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Original Article

Composition of the Benthic Macrofauna of an estuary on the Amazon Coast of Brazil

Composição da Macrofauna Bêntica de um estuário na Costa Amazônica do Brasil

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Abstract

This study characterized the benthic macrofauna of the Jacaré estuary, located on the Amazon coast of Maranhão, a poorly studied region subjected to anthropogenic pressures from port activities and insufficient wastewater treatment. Seasonal sampling conducted between 2023 and 2024 assessed environmental variables, sediment grain size, trace metals, and faunal composition. The macrofauna was dominated by polychaetes and mollusks, particularly *Heteromastus* sp., *Streblospio benedicti*, and *Solariorbis schumoi*. Community structure was mainly influenced by salinity, pH, organic matter, and sediment texture. High concentrations of aluminum, iron, and boron were recorded in the water, while aluminum, iron, and manganese accumulated in sediments. Diversity and richness reached their highest values between June and December, whereas equitability remained high throughout most sampling events. Multivariate analyses revealed temporal shifts in macrofaunal composition and a strong association between opportunistic species and metal concentrations, especially copper. The predominance of tolerant taxa such as *Heteromastus* sp. and *S. benedicti* highlights their potential as bioindicators. These findings expand the ecological knowledge of Amazonian estuaries and underscore the need for continuous monitoring to support conservation and management strategies in vulnerable coastal systems.

Keywords: tropical estuaries, Reentrâncias Maranhenses, shipping terminals, monitoring.

Resumo

Este estudo caracterizou a macrofauna bentônica do estuário do Jacaré, na costa amazônica do Maranhão, uma região pouco investigada e sujeita a pressões antrópicas associadas a atividades portuárias e deficiências no saneamento. Amostragens realizadas entre 2023 e 2024 avaliaram variáveis ambientais, granulometria, metais traço e composição faunística. A macrofauna foi dominada por poliquetas e moluscos, destacando-se *Heteromastus* sp., *Streblospio benedicti* e *Solariorbis schumoi*. A estrutura da comunidade foi influenciada principalmente por salinidade, pH, matéria orgânica e textura sedimentar. Elevadas concentrações de alumínio, ferro e boro foram registradas na água, enquanto alumínio, ferro e manganês acumularam-se nos sedimentos. A diversidade e a riqueza atingiram seus valores máximos entre junho e dezembro, enquanto a equitabilidade se manteve elevada na maior parte das amostragens. As análises multivariadas evidenciaram mudanças temporais na composição da macrofauna e forte associação entre espécies oportunistas e concentrações de metais, especialmente cobre. A predominância de táxons tolerantes, como *Heteromastus* sp. e *S. benedicti*, reforça seu potencial como bioindicadores. Os resultados ampliam o conhecimento sobre estuários amazônicos e destacam a necessidade de monitoramento contínuo para apoiar ações de conservação.

Palavras-chave: estuários tropicais, Reentrâncias Maranhenses, terminais de embarque, monitoramento.

1. Introduction

Worldwide, growing economic and social demands have increasingly impacted the coastal zone. Human activities, such as dredging, landfills, inadequate waste disposal, and the installation of ports and shipping infrastructure, all alter the natural dynamics of coastal ecosystems. The environments most affected by these processes include estuaries, which are semi-enclosed bodies of water in which seawater is mixed with the freshwater from terrestrial sources (Patchineelam and Kjerfve, 2004; Qin and Shen, 2017). Estuaries are highly productive ecosystems that

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serve essential functions, including nutrient cycling, food production, and the protection of a rich diversity of species and habitats (Burton, 2020).

The benthic macrofauna encompasses a prominent group of organisms that plays a fundamental role in estuarine ecosystems. These organisms are macroscopic – they can be retained in sieves that have a 0.5-mm mesh – and, by definition, at least one phase of their life cycle is associated with the bottom substrate (Checon et al., 2022). The benthic macrofauna is rich and diverse, comprising a variety of invertebrate groups, including crustaceans, molluscs, and annelids (Tawanggian et al., 2022).

The composition and structure of the benthic macrofauna can be used to evaluate the biological quality of coastal and transitional waters, given that these organisms have some essential traits that make them excellent biological indicators, such as a relative lack of mobility, extreme sensitivity, and their capacity to respond rapidly to fluctuations in physicochemical variables, responding to a range of different environmental conditions (Zaghloul et al., 2020).

The effective long-term protection of estuarine ecosystems requires a profound understanding of local biodiversity to ensure the establishment of a comprehensive species database, supporting the development of efficient conservation and environmental management measures. Any evaluation of biodiversity involves a series of major challenges, especially given the general shortage of taxonomic specialists and the time and resources needed to collect and identify the organisms (Heino, 2010; Corte et al., 2017). These difficulties are particularly pronounced in developing countries, such as Brazil, where a chronic lack of resources and taxonomic specialists further complicates the process (Amaral et al., 2016).

In Brazil, research on benthic macrofauna has traditionally been concentrated in the southern and Southeastern regions. The estuaries along Brazil's northern coast, particularly those located on the Amazonian coast of Maranhão, remain poorly studied and underrepresented in the scientific literature (Soares et al., 2022). This scarcity of research also reflects broader biodiversity knowledge gaps, such as the Wallacean shortfall and aspects of the Eltonian shortfall, which relate to species' ecological roles and co-occurrence patterns (Hortal et al., 2015). By documenting the benthic macrofauna in an understudied Amazonian estuary, our study contributes to reducing these gaps.

This gap is critical, considering that the region is part of the Reentrâncias Maranhenses Environmental Protection Area (EPA Reentrâncias Maranhenses). Despite its protected status, the area remains vulnerable to invasion by exotic species due to the constant discharge of ballast water by foreign vessels docking at the local shipping terminals, which can have a major impact on the equilibrium of the area's aquatic ecosystems.

Given this scenario, we hypothesize that the structure of the benthic macrofauna in the Jacaré estuary is strongly influenced by local environmental conditions. Specifically, variations in salinity, pH, sediment granulometry, organic matter content, and metal concentrations are expected to exert significant effects on species composition and abundance. Investigating these relationships allows us to identify which factors most strongly shape the community and to better understand the ecological processes that operate in Amazonian estuaries.

In light of the environmental and socioeconomic importance of the region, this study provides new data on the diversity and ecological patterns of the benthic macrofauna of the Jacaré estuary, located in the eastern sector of the Amazon coast of northern Brazil. The aim of this study was to describe the composition and structure of the benthic macrofauna of the Jacaré estuary and to evaluate how environmental variables influence community patterns.

2. Material and Methods

2.1. Study area

The study area is situated in the estuarine zone surrounding the municipality of Alcântara, located in eastern São Marcos Bay, on the Amazon coast of northern Brazil (Figure 1). São Marcos Bay is a major estuarine complex that extends over approximately 100 kilometers and contains one of the largest shipping terminals of the Brazilian coast, which is the second largest in Latin America, in terms of the volume of cargo shipped annually through the port (Amaral and Alfredin, 2010).

This region has a hot, semi-humid climate with two well-defined seasons: a rainy season (January to June) and a dry season (July to December). Mean total annual precipitation is approximately 2000 mm (Azevedo and Cutrim, 2007). The municipality of Alcântara is located within the Reentrâncias Maranhenses Environmental Protection Area (EPA Reentrâncias Maranhenses), which has been recognized as a RAMSAR site, that is, a protected area of international importance and also includes the Alcântara Missile Launch Center, given its location near the Equator (Beckman, 2018). The municipality of Alcântara also faces a number of serious challenges, in terms of its infrastructure and public sanitation system, given that it lacks sufficient water treatment plants or an adequate public sewage disposal system.

2.2. Field procedures and biological analyses

Six quarterly field campaigns were conducted at three sampling sites in the Jacaré estuary between June 2023 and September 2024. The sampling design for the study of the benthic fauna consisted of collecting three replicates at each site during each campaign, using a Van Veen grab (sampling area 682 cm^2). Additionally, one sediment sample per site was collected for the physical and chemical characterization of the substrate and for determining heavy metal concentrations. The physicochemical parameters of the water (temperature, pH, salinity, and dissolved oxygen) were recorded in situ using a multiparameter probe. The faunal samples were immediately fixed in 4% formaldehyde, washed through a 0.5 mm sieve, preserved in 70% ethanol, and later identified under a stereomicroscope to the lowest possible taxonomic level with the aid of specialized literature.

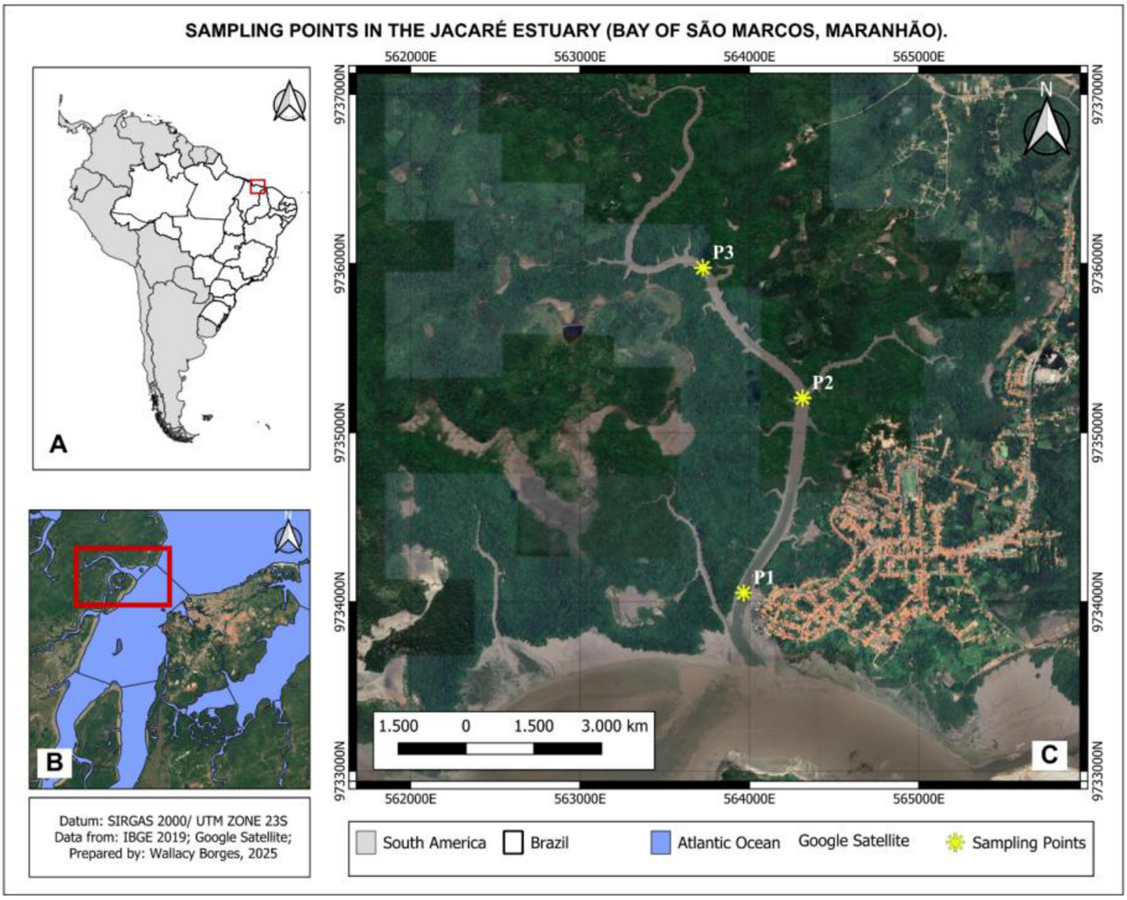

Figure 1. Location of the sampling points (P1–P3) in the Jacaré estuary, in the municipality of Alcântara, in the northwestern extreme of São Marcos Bay, in Maranhão, northern Brazil.

2.3. Data analysis

Environmental variables (temperature, salinity, pH and dissolved oxygen) were tested for normality (Shapiro-Wilk) and homogeneity of variances (Levene). When assumptions were met, differences among months were assessed with one-way ANOVA ($p < 0.05$); otherwise, the Kruskal-Wallis test was applied. For each sample, density, frequency of occurrence, species richness (Margalef's D), diversity (Shannon-Wiener, H'), and equitability (Pielou's J') were calculated. Species were classified as constant (>50% of samples), accessory (25–50%), or accidental (<25%) (Dajoz, 1983). Sediment grain size (gravel, sand, silt, clay) was determined following Suguio (1973), and organic matter content was measured using loss on ignition (Walkley and Black, 1934). The metals (Al, Cu, Fe, B, Cr, Mn) in water and sediment were analyzed by the accredited laboratory LIMNOS Hidrobiologia e Limnologia LTDA. Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was employed for the analysis, with samples first undergoing acid digestion to ensure complete metal dissolution.

To assess temporal variation in community structure, we calculated Bray–Curtis dissimilarities from the species abundance matrix and evaluated the homogeneity of multivariate dispersions (PERMDISP) for months and years. Because heterogeneity could not be corrected through transformations (square root, log(x+1), and Hellinger), analyses were conducted accepting post-hoc tests only for $p < 0.01$. Community structure was visualized using NMDS, and differences among years and months were tested with PERMANOVA (adonis2; 9,999 permutations). To identify the taxa contributing most to temporal dissimilarities, we applied SIMPER, and performed an indicator species analysis (multipatt; 9,999 permutations) to determine taxa significantly associated with each period.

Multivariate analysis was conducted using Redundancy Analysis (RDA) after applying a Hellinger transformation to the biotic matrix, justified by a DCA that indicated a long gradient. Collinearity among predictors was assessed using VIFs, removing variables with VIF > 6 and grouping predictors into physical and chemical sets. Physical variables were square-root transformed and chemical variables were standardized to meet assumptions of linearity and scale. Significant predictors were selected through forward selection with permutation tests, resulting in the final RDA model. Global significance and canonical axes were tested using 999 permutations, and explained variance was expressed as adjusted R^2. Species contributions and variance partitioning between physical and chemical sets were also evaluated. All analyses were conducted in R using the vegan package.

3. Results

3.1. Environmental variables

The water temperature ranged from 28.26 ºC in March 2024 to 29.9 ºC in June 2024. Salinity varied from a minimum of 18.86 ppt in June 2023 to a maximum of 29.96 ppt in December 2023. The lowest pH (6.11) was recorded in March 2024, and the highest (8.02) in September 2023. Dissolved oxygen reached its lowest concentration (5.53 mg.L^{-1}) in September 2023, and its highest (8.8 mg.L^{-1}) in June 2024.

Three of the environmental variables analyzed here – temperature, salinity, and pH – were normally distributed ($p>0.05$), while dissolved oxygen deviated significantly ($p<0.05$). Temperature ($F = 10.2$, $p = 0.006$), salinity ($F = 13.79$, $p = 0.003$), and pH ($F = 22.27$, $p = 0.0008$) all varied significantly among months (Table 1). Except for the exceptionally low pH values recorded in March and June 2024, all the variables were within the limits recommended by the Brazilian National Environment Council (CONAMA) for water of adequate quality for human contact (Brasil, 2005).

3.2. Granulometry and organic material

A predominance of silt and clay was recorded in the sediments in the first four months of the study period (June 2023–March 2024), whereas June and September 2024 were marked by the presence of fine sand and silt. The concentration of organic material peaked in September 2023 (34.33 g.dm^{-3}), and was lowest in September 2024 (18.14 g.dm^{-3}) (Table 2).

3.3. Metals in water

Overall, the concentrations of the analyzed metals indicated a contamination scenario, with most elements exceeding the limits established by CONAMA Resolution No. 357/2005 (Brasil, 2005). Aluminum (Al) exhibited the highest values, far surpassing the reference limit (0.1 mg·L^{-1}) at all sites and in all months, especially in Sept/2023, when it reached 35.67 mg·L^{-1} at P3. Iron (Fe) also exceeded the reference value (0.3 mg·L^{-1}) in several samples, with maximum concentrations of 4.43 mg·L^{-1} at P2 (Sept/2023) and 3.15 mg·L^{-1} at P3 (Jun/2024).

Boron (B) showed persistently elevated concentrations above the limit (0.5 mg·L^{-1}), peaking at 4.55 mg·L^{-1} at P1 (Dec/2023). Manganese (Mn) and copper (Cu), although generally presenting values below the detection limit, exhibited occasional exceedances. Mn surpassed the 0.1 mg·L^{-1} limit at P1 (0.22 mg·L^{-1}) and P3 (0.35 mg·L^{-1}) in Sept/2023, while Cu exceeded its limit (0.005 mg·L^{-1}) at P1 and P2 in the same month. In contrast, chromium (Cr) remained at low concentrations, staying within the standards established by current legislation (Table 3).

3.4. Metals in sediment

Metal concentrations in the sediments varied substantially across sampling sites and periods. Aluminum (Al) showed the highest recorded values, with peaks above 60,000 mg·kg^{-1}, particularly at P2 and P3, indicating strong accumulation of

Table 1. Variation in the mean and standard deviation (SD) of the environmental parameters of the water recorded among the three sampling points monitored in the present study in the Jacaré estuary in Maranhão, northern Brazil.

Environmental variable	Unit of measurement	Mean±SD recorded in:						*p*
		June/23	Sept/23	Dec/23	Mar/24	June/24	Sept/24	
Temperature	ºC	29.16±0.58	28.73±0.55	29.02±0.26	28.26±0.37	29.9±0.2	28.4±0.26	0.006*
Salinity	ppt	18.86±1.60	29.5±0.26	26.96±1.92	19.07±5.29	24.7±7.21	25.53±0.11	0.003*
pH	-	7.77±0.17	8.02±0.27	6.96±0.20	6.11±0.43	6.14±0.08	7.06±0.10	0.0008*
Dissolved Oxygen	mg.L^{-1}	8.06±1.09	5.53±0.50	6.16±0.40	5.56±1.45	8.8±3.70	5.53±0.35	0.06†

**p* value for the one-way ANOVA.
†p value for the Kruskal-Wallis test.

Table 2. Variation in the mean and standard deviation (SD) of the granulometric composition of the sediment and the concentration of organic material recorded at the three sampling points monitored in the present study in the Jacaré estuary in Maranhão, northern Brazil.

Variable	Unit of measurement	Mean±SD recorded in:					
		June/23	Sept/23	Dec/23	Mar/24	June/24	Sept/24
Coarse sand	%	0±0	0.33±0.57	0.66±0.57	0±0	0±0	0±0
Fine sand	%	3±2	24.33±19.39	9±12.16	4.33±2.30	59.93±9.69	53.92±7.54
Silt	%	31±2	50.00±4.35	76.33±12.42	84.33±4.16	39.93±9.60	44.72±6.07
Clay	%	36±2	25.33±14.46	14±1.63	11.33±3.05	0.13±0.11	1.35±2.34
OM	g.dm^{-3}	28.66±8.14	34.33±5.13	28±2.64	22.66±3.78	23.58±13.59	18.14±3.92

Table 3. Concentrations of dissolved metals (mg.L⁻¹) in surface water samples from the Jacaré estuary in Maranhão, northern Brazil.

Metal	Points	June/23	Sept/23	Dec/23	Mar/24	June/24	Sept/24
Al	P1	0.44	27.15	0.35	9.04	0.74	5.07
	P2	13.51	12.44	<0.05	3.50	4.61	2.39
	P3	3.41	35.67	0.31	6.49	4.51	3.38
	Mean	5.786	25.087	0.33	6.343	3.28	3.61
Cu	P1	<0.001	0.056	0.019	0.011	<0.0010	0.014
	P2	0.02	0.05	< 0.0010	0.002	< 0.0010	0.001
	P3	0.012	0.012	0.014	0.011	< 0.0010	0.001
	Mean	0.016	0.039	0.016	0.008	< 0.0010	0.005
Fe	P1	0.37	0.02	0.06	0.02	0.58	2.57
	P2	< 0.020	4.43	< 0.020	1.78	3.33	0.99
	P3	1.5	0.02	0.02	0.02	3.15	1.59
	Mean	0.935	1.49	0.04	0.60	2.35	1.71
B	P1	1.500	< 0.010	4.550	1.490	1.1	1.61
	P2	1.660	< 0.010	< 0.010	1.400	1.91	2.36
	P3	2.890	< 0.010	3.870	< 0.010	1.89	2.42
	Mean	2.017	< 0.010	4.21	1.445	1.63	2.13
Cr	P1	< 0.010	0.06	< 0.010	0.02	< 0.010	0.01
	P2	0.03	0.03	< 0.010	< 0.010	< 0.010	< 0.010
	P3	0.01	0.07	< 0.010	0.01	< 0.010	< 0.010
	Mean	0.02	0.053	< 0.010	0.015	< 0.010	0.01
Mn	P1	<0.05	0.22	< 0.050	0.21	< 0.050	< 0.050
	P2	0.15	0.2	< 0.050	< 0.050	< 0.050	< 0.050
	P3	0.05	0.35	< 0.050	0.13	< 0.050	< 0.050
	Mean	0.1	0.25	< 0.050	0.17	< 0.050	< 0.050

Values below the detection limit are indicated with "<". Reference Value: Al (0.1 mg.L⁻¹), Cr (0.05 mg.L⁻¹), Cu (0.005 mg.L⁻¹), B (0.5 mg.L⁻¹), Fe (0.3 mg.L⁻¹) and Mn (0.1 mg.L⁻¹).

this fraction in the sediment. Iron (Fe) exhibited similarly high and consistent concentrations throughout the entire monitoring period. Manganese (Mn) displayed marked enrichment, reaching values above 700 mg·kg⁻¹ at P2 and remaining elevated at the other sites. Chromium (Cr) showed intermediate and relatively stable concentrations, ranging between 55 and 85 mg·kg⁻¹. Copper (Cu) remained at low to moderate levels, with small occasional increases, while boron (B)—absent or below the detection limit for much of the early sampling period—showed substantial increases beginning in Mar/2024. Overall, the results indicate distinct accumulation patterns among the metals, with Al, Fe, and Mn standing out due to their magnitude, whereas Cu, Cr, and B exhibited more moderate temporal variations (Table 4).

3.5. Composition of the benthic fauna

Overall, a combined density of 1035.9 ind.m^{-2} was recorded in the study estuary, including organisms of seven different taxonomic groups – the Crustacea, Insecta, Mollusca, Oligochaeta, Polychaeta, Nematoda, and Nemertea. The polychaetes (789.63 ind.m^{-2}) and molluscs (154.08 ind.m^{-2}) were the two predominant groups. In 2023, the overall density of individuals per month was 52.93 ind.m^{-2} in June, 35.28 ind.m^{-2} in September, and 254.37 ind.m^{-2} in December, while in 2024, it was 223.5 ind.m^{-2} in March, 152.92 ind.m^{-2} in June, and 316.9 ind.m^{-2} in September. Total density was 429.35 ind.m^{-2} in the rainy season and 606.55 ind.m^{-2} in the dry season. The species with the highest overall densities (Table 5) were *Heteromastus* sp., with 577.20 ind.m^{-2}, *Streblospio benedicti* Webster, 1879 (130.86 ind.m^{-2}), and *Solariorbis schumoi* Vanatta, 1913 (ind.m^{-2}).

Constant species (>50% occurrence) included *Littoraria flava* (P. P. King, 1832), *Melampus coffea* (Linnaeus, 1758), *S. schumoi*, *Heteromastus* sp., *Nephtys fluviatilis* Monro, 1937, and *S. benedicti*. Accessory species (25–50%) comprised taxa such as *Benthonella tenella* (Jeffreys, 1869), *Lumbrineris* sp., *Sigambra grubii* Müller, 1858, and nemerteans, while the remaining taxa were occasional (<25%). Seasonal analysis showed that *L. flava*, *S. schumoi*, *Heteromastus* sp., and *S. benedicti* were constant year-round. Other species, that is, *B. tenella*, *Goniada* sp., *Lumbrineris* sp., *M. papillicornis*, *S. grubei*, *N. fluviatilis*, and Nemertea, were constant only during the dry season (Figure 2a), while *B. unifasciata* and

Table 4. Concentrations of metals (mg.kg⁻¹) in surface sediments from the Jacaré estuary in Maranhão, northern Brazil.

Metal	Points	June/23	Sept/23	Dec/23	Mar/24	June/24	Sept/24
Al	P1	24,278.77	25,257.58	41,032.96	2,848.2	57,067.59	31,176.35
	P2	51,039.28	29,597.39	1,107.46	38,633.87	44,605.52	32,492.05
	P3	61,015.43	45,874.49	60,245.03	51,452.24	40,726.84	33,207.66
	Mean	45,444.49	33,576.48	34,128.48	30,978.1	47,466.65	32,292.02
Cu	P1	< 0.20	9.64	7.98	4.04	12.23	4.13
	P2	< 0.20	6.27	7.64	5.53	20.67	3.64
	P3	< 0.20	7.72	6.23	4.35	11.18	4.14
	Mean	< 0.20	7.87	7.28	4.64	14.69	3.97
Fe	P1	27,867.55	30,301.25	22,843.09	1,977.33	29,244.53	50,359.5
	P2	45,370.46	36,808.78	23,890.55	38,006.57	20,463.51	47,625.2
	P3	48,830.26	43,330.34	14,325.68	43,677.01	12,996.25	49,945.43
	Mean	40,689.42	36,813.45	20,353.10	27,886.97	20,901.43	49,310.04
B	P1	< 0.10	< 0.10	< 0.10	363.85	7,133.2	5,368.48
	P2	< 0.10	< 0.10	< 0.10	< 0.10	1,816.57	4,913.55
	P3	< 0.10	< 0.10	< 0.10	< 0.10	4,260.32	3,206.67
	Mean	< 0.10	< 0.10	< 0.10	363.85	4,403.36	4,496.23
Cr	P1	<0.20	64.09	62.64	57.66	13.37	75.48
	P2	74.29	85.43	81.47	74.87	55.6	76.41
	P3	<0,20	76.23	68.4	65.16	41.87	77.85
	Mean	74.29	75.25	70.83	65.89	36.94	76.58
Mn	P1	35.38	195.27	265.32	453.82	274.75	381.47
	P2	716.26	476.51	492.84	550.63	292.01	400.24
	P3	148.53	298.41	300.12	377.38	207.19	329.5
	Mean	300.05	323.39	352.76	460.61	257.98	370.4

Values below the detection limit are indicated with "<".

M. coffea, and the nematodes were constant only during the rainy season (Figure 2b).

3.6. Ecological indices

The ecological indices showed marked variations across the sampling periods. The highest diversity values (Shannon) occurred at P2 in June 2023 (1.79), at P2 in December 2023 (1.96), and at P1 in September 2024 (1.69), as well as the highest richness values (Margalef), which reached 2.79 at P2 in June 2023 and 2.41 in December 2023. In March 2024, there was a sharp reduction in community structure, especially at P3, associated with the dominance of a single species, *Heteromastus* sp. Evenness remained high in most sampling events (reaching 1.0 at P2 in June 2023 and P2 in September 2023). Overall, the data indicate higher diversity and stability between June and December, followed by a marked decline in March (Figure 3).

3.7. Non-Metric Multidimensional Scaling (NMDS) e Permanova

The NMDS analysis revealed temporal changes in the structure of the macrobenthic community. Samples collected in 2023 clustered on the left side of the ordination, whereas those from 2024 were distributed to the right of NMDS1, reflecting a gradual reorganization of the assemblages. PERMANOVA confirmed this difference, with a significant effect of year ($F = 3.75$; $p = 0.002$), demonstrating that macrofaunal composition changed substantially between periods. In contrast, the month factor was not significant ($F = 1.24$; $p = 0.216$), suggesting that intra-annual seasonal variation did not explain community structure.

The 2023 assemblages were more closely associated with *Solariorbis schumoi*, Nematoda, Oligochaeta, and *Littoraria flava*, whereas 2024 showed a higher occurrence of opportunistic species such as *Heteromastus* sp., *Streblospio benedicti*, *Lumbrineris* sp., and *Sigambra grubii* (Figure 4). This pattern indicates temporal turnover within the community, with an increasing predominance of tolerant taxa, possibly in response to the environmental changes recorded in the estuary.

3.8. Redundancy Analysis - RDA

The Redundancy Analysis (RDA) showed that the selected environmental variables explained a significant

Table 5. The density (ind/m²) and frequency of occurrence (Fo%) of the different components of the benthic macrofauna recorded in the Jacaré estuary, in Maranhão, northern Brazil in the different samples of the study period.

Taxon	Density (ind.m^{-2}) recorded in:							Fo%
	June/23	**Sept/23**	**Dec/23**	**Mar/24**	**June/24**	**Sept/24**	**All months**	
Crustacea								
Tanaidacea	0	0	0	0	1.47	5.88	7.35	33.33
Insecta								
Chironomidae	0	0	0	1.47	0	2.94	4.41	33.33
Mollusca								
Barleeia unifasciata	4.41	0	0	0	5.88	0	10.29	33.33
Benthonella tenella	1.47	1.47	2.94	0	0	0	5.88	50.00
Ctna sp.	1.47	0	0	0	0	0	1.47	16.66
Heleobia australis	0	1.47	0	0	0	0	1.47	16.66
Littoraria angulifera	0	0	2.94	0	1.47	0	4.41	33.33
Littoraria flava	5.88	4.41	2.94	2.94	0	1.47	17.64	83.33
Melampus coffea	1.47	0	2.94	1.47	1.47	0	7.35	66.66
Parvanachis obesa	0	0	2.94	2.94	0	0	5.88	33.33
Phyllodina tenuisculpta	1.47	0	0	0	0	0	1.47	16.66
Solariorbis schumoi	33.82	0	38.23	17.64	2.94	1.47	94.1	83.33
Stramonita brasiliensis	0	0	1.47	0	0	0	1.47	16.66
Thaisella coronata	0	1.47	0	0	0	0	1.47	16.66
Turbonilla sp.	0	0	1.47	0	0	0	1.47	16.66
Oligochaeta	0	0	41.17	0	4.41	0	45.58	33.33
Polychaeta								
Capitella acaraensis	0	1.47	0	0	0	0	1.47	16.66
Capitella sp.	0	1.47	0	0	0	0	1.47	16.66
Dorvileia sp.	0	0	5.88	0	0	0	5.88	16.66
Goniada sp.	0	1.47	0	0	0	1.47	2.94	33.33
Heteromastus sp.	0	5.88	110.29	169.11	75	216.92	577.2	83.33
Hermundura tricuspis	0	0	5.88	1.47	0	0	7.35	33.33
Isolda pulchella	0	1.47	0	0	0	0	1.47	16.66
Lumbrineris sp.	0	0	13.23	2.94	0	5.88	22.05	50.00
Magelona papillicornis	0	1.47	0	0	0	2.94	4.41	33.33
Nereididae	0	0	0	0	0	1.47	1.47	16.66
Nephtys fluviatilis	0	1.47	2.94	0	2.94	2.94	10.29	66.66
Paraonis sp.	0	0	0	2.94	0	0	2.94	16.66
Scoloplos sp.	0	0	2.94	1.47	0	0	4.41	33.33
Sigambra grubii	0	1.47	0	0	10.29	11.76	23.52	50.00
Streblospio benedicti	0	7.35	13.23	17.64	30.88	61.76	130.86	83.33
Timarete ceciliae	0	1.47	0	0	0	0	1.47	16.66
Nematoda	2.94	0	0	0	16.17	0	19.11	33.33
Nemertea	0	1.47	2.94	1.47	0	0	5.88	50.00
Total	**52.93**	**35.28**	**254.37**	**223.5**	**152.92**	**316.9**	**1035.9**	

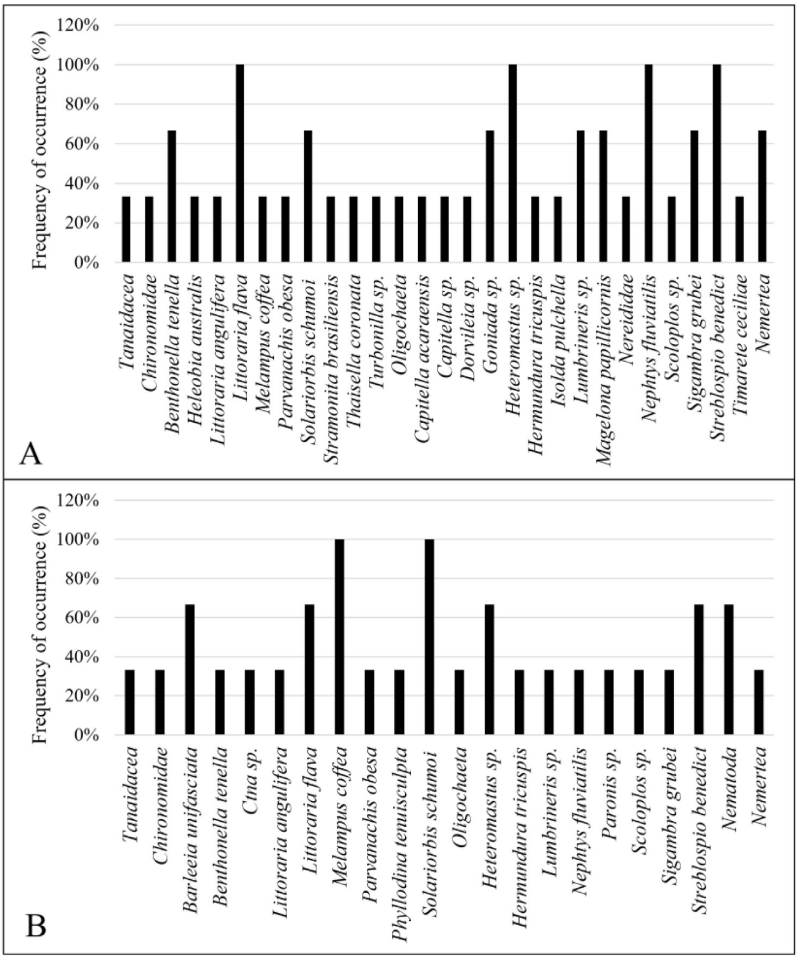

Figure 2. Frequency of occurrence of the different species recorded in the: (a) dry season, (b) rainy season, in the Jacaré estuary, in Maranhão, northern Brazil.

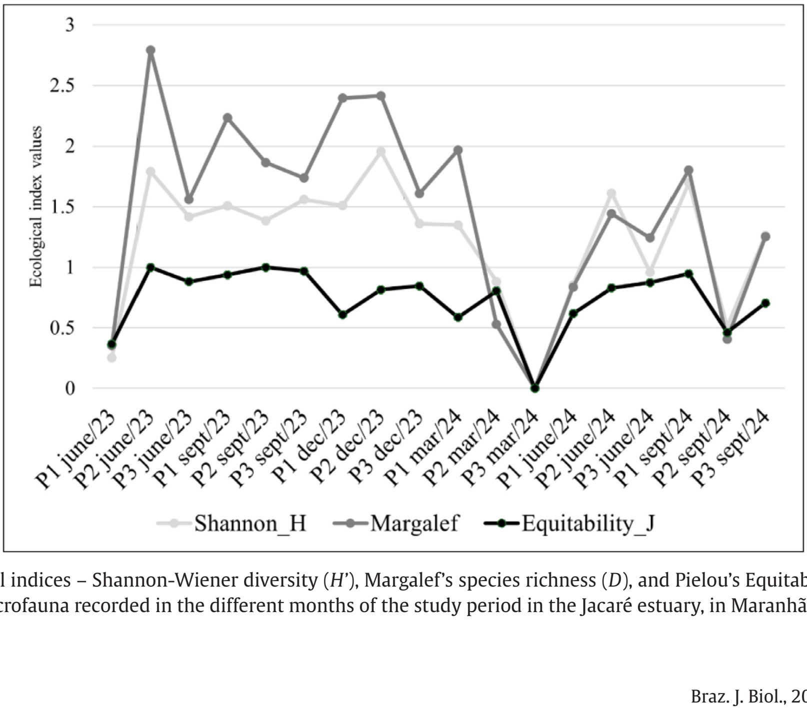

Figure 3. Ecological indices – Shannon-Wiener diversity (*H'*), Margalef's species richness (*D*), and Pielou's Equitability (*J'*) – recorded for the benthic macrofauna recorded in the different months of the study period in the Jacaré estuary, in Maranhão, northern Brazil.

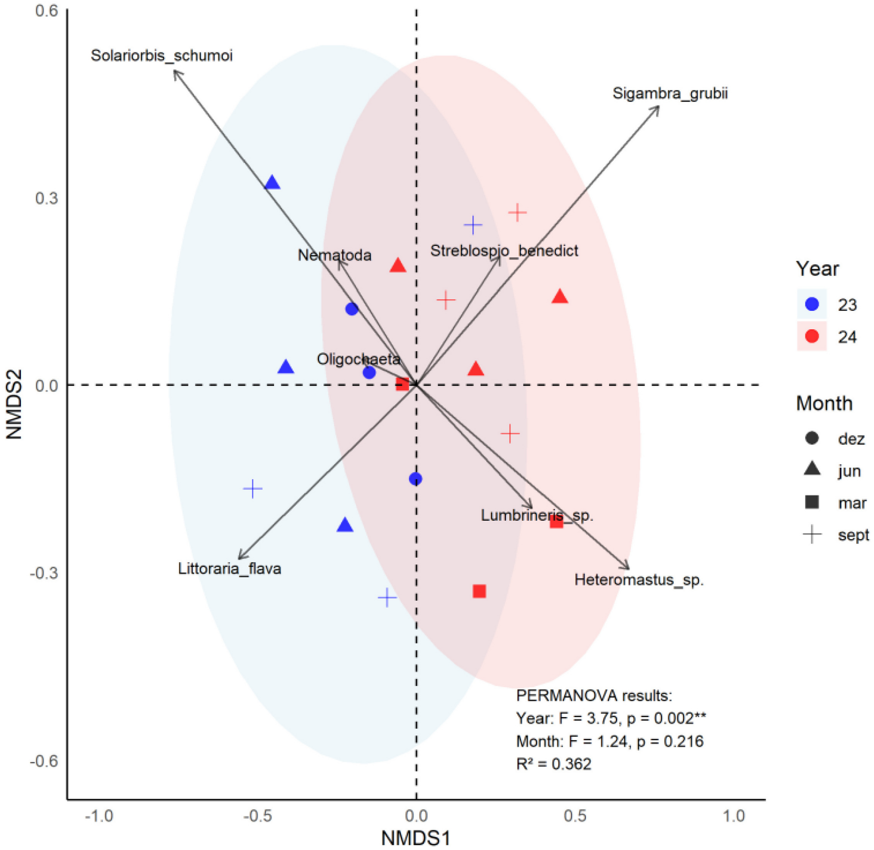

Figure 4. NMDS ordination of benthic macrofauna composition recorded during the sampling months in the Jacaré estuary, Maranhão, northern Brazil.

portion of the variation in benthic macrofaunal composition (adjusted $R^2 = 0.29$; $p = 0.001$). RDA1 accounted for 24.2% of the explained variance and RDA2 for 12.5%. The variables exerting the strongest influence on the ordination were sediment copper (Cu_S), water copper (Cu_W), organic matter (OM), and clay content. *Heteromastus* (het) and *Streblospio benedicti* (sben) aligned with the positive direction of RDA1 and were associated with Cu_S, whereas *Solariorbis schumoi* (sch), *Barleeia unifasciata* (buni), and *Bentonella tenella* (bten) grouped on the opposite side, closer to OM and clay. *Littoraria flava* (lfla) was positioned near Cu_W in the upper portion of the plot. Overall, RDA1 primarily reflected the influence of sediment copper, while RDA2 captured variation associated with dissolved copper and sediment texture (Figure 5).

4. Discussion

The water variables (temperature, salinity, and pH) varied significantly among months, with salinity emerging as the main driver of benthic community structure in estuaries (Verdelhos et al., 2015). The Jacaré estuary is a polyhaline system (18–30 ppt), similar to other estuaries on the Maranhão coast (Cutrim et al., 2018; Rodrigues, 2021), although wider salinity fluctuations have been reported elsewhere (Oliveira and Mochel, 1999; Sousa et al., 2023). Such variations generally reduce species richness, favoring opportunistic taxa (Van Diggelen and Montagna, 2016).

The pH values were mostly neutral to slightly alkaline, as described in previous studies (Rodrigues and Cutrim, 2010; Cutrim et al., 2018). However, in March and June 2024, acidic values fell below CONAMA standards, which may compromise species physiology (Silva et al., 2008). Dissolved oxygen remained above 5 mg L^{-1}, favorable to aquatic life, whereas hypoxic conditions are known to reduce diversity and biomass (Rabalais et al., 2010).

The sediment of the study area was composed predominantly of silt and clay, which is typical of the estuaries of the Amazon region (Aviz et al., 2012). Sediment with a similar composition was also recorded in the mangroves of the coast of Maranhão by Sousa et al. (2015) and on the coast of the neighboring state of Pará (Barbosa et al., 2015). The evidence indicates that sediments rich in silt and clay, which are common in estuarine environments, create ideal conditions for benthic organisms, given the greater stability of the environment, and the availability of both organic material and feeding resources (Silva-Camacho et al., 2017).

The water metals show recurrent exceedances of the limits established by CONAMA Resolution 357/2005 for

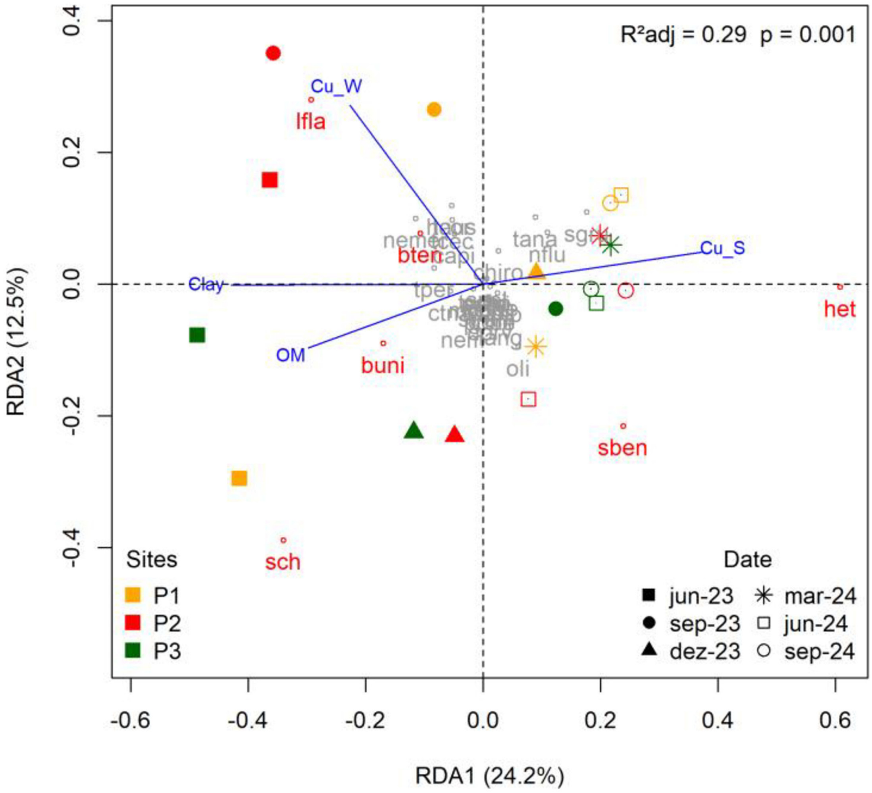

Figure 5. Redundancy Analysis (RDA) ordination illustrating the relationship between benthic macrofauna composition and environmental variables in the Jacaré estuary, Maranhão, northern Brazil). Copper from water (Cu_W); Copper from sediment (Cu_S); Organic Material (OM); *Heteromastus* (het); *Streblospio benedicti* (sben); *Solariorbis schumoi* (sch); *Barleeia unifasciata* (buni); *Bentonella tenella* (bten) and *Littoraria flava* (Ifla).

Al, Fe, Cu, and B, while Cr remained within the standard (Brasil, 2005). These results are consistent with Brazilian surveys that identify Al, Fe, and B among the parameters that most frequently exceed the regulation in estuarine environments (Pavione et al., 2019). The high Al value in Jun/23 and the oscillations of Fe and Mn are compatible with the hydrological seasonality of the Gulf of Maranhão, where the increase in river discharge during the rainy season intensifies the input and mobilization of metals into the water column. Local studies report high Fe associated both with continental input and with port activities (Santos et al., 2023; Torres et al., 2023).

In the sediment, Mn stood out for its high values, similar to those described for São Marcos Bay. Elevated concentrations of manganese have already been observed in the port area in studies by (Sousa et al., 2023; Oliveira et al., 2023). High concentrations of manganese in the studied area may be related to port cargo, since this mineral is the main product handled in the loading activities of the São Luís Port Complex (Amaral and Alfredin, 2010).

Polychaetes and mollusks were the dominant faunal groups in the study area. Assemblages of this type are frequently reported in ecological studies of benthic macrofauna in soft-bottom aquatic environments in both temperate and tropical regions (Oliveira and Mochel, 1999; Amaral et al., 2003; Martins and Almeida, 2014). *Heteromastus* sp., *Streblospio benedicti,* and *Solariorbis schumoi* were the species with the highest densities and were present at all sampling stations. Seasonal changes in community structure reflect ecological filtering driven by salinity, pH, oxygen, and sediment characteristics (Levin et al., 2001). Predatory taxa (*N. fluviatilis*, *Goniada* sp., *Lumbrineris* sp.) were restricted to the dry season, whereas *M. coffea* and *B. unifasciata* were more frequent during the rainy season, likely due to increased organic input.

The higher diversity and richness recorded between June and December point to a period of greater habitat stability, allowing a more balanced distribution of taxa across sites. In contrast, the marked decline observed in March, particularly the reduction in diversity at P3, indicates a disturbance event or unfavorable conditions that promoted the dominance of tolerant species such as *Heteromastus* sp., a pattern commonly reported in impacted estuarine habitats (Muniz and Venturini, 2001).

The patterns observed in the NMDS reflect the combined influence of grain size, organic matter, and metals on macrofaunal structure. The separation of June/23 corresponds to finer sediments with higher clay content, which favor more sensitive species. The transitional pattern throughout 2023 aligns with increases in silt and metal concentrations. The grouping observed in 2024 is associated with the replacement of sensitive taxa by tolerant opportunistic species, such as *Heteromastus* sp., in response to higher fine sand content and chemical stress (Elliott et al., 2007). Overall, the temporal gradient indicates a progressive reorganization of the community driven by physical and chemical changes in the estuary

The distribution of the macrofauna was strongly influenced by grain size and organic matter, classical factors that structure benthic communities in estuaries (Gray and Elliott, 2009). The association of *Heteromastus* sp. and *Streblospio benedicti* with higher concentrations of Cu in both water and sediment indicates tolerance to chemical stress, a characteristic already described for opportunistic species resistant to disturbance (Dean, 2008).

Species such as *Solariorbis schumoi* and *Barleeia unifasciata* were concentrated in areas of fine sediment, consistent with the known preference for environments rich in organic matter and microdetritus (Alongi et al., 1998).

In the Brazilian estuarine context, the presence of *Heteromastus* and *S. benedicti* is associated with environments experiencing some degree of disturbance. These species are classified as opportunists that rapidly colonize and proliferate under conditions unfavorable to more sensitive taxa. The national literature establishes that the dominance of Capitellidae and Spionidae is directly linked to organic enrichment in coastal ecosystems, as demonstrated on beaches of the São Paulo coastline (Amaral et al., 1998) and in studies of other opportunistic families along the Amazon coast (Feres et al., 2008). The structure of polychaete communities in highly impacted environments, such as Guanabara Bay, is frequently dominated by tolerant species like *S. benedicti* (Santi and Tavares, 2007). Recognition of the bioindicator role of these genera is such that *Heteromastus* has been consistently included in the application of the Marine Biotic Index (AMBI) in environmental quality assessments along the southern and southeastern Brazilian coast (Muniz et al., 2005).

The dominance of opportunistic polychaetes, such as species of *Heteromastus* and *S. benedicti*, reflects their high ecological flexibility, a key factor for their success in colonizing impacted estuaries (Hutchings, 1998). This flexibility is evident in their wide geographic distribution and euryecology, which allows them to persist under unstable environmental conditions. Physiologically, they exhibit broad tolerance to salinity and temperature variations typical of estuarine zones, ensuring their survival under different environmental regimes. Moreover, their opportunistic deposit-feeding strategy favors persistence in environments with high organic enrichment and provides resistance to chemical stressors such as heavy metals, a phenomenon already documented in Brazilian bays under strong industrial impact (Dean, 2008).

5. Conclusions

The present study expands the understanding of benthic macrofauna in a poorly investigated Amazonian estuary, revealing spatial and temporal patterns linked to environmental gradients and anthropogenic pressures. The characterization of the community, together with ecological indicators, demonstrates sensitivity to variations in salinity, organic matter, and metals, reinforcing the usefulness of benthic fauna as a tool for environmental assessment. Furthermore, by documenting dominant species typically associated with impacted environments, such as *Heteromastus* sp. and *Streblospio benedicti*, the study contributes to reducing the significant taxonomic and biogeographical gaps that persist in the Amazon region. Overall, these findings highlight the need for continuous monitoring that integrates ecological and physicochemical approaches, thereby supporting conservation strategies and coastal management in highly vulnerable estuarine ecosystems.

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Data Availability Statement

The entire data set supporting the results of this study was published in the article itself.

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