1 records two species, with *Laguncularia racemosa* being the most predominant, followed by *Avicennia germinans*. B2 presented four species, where *Laguncularia racemosa* showed the highest abundance, followed by *Avicennia germinans*; while *Rhizophora harrisonii* and *Conocarpus erectus* recorded lower densities. B3, also with four species, showed a higher dominance of *Conocarpus erectus*, followed by *Rhizophora harrisonii*; in this block, *Avicennia germinans* presented a lower value, as did *Laguncularia racemosa*. Finally, B4 presented two species: *Conocarpus erectus* and *Avicennia germinans* (Figure 4).

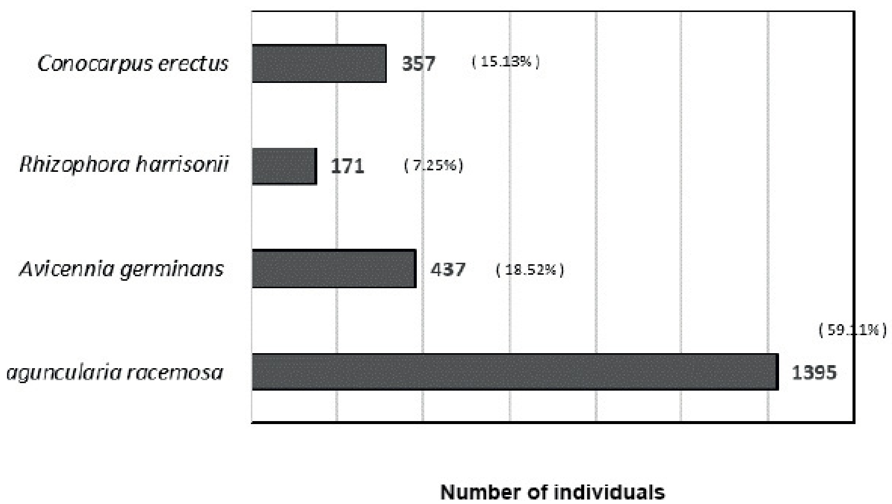

Figure 2. Total individuals per species.

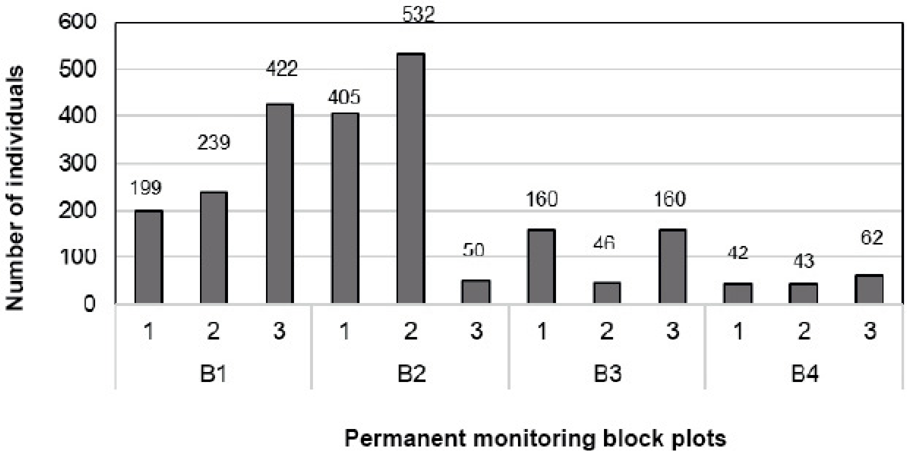

Figure 3. Number of individuals per plot in the permanent monitoring blocks.

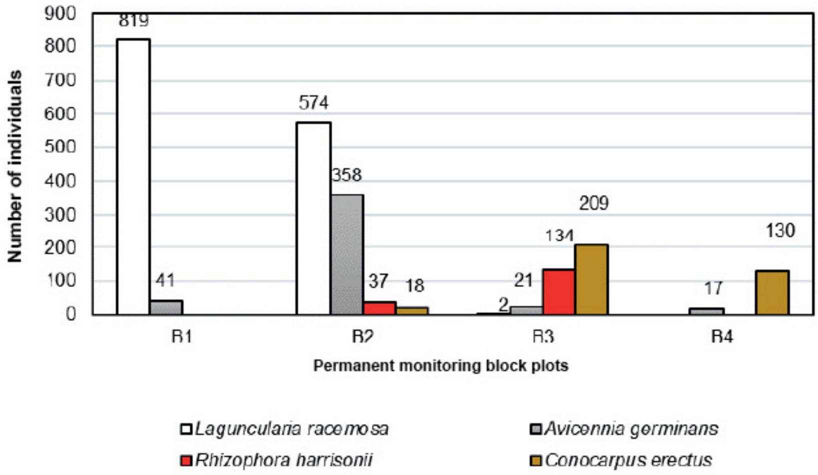

Figure 4. Number of species per permanent monitoring block.

3.2. Size category and summary of diameters and height

The analysis by size category showed a heterogeneous population structure among the blocks. In Brinzal, the highest concentration of regeneration was recorded in B1, while the other blocks recorded low values. In Latizal, the distribution was mainly concentrated in B1 and B2, showing a transition toward intermediate stages of development. In the tree stratum, B2 presented the highest concentration of adult individuals, with higher diameters and heights than the other blocks (Table 2).

In Table 3, notable variation between species and blocks is shown. *Laguncularia racemosa* presented its highest average diameter in B2, while *Avicennia germinans* and *Rhizophora harrisonii* recorded higher values in B3. In the case of *Conocarpus erectus*, the highest average was observed in B2. B3 concentrated the maximum diameters of all evaluated species, with *Conocarpus erectus* standing out with the highest recorded value.

Table 4 shows the variation in average heights among species and blocks. *Laguncularia racemosa* reached its highest average in B2, as did *Rhizophora harrisonii* and *Conocarpus erectus*, while *Avicennia germinans* recorded its highest average height in B3. Blocks B2 and B3 presented the maximum heights for all species, reaching values of up to 16 m in height.

3.3. Basal area

B3 recorded the highest total basal area value (2.686 m^2), with dominance of *Conocarpus erectus* (1.7149 m^2), followed by *Avicennia germinans* (0.8633 m^2). *Rhizophora harrisonii* and *Laguncularia racemosa* showed considerably lower values (0.0588 m^2 and 0.0013 m^2, respectively). B2 obtained high values due to the contribution of *Laguncularia racemosa* (1.099 m^2) and *Avicennia germinans* (0.9132 m^2). The blocks with the lowest basal areas were B4 (0.8246 m^2), dominated by *Conocarpus erectus* (0.6747 m^2), and B1 (0.2469 m^2), where *Laguncularia racemosa* presented the highest contribution to basal area (Figure 5).

Table 2. Size category by species in the permanent monitoring blocks.

Species	B1	B2	B3	B4	Total
Brinzal (31 - 150 cm)					
Laguncularia racemosa	407	0	0	0	407
Avicennia germinans	40	0	1	0	41
Rhizophora harrisonii	0	2	104	0	106
Conocarpus erectus	0	0	10	3	13
TOTAL	447	2	115	3	567
Latizal (151 - 300 cm)					
Species	B1	B2	B3	B4	Total
Laguncularia racemosa	84	26	0	0	110
Avicennia germinans	0	25	1	1	27
Rhizophora harrisonii	0	6	19	0	25
Conocarpus erectus	0	0	32	29	61
TOTAL	84	57	52	30	223
Tree stratum ≥ 301 cm					
Species	B1	B2	B3	B4	Total
Laguncularia racemosa	328	548	2	0	878
Avicennia germinans	1	333	19	16	369
Rhizophora harrisonii	0	29	6	0	35
Conocarpus erectus	0	18	167	98	283
TOTAL	329	928	194	114	1565

3.4. Importance Value Index

The IVI showed variations in species dominance according to size category and PMBs. In B1, *Laguncularia racemosa* was the dominant species in all categories. In B2, *Rhizophora harrisonii* presented the highest importance in the seedling stratum, while *Laguncularia racemosa* predominated in the sapling and tree strata. In B3, *Rhizophora harrisonii* stood out in the seedling stratum; in contrast, *Conocarpus erectus* showed greater importance in the sapling and tree strata. Finally, in B4, *Conocarpus erectus* was the dominant species across all three categories (Table 5).

3.5. Analysis of soil macro and microelements

The analysis of macronutrients showed low levels of N in all four PMBs, while P presented high values in B1, B2, and B3, and a low level in B4. K was found to be high in all blocks.

For the micronutrients, Ca recorded low values in B1 and B4, and medium values in B2 and B3. Mg and Fe remained at high concentrations in all four PMBs. Mn showed low values in B4 and high values in the other blocks. Cu showed variability among blocks, with a high value in B2, medium in B1 and B3, and low in B4. Zn ranged between medium and low values depending on the block.

Regarding pH, the PMBS that presented a slightly alkaline pH were B1 and B2, while B3 and B4 were alkaline. Finally, organic matter showed low percentages in all PMBs (Table 6).

3.6. Analysis of water electrical conductivity

The analysis of water electrical conductivity [EC] showed variations among the PMBs, with the lowest value recorded in B3 and the highest values in B2, B4, and B1 (Table 7).

3.7. Correlation of soil physicochemical variables

Spearman's correlation identified a positive and significant correlation between *Laguncularia racemosa* and zinc, showing an increase in abundance in sites with higher content of this nutrient. Likewise, *Rhi-*

Table 3. Average diameter, maximum and minimum diameter of mangrove species in PMBs.

PMBs	B1				B2				B3				B4			
Species*	**N°**	**Average diameter (cm)**	**Maximum diameter (cm)**	**Minimum diameter (cm)**	**N°**	**Average diameter (cm)**	**Maximum diameter (cm)**	**Minimum diameter (cm)**	**N°**	**Average diameter (cm)**	**Maximum diameter (cm)**	**Minimum diameter (cm)**	**N°**	**Average diameter (cm)**	**Maximum diameter (cm)**	**Minimum diameter (cm)**
L.R	819	1.76	4	0.2	574	4.5	17.8	1.5	2	2.8	3.5	2.1	0	0	0	0
A.G	41	0.89	3.7	0.4	358	4.4	31.5	1.2	21	20.7	39.2	1	17	10.2	17.2	5.7
R.H	0	0	0	0	37	4.01	14.3	1	134	1.3	15.9	0.3	0	0	0	0
C.E	0	0	0	0	18	13.1	25.8	5.1	209	7.3	43.4	0.3	130	7.3	20.1	1.0

*L.R: *Laguncularia racemosa*; A.G: *Avicennia germinans*; R.H: *Rhizophora harrisonii*; C.E: *Conocarpus erectus*

Table 4. Average height, maximum and minimum height of mangrove species in the PMBs.

PMBs	B1				B2				B3				B4			
Species*	**N°**	**Average height (m)**	**Maximum height (m)**	**Minimum height (m)**	**N°**	**Average height (m)**	**Maximum height (m)**	**Minimum height (m)**	**N°**	**Average height (m)**	**Maximum height (m)**	**Minimum height (m)**	**N°**	**Average height (m)**	**Maximum height (m)**	**Minimum height (m)**
L.R	819	2.6	6.5	0.4	574	7.7	16	2	2	4.5	5	4	0	0	0	0
A.G	41	0.7	5	0.4	358	5.7	16	2	21	9.3	15	1	17	5.2	8	3
R.H	0	0	0	0	37	6.3	12	1.5	134	1.4	16	0.3	0	0	0	0
C.E	0	0	0	0	18	6.8	11	5	209	5.4	14	0.5	130	4.3	6.3	0.6

* L.R: *Laguncularia racemosa*; A.G: *Avicennia germinans*; R.H: *Rhizophora harrisonii*; C.E: *Conocarpus erectus*

zophora harrisonii showed a positive correlation with nitrogen, calcium, manganese, and organic matter, indicating that its presence is associated with higher levels of these nutrients. On the other hand, *Avicennia germinans* showed a positive tendency with potassium, copper, and zinc, while *Conocarpus erectus* tended to correlate positively with calcium (Table 8).

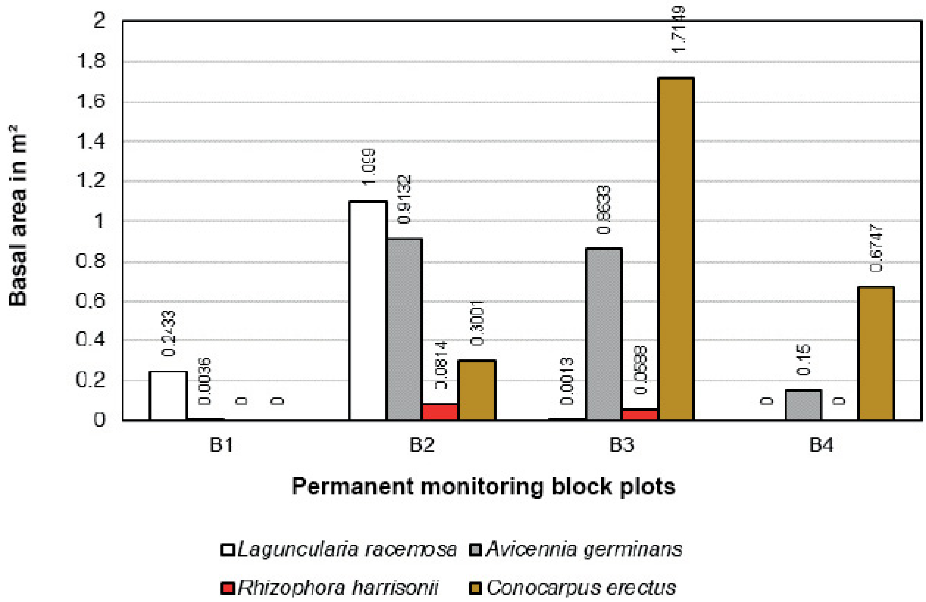

Figure 5. Basal area (m^2) of mangrove species by permanent monitoring blocks.

Table 5. Importance Value Index by size category.

PMBs	Species*	Size category**					
		Brinzal		Latizal		Tree (arboreal)	
		Ab	Re%	Ab	Re%	Ab	Re%
B1	L.R	225.95	75.32	300	100	249.07	83.02
	A.G	74.05	24.68	0	0	50.93	16.98
	R.H	0	0	0	0	0	0
	C.E	0	0	0	0	0	0
B2	L.R	0	0	135.61	45.2	127.16	42.39
	A.G	0	0	127.25	42.42	107.32	35.77
	R.H	300	100	37.14	12.38	39.8	13.27
	C.E	0	0	0	0	25.72	8.57
B3	L.R	0	0	0	0	15.37	5.12
	A.G	35.48	11.83	50.39	16.8	71.24	23.75
	R.H	218.64	72.88	78.86	26.29	19.23	6.41
	C.E	45.88	15.29	170.76	56.92	194.6	64.72
B4	L.R	0	0	0	0	0	0
	A.G	0	0	33.84	11.28	99.67	33.22
	R.H	0	0	0	0	0	0
	C.E	300	100	266.16	88.72	200.33	66.78

* L.R: *Laguncularia racemosa*; A.G: *Avicennia germinans*; R.H: *Rhizophora harrisonii*; C.E: *Conocarpus erectus.*
** *Ab*: *Absolute; Re%*: *Relative.*

Table 6. Result of soil analysis of the permanent monitoring blocks.

PMBs	Macroelements			Microelement						pH	OM (%)
	N	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Cu**	**Zn**		
	%	mg kg^{-1}	cmol kg^{-1}	cmol kg^{-1}	cmol kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}		
B1	0.06	18.6	1.28	3.93	7.93	153.5	7.69	3.95	3.38	7.67	1.24
B2	0.07	17.9	2.51	7.95	11.70	129.3	11.86	5.52	3.14	7.91	1.37
B3	0.12	53.9	1.97	8.42	10.62	197.1	14.05	4.49	2.32	8.19	2.35
B4	0.01	6.6	0.70	3.96	3.75	48.2	4.51	1.11	1.60	8.59	0.18

Table 7. Electrical Conductivity Analysis of Water.

PMBs	**Electrical conductivity(dS m^{-1})**
B1	38.7
B2	43.9
B3	25.0
B4	42.7

Table 8. Spearman correlation of the physicochemical variables of soil and water with the abundance of mangrove species.

Variable	L.R_rho	L.R_p	A.G_rho	A.G_p	R.M_rho	R.M_p	C.E_rho	C.E_p
N	0.2	0.8	0.4	0.6	0.949	0.051	0.4	0.6
P	0.4	0.6	0.2	0.8	0.632	0.368	0.2	0.8
K	0.4	0.6	0.8	0.2	0.738	0.262	0	1
Ca	-0.4	0.6	0	1	0.949	0.051	0.8	0.2
Mg	0.4	0.6	0.8	0.2	0.738	0.262	0	1
Fe	0.4	0.6	0.2	0.8	0.632	0.368	0.2	0.8
Mn	0.2	0.8	0.4	0.6	0.949	0.051	0.4	0.6
Cu	0.4	0.6	0.8	0.2	0.738	0.262	0	1
Zn	1	0	0.8	0.2	-0.105	0.895	-0.8	0.2
pH	-1	0	-0.8	0.2	0.105	0.895	0.8	0.2
MO	0.2	0.8	0.4	0.6	0.949	0.051	0.4	0.6
Electrical conductivity	0	1	0.4	0.6	-0.316	0.684	-0.4	0.6

4. Discussion

4.1. Dendrometric analysis

In the Esmeraldas canton, the recorded mangrove species correspond to the RVSMERE, where three mangrove species were identified: *Rhizophora harrisonii*, *Laguncularia racemosa*, and *Avicennia germinans* (Ministerio del Ambiente, Agua & Transición Ecológica [MAATE], 2015). On the other hand, in the study conducted by Andrade Chica (2019) on the analysis of structure and floristic composition in the RVSMERE, the species *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicennia germinans* were identified. When comparing the species found in the study area, it is composed of: *Rhizophora harrisonii*, *Laguncularia racemosa*, *Avicennia germinans*, and *Conocarpus erectus*, expanding the floristic diversity in the canton in contrast to previous studies.

The presence of the species *Conocarpus erectus* in the study area could be related to seed transport by marine currents in connection with the mangroves of the northern zone of Esmeraldas province, such as the Manglares Cayapas–Mataje Ecological Reserve, which records four mangrove species, including *Conocarpus erectus* (Macías Vargas, 2022). This is because the establishment and zonation of mangroves are related to the influence of tides on propagules and seedlings according to their buoyancy, allowing them to establish in intertidal or estuarine zones depending on their adaptability (Wang & Wang, 2019). It should also be considered that the natural restoration of mangrove areas is influenced by hydrology, which facilitates the dispersal of propagules (Echeverría-Ávila et al., 2019).

The number of individuals in each PMBS was influenced by the location of the plots. In the case of B1, which corresponds to a fringe mangrove due to its direct contact with the sea and frequent flooding (MAATE & FAO, 2014), the increase in the number of individuals in plot 3 was due to sedimentation, since plots 1 and 2 had sandy soil. This is contrary to what Barrantes Leiva and Cerdas Salas (2016) reported, who indicated that *Avicennia spp.* and *Laguncularia racemosa* tend to be more easily distributed in sandy substrates than other species, whose distribution is more homogeneous in muddy substrates.

In the case of B2, considered a riverine mangrove located along the margin of the Colope River and under the influence of tides and freshwater inputs (MAATE & FAO, 2014), most individuals were concentrated in plots 1 and 2 (Figure 4), located in the lower and middle part of the Colope River estuary, influenced by freshwater discharge and sedimentation. In contrast, plot 3, located in the upper area, was affected by anthropogenic interventions such as logging, solid waste pollution, agricultural expansion, and human settlements, which may have influenced the number of individuals of the species, as it is known that these activities impact mangrove ecosystem development (Vences et al., 2016).

Blocks B3 and B4 were considered riverine mangroves because they are located along the margins of the Colope estuary and the El Eden estuary. As in the case of B2, the plots are found in areas with high levels of anthropogenic disturbance. Morancy et al. (2021) emphasize that significant changes in the mangrove ecosystem are potential drivers of the decline in the sustainability and quality of this ecosystem, due to the unsustainable use of resources by the communities that inhabit them. Likewise, Cuevas-Díaz et al. (2020) indicate that the main destruction of mangrove ecosystems is associated with the increase in human settlements, land clearing and filling, livestock activities, and industrial developments, thus affecting soil, flora, and water.

In the results of this study, the presence of species varied according to the PMBs. In B1, the establishment of *Laguncularia racemosa* predominated, considering the site's physiography, the constant presence of seawater, higher light availability, and low vegetation cover. Moreira Estrella (2020) & Rodríguez (2022) describe that *Laguncularia racemosa* has a greater distribution and development in muddy, mostly silty substrates, with low vegetation and higher light availability. They also emphasize that it is a colonizing species that can establish in predominantly rocky or even artificial substrates, due to its colonization capacity and tolerance to stressful environments.

B2 presented the highest number of species, with *Laguncularia racemosa* recording the greatest number of individuals, followed by *Avicennia germinans*. According to Rodríguez (2022), *Laguncularia racemosa* is a species with greater ecological plasticity and adaptability, serving as an indicator of degraded lands undergoing recovery. On the other hand, the significant presence of *Avicennia germinans*, with the highest number of individuals found in areas with low flooding, indicates that it is a species capable of developing under favorable conditions and with low disturbance (Drouet Yánez, 2019). This is because it does not tolerate long periods of flooding, as it lacks or has very few pneumatophores, and these are of small height, which limits the respiration process when exposed to flooding (González-Hernández et al., 2017).

Regarding the most predominant species in B3, these were *Conocarpus erectus*, followed by *Rhizophora harrisonii*, which presented the highest percentage of recorded individuals. In B4, the predominant species was *Conocarpus erectus*. These results were attributed to the location of the study site, since the sampling area is situated farther inland. This indicates that the establishment of *Conocarpus erectus* is characteristic of the transition zone between mangroves and terrestrial forests; therefore, it develops better away from water and in sandy sites (Avellán Jiménez, 2018). On the other hand, the low presence of *Rhizophora harrisonii* is due to its preference for habitats with greater saline influence and higher levels of flooding (Rodríguez, 2022).

The species showed a uniform distribution, with *Avicennia germinans* standing out as it was established in all four study blocks, showing similarity to the results reported by Andrade Chica (2019) in the RVSMERE, where the predominant species was *Laguncularia racemosa*, followed by *Avicennia germinans*, due to the ability of both species to grow under adverse environmental conditions. This is because *Avicennia germinans* has a survival mechanism in saline environments by reducing the amount of water lost through its leaves and adjusting the photosynthetic process, which could be affected by changes in leaf size (Budiadi et al., 2022).

4.2. Size category and summary of diameters and height

All PMBs recorded the three size categories, with each PMBs differing in the abundance of the various species. In the case of B1, the predominant species in all categories was *Laguncularia racemosa*, which recorded a height range of 0.4 m to 6.5 m and a diameter range of 0.2 cm to 4 cm. It is a dominant species capable of establishing in open areas with higher radiation and a variety of substrates, maintaining broad structural ranges (Tomlinson, 2016). In contrast, *Avicennia germinans* was found only in the seedling category, with a diameter range of 0.4 cm to 3.7 cm and a height range of 0.4 m to 5 m, indicating a developing mangrove at an early successional stage. The presence of this species indicates the beginning of regeneration under conditions of greater competition or high salinity (Rodríguez, 2022).

The presence of *Laguncularia racemosa* and *Avicennia germinans* in B1 demonstrates mangrove development due to their tolerance to highly disturbed environments and their optimal morphology, such as long roots that can withstand deeper erosion before being displaced. Therefore, the development of shoot length and root length over time can be used as simple indicators to predict seedling survival (Van Hespen et al., 2022).

In the case of B2, heterogeneity was observed in the distribution of species, highlighting the absence of individuals in the seedling category, with only two recorded individuals belonging to *Rhizophora harrisonii*. According to the study conducted by Valle et al. (2016), which showed a predominance of *Rhizophora harrisonii* saplings, this situation was attributed to factors such as saline stress, since the sea is its main source of water.

Likewise, in B2, the species *Laguncularia racemosa* and *Avicennia germinans* presented a greater number of individuals in the sapling and tree categories. Most individuals belonged to the tree category, showing a height range between 1.5 m and 16 m and a diameter range between 1 cm and 31.51 cm. The absence of individuals in the seedling category could suggest problems in the regeneration processes and successional dynamics of the ecosystem, related to natural and anthropogenic disturbances that limit dispersal and development (Adams & Rajkaran, 2020).

B3 presented three size categories, with *Rhizophora harrisonii* being the species with the greatest abundance of seedlings but a low abundance in the tree category, showing a height range from 0.3 m to 16 m and a diameter range from 0.3 cm to 15.9 cm, suggesting difficulties in progressing toward mature stages. This pattern is consistent with that described by Valle Estrada (2007), who also observed that most individuals at several sampling stations were concentrated in the seedling category, especially in sites with less favorable conditions for their development.

B2 and B3 could be considered mangrove forests at an intermediate stage of ecological succession, as they presented species in different phases of development and growth, with a predominance of juveniles in the process of establishment (Velázquez-Pérez et al., 2019).

In B4, *Conocarpus erectus* was the only species recorded in all size categories, with the greatest abundance in the tree category and height ranges between 0.6 m and 6.3 m and diameter ranges between 1 cm and 20.1 cm. Observations from the study area and the collected data indicate that its exclusive presence reflects unfavorable ecosystem conditions. This agrees with Sierra (2018), who reported that *Conocarpus erectus* dominates the seedling and pole categories in areas subjected to anthropogenic impacts such as timber extraction, affecting mangrove structure. Therefore, *Conocarpus erectus* is considered a species established on uplands and in areas degraded by anthropogenic disturbance, with positive implications for ecosystem regeneration and restoration because it is a species adapted to drought conditions (Riaz et al., 2016).

4.3. Basal area

In our study, in B2 the greatest basal area corresponded to *Laguncularia racemosa*, followed by *Avicennia germinans*, a result associated with the number of individuals recorded for each species. This trend is consistent with the findings of Andrade Chica (2019), who reported a greater basal area for *Laguncularia racemosa* because it was the species with the highest number of individuals, followed by *Avicennia germinans*, which has a wider distribution and establishment in more disturbed sites. However, this contrasts with the results reported by Rodríguez Reales (2022) in the Ciénaga de Mallorquín, where *Avicennia germinans* was the most dominant species, followed by *Rhizophora mangle*, with *Avicennia germinans* presenting the greatest basal area in environments influenced by freshwater inputs.

The dominance of *Conocarpus erectus* in B3 was due to the greater number of individuals recorded, despite *Avicennia germinans* presenting a higher mean diameter (20.7 cm) but lower abundance. In contrast, Yépez Rendón (2021) reported a greater basal area for *Rhizophora mangle* and a lower basal area for *Conocarpus erectus*, since the latter was found in only one of the evaluated plots. On the other hand, the lowest basal areas corresponded to B1 and B4 because, in B1, most individuals belonged to the seedling category, whereas B4 had the lowest number of recorded individuals.

4.4. Importance Value Index

The IVI values obtained showed that in B1 the seedling, sapling, and tree categories were dominated by *Laguncularia racemosa*, whose status as a colonizing species explains its continuous presence throughout the mangrove successional process (Moreira Estrella, 2020; Rodríguez, 2022). In contrast, *Avicennia germinans* presented a low IVI in these categories due to its limited representation in the sapling and tree categories. Similar results were reported by Sánchez Montes (2007) in the mangroves of Isla Fuerte (Colombian Caribbean), where *Laguncularia racemosa* also showed the highest IVI values in the seedling, sapling, and pole size classes, a pattern attributed to its high regeneration potential. This reinforces the interpretation that it is a species with a high degree of regeneration and few anthropogenic stressors, conditions that favor its early establishment and persistence.

In B2, the seedling category was composed exclusively of *Rhizophora harrisonii*, with an IVI of 100%. In the sapling and tree categories, the highest IVI corresponded to *Laguncularia racemosa*, followed by *Avicennia germinans*, while *Rhizophora harrisonii* recorded a lower IVI in the sapling category. In the tree category, *Conocarpus erectus* presented the lowest IVI and was absent from both the seedling and sapling categories, suggesting a low regeneration capacity in this block. These patterns differ from those reported by Yépez Rendón (2021), who found a higher IVI for *Rhizophora mangle* (30.84%) and a lower IVI for *Conocarpus erectus* (17.23%), attributing the superior performance of *Rhizophora mangle* to its greater adaptation and establishment in exposed areas with strong wave action. The variations in IVI among studies may be explained by competition for nutrients, space, and sunlight, as well as substrate type and tidal regime. A high IVI indicates that certain species compete effectively and are dominant within their environment, exerting greater control over available resources and showing better adaptation to their habitat (Dewiyanti et al., 2023).

In B3, *Rhizophora harrisonii* was the species with the highest IVI in the seedling category, followed by *Conocarpus erectus*. In the sapling and tree categories, *Conocarpus erectus* recorded the highest IVI, demonstrating good regeneration capacity and better establishment on upland sites. Although *Conocarpus erectus* showed a low basal area, its contribution to the IVI confirms its high ecological importance within the community structure (Ismail et al., 2021). Similarly, Avellán Jiménez (2018) reported a high IVI for *Conocarpus erectus* (50.51%) in the mangroves of the Guayaquil Historical Park, reinforcing the idea that this species contributes significantly to the character and structure of the ecosystem, particularly in areas with more disturbed or anthropogenically modified conditions.

In B4, *Conocarpus erectus* ranked first, recording the highest IVI across all size categories. The B4 plots were located on upland sites without direct influence from seawater, conditions under which this species tends to establish more successfully. In contrast, *Avicennia germinans* presented the lowest IVI in all size categories, indicating limited regeneration in this block. This structural configuration reflects an advanced degradation process, due to the low regeneration capacity of the mangrove in this block and the high degree of anthropogenic disturbance. Continuous resource extraction and land-use change drastically reduce the regeneration potential of the mangrove, accelerating its deterioration and eventual disappearance (Sánchez Montes, 2007).

4.5. Analysis of soil macro and microelements

The results of the soil analysis in our study showed that the macronutrients phosphorus and potassium were present at high concentrations in the PMBs, with the exception of B4, which exhibited very low phosphorus levels. Regarding nitrogen, all PMBs recorded very low concentrations. According to Drouet Yánez (2019), high nitrogen and phosphorus levels are generally associated with greater amounts of organic matter; therefore, the low nitrogen and phosphorus levels found in our study are consistent with the low organic matter contents recorded in the PMBs. B4 was the block with the lowest concentrations of nitrogen, phosphorus, and organic matter. In contrast, B3 presented the highest levels of nitrogen, phosphorus, and organic matter. Kallushettihalli Mallappa and Kumara (2020) point out that mangroves may exhibit variations in nutrient availability depending on the stage of ecosystem development and local environmental conditions.

In our investigation, a slightly alkaline and alkaline pH was recorded in all PMBs, accompanying high concentrations of manganese and iron. Copper showed a high concentration in B2, medium in B1 and B3, and low in B4. Calcium showed low concentrations in B1 and B4, and medium concentrations in B2 and B3. Regarding zinc, B1 and B2 showed medium concentrations, while in B3 and B4 they were low. Drouet Yánez (2019) reported in their study an increase in microelements, such as iron, copper, and manganese, while zinc and calcium presented low values, attributing this to the presence of a slightly acidic pH in most of the plots. Additionally, they indicated that the decrease in zinc could be associated with the increase in phosphorus. These results contrast with ours, given that the alkaline pH recorded in the PMBs did not coincide with that generalized decrease in microelements.

On the other hand, Alongi (2021) states that the reserves of Mg, K, Mn, Zn, and Ni may decrease with increasing mangrove productivity [NP], due to greater nutrient transformation and uptake. This relationship may help interpret the variations observed among the PMBS, especially in elements such as zinc and manganese.

However, Torán Figueroa (2020) reported high and medium concentrations of P, K, Ca, Mg, S, Zn, Cu, Fe, Mn, and B in its sampling units, attributing these values to the swampy soil texture. Additionally, it was noted that in sectors with neutral pH, mangroves with greater height were found, since this pH range favors nutrient absorption.

In contrast, Andrade Chica (2019) reported mostly slightly acidic soils and determined that this pH increases the maximum availability of phosphorus. On the other hand, Rodríguez Villón (2015) recorded slightly alkaline to alkaline pH values accompanied by high concentrations of phosphorus and potassium. These results are consistent with those of our study, where slightly alkaline to alkaline pH values were also obtained, along with elevated levels of potassium and phosphorus.

Different mangrove species exhibit nutrient uptake rates and distribution patterns that vary depending on the development site. The availability and distribution of macro- and micronutrients change according to the growth stages of the species, implying that each phase requires different amounts of essential nutrients (Hossain et al., 2003). In this sense, the interaction between nitrogen, phosphorus, and potassium directly influences leaf number, height, and branching, depending on the species type (Yates et al., 2002).

The most relevant factor for mangrove growth is soil nutrient concentration, with nitrogen, phosphorus, and potassium being the most determining elements. Potassium levels are especially important for species such as *Rhizophora apiculata*, while phosphorus enrichment favors the development of *Rhizophora mangle* (Kathiresan & Bingham, 2001).

4.6. Analysis of water electrical conductivity

In this study, it was observed that B2 presented the highest EC (43.9 dS m^{-1}) among the four blocks, considering that, being a riverine type, it receives less direct influence from the sea and a greater freshwater discharge. In contrast, B1, which is directly exposed to marine influence, showed a lower EC (38.7 dS m^{-1}). This behavior differs from what was described by Kusmana (1991), who stated that EC tends to be higher in areas with greater seawater influence and lower in sites with fluvial discharge and limited marine flooding. These differences observed in this study could be attributed to significant local conditions in B2.

It was considered that electrical conductivity was one of the important soil factors influencing mangrove forest patterns. High EC values were due to seawater input during high tides and water evaporation. In addition, EC is higher in coastal zones and gradually decreases as one moves inland (Kallushettihalli Mallappa & Kumara, 2020).

According to Kathiresan and Bingham (2001), salinity influences mangrove growth; therefore, plants must possess a certain level of tolerance to it. During the seedling stage, they require low salinity levels, but their tolerance increases as they grow. It is considered that the species *Avicennia spp.* and *Rhizophora spp.* are the most tolerant to high salinity levels. However, in the study by Guadamuz and Sean-Bloomfield (2019), a higher percentage of *Rhizophora mangle* individuals was recorded in a young mangrove forest under growth and development, finding greater incidence in areas with lower salinity, which allowed its colonization across the entire surface. In our study, it was observed that the blocks with higher EC showed scarce or no presence of *Rhizophora harrisonii*. In contrast, the block with lower EC, corresponding to B3, showed a notable presence of this species.

B2 presented higher EC, with *Avicennia germinans* being the second most abundant species in the block. Despite its tolerance, its growth may be affected by the displacement of potassium by sodium, which interferes with nutrient absorption capacity and would limit its development (Reef et al., 2015). In contrast, Reef et al. (2012) established that high salinity allows plants to develop strategies to cope with drought stress, and *Avicennia marina* seedlings grown under high salinity conditions showed greater adaptation to saline environments and high nutrient concentrations, a characteristic of the genus *Avicennia*. In our study, in B1, which was directly influenced by the sea and presented high EC levels, seedlings in the seedling category were recorded.

4.7. Correlation of soil physicochemical variables

No statistically significant correlation ($p > 0.05$) was found between the abundance of *Avicennia germinans*, *Rhizophora harrisonii*, and *Conocarpus erectus* and the evaluated physicochemical variables. However, *Laguncularia racemosa* showed a significant correlation with zinc ($\rho = 1.000$; $p = 0.000$). Although the remaining correlations were not statistically significant, *Rhizophora harrisonii* showed strong trends with nitrogen, calcium, manganese, and organic matter without statistical significance, as did *Avicennia germinans*, which showed a positive trend with potassium, copper, and zinc, and *Conocarpus erectus* with calcium.

The association between *Laguncularia racemosa* and soil zinc is consistent with Pimentel Victório et al. (2023), who demonstrated the ability of *Laguncularia racemosa* to accumulate metals in its tissues and reflect sediment contamination; therefore, its metal tolerance makes it a good indicator of disturbed mangroves. The correlation and tendency of *Rhizophora harrisonii* with N, Ca, Mn, and organic matter are consistent with Cerón-Souza et al. (2021), who link *Rhizophora* species with sediments rich in organic matter and nutrient retention, controlling the availability of nitrogen and metals. In mangroves of the Nyong River estuary (Cameroon), Mama et al. (2024) reported that soils with high organic matter and nitrogen contents showed greater dominance of *Rhizophora*.

On the other hand, the tolerance and tendency of *Conocarpus erectus* to relate with EC and Ca correspond to its ability to withstand wide salinity ranges and develop under brackish conditions, explaining its presence in patches with high conductivity (Asif, 2014). *Conocarpus erectus* is a species with strong potential under stressful conditions such as salinity and low nutrient availability, which provides an adaptive trait that supports its adaptability and dominance (Iqbal et al., 2024). For *Avicennia germinans*, the positive trends with K, Mg, Cu, and Zn are consistent with Diyah Retnosari et al. (2024), who reported the accumulation of Cu and Zn in roots due to its high capacity for metal uptake from sediments, and its translocation rates may depend on the chemical characteristics of the sediment (El Ashmawy et al., 2021).

5. Conclusions

The floristic composition of the study area was characterized by the presence of four species: *Laguncularia racemosa*, *Avicennia germinans*, *Rhizophora harrisonii*, and *Conocarpus erectus*, which were evenly distributed across the study blocks. The results indicate that B1 corresponds to a developing mangrove, due to the presence of *Laguncularia racemosa* as a colonizing species, found across all size categories. On the other hand, B2, despite the absence of seedlings, showed good regenerative capacity, with a predominance of juvenile trees, suggesting an intermediate successional stage. B3 also exhibited a higher prevalence of juvenile trees, whereas B4 did not present optimal development conditions, with its structure being affected by strong anthropogenic impact.

Each study block registered species according to their successional stage, physiography, environmental gradients, and anthropogenic factors. The highest number of individuals was associated with areas influenced by freshwater discharge, direct marine contact, and sedimentation. In contrast, the lowest number of individuals was related to the impact of human interventions.

Soil and water analyses highlighted the importance of organic matter concentration, pH, and electrical conductivity. Low organic matter levels across all PMBs affected the concentrations of essential macronutrients such as nitrogen and phosphorus. Additionally, alkaline pH was associated with higher concentrations of potassium and phosphorus. Electrical conductivity, related to salinity, also influenced species distribution patterns in the mangrove.

Finally, the study area showed that *Laguncularia racemosa* was mainly associated with soil zinc, while *Rhizophora harrisonii* was related to nitrogen, calcium, manganese, and organic matter. *Conocarpus erectus* showed affinity with electrical conductivity and calcium, evidencing its tolerance to saline conditions. In contrast, *Avicennia germinans* showed positive trends with potassium, magnesium, copper, and zinc. These associations demonstrate that nutrient and salt availability directly influence species distribution in the study area.

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Contributor roles

- Laura Suarez: conceptualization, investigation, methodology, resources, formal analysis, writing – original draft, writing – review & editing.
- Edison Velasco: funding acquisition, resources, project administration, writing – review & editing.
- Gabriel Suarez: data curation, formal analysis, writing – review & editing.

Data Availability

The data will be available on request.

Use of Artificial Intelligence

The authors declare that no artificial intelligence has been used in the preparation of the manuscript.

Ethical Implications

The authors declare that there are no ethical implications.

Conflict of Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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