

**Benthic meiofauna response to mangrove oyster farming
(*Crassostrea gasar*) in an Amazonian estuary**
Resposta da meiofauna bentônica à criação de ostras-do-mangue
(*Crassostrea gasar*) em um estuário amazônico

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Abstract: Mariculture is expanding rapidly in northern Brazil, where oyster farming is a key economic activity. However, little is known about its effects on estuarine communities. This study assessed the influence of oyster farming (*Crassostrea gasar*) on the structure of the meiofauna community in the Curuçá Estuary (Pará, Amazon region). Sampling was conducted at two sites: an area beneath the oyster farming tables and a control area located 100 m away. Both areas had fine, well-sorted sediments, with higher organic matter content in the farming area. Twelve meiofauna groups were recorded, dominated by Nematoda and Oligochaeta. Density was lower in the cultivation area, while species richness did not differ between the sites. Gastropoda and Bivalvia were found beneath the cultivation tables, indicating enrichment. Multivariate analyses revealed differences in community structure associated with grain size and organic matter content. Overall, oyster cultivation induced moderate and limited changes, without exceeding ecological limits. The selective responses of meiofauna taxa highlight their potential as early indicators of aquaculture impacts in tropical estuaries and underscore the need for continuous environmental monitoring.

Keywords: Meiofauna. Bioindicator. Aquaculture. Amazon coast. *Crassostrea gasar*. Benthic ecology.

Resumo: A maricultura está expandindo rapidamente no Norte do Brasil, onde o cultivo de ostras representa uma atividade econômica essencial. No entanto, pouco se sabe sobre seus efeitos nas comunidades de estuários. Este estudo avaliou a influência do cultivo de ostras (*Crassostrea gasar*) sobre a estrutura da comunidade de meiofauna no estuário de Curuçá (Pará, Amazônia). As amostragens foram realizadas em dois locais: uma área sob as mesas de cultivo de ostras e uma área-controle, situada a 100 m de distância. Ambas as áreas apresentaram sedimentos finos e bem selecionados, com teor de matéria orgânica maior na área de cultivo. Foram registrados doze grupos de meiofauna, dominados por Nematoda e Oligochaeta. A densidade foi menor na área de cultivo, a riqueza não diferiu entre os locais. Gastropoda e Bivalvia ocorreram sob as mesas de cultivo, indicando enriquecimento. As análises multivariadas revelaram diferenças na estrutura da comunidade associadas ao tamanho dos grãos e ao teor de matéria orgânica. De modo geral, o cultivo de ostras induziu mudanças moderadas e restritas, sem ultrapassar limites ecológicos. As respostas seletivas dos táxons de meiofauna ressaltam seu potencial como indicadores precoces dos impactos da aquicultura em estuários tropicais e destacam a necessidade de monitoramento ambiental contínuo.

Palavras-chave: Meiofauna. Bioindicador. Aquicultura. Costa amazônica. *Crassostrea gasar*. Ecologia bentônica.

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INTRODUCTION

Mangrove ecosystems constitute highly productive and dynamic transitional environments that connect terrestrial and marine systems in tropical and subtropical regions (Alongi, 2020). Although they occupy less than 1% of global coastal areas (Bunting et al., 2022), these forests rank among the planet's most efficient natural systems in terms of primary productivity and ecological functioning (Bouillon et al., 2008; Pinheiro et al., 2025). Brazil holds the second-largest mangrove area in the world, covering roughly 11,400 km², with more than two-thirds situated along the Amazonian coast (Bunting et al., 2022). The Amazonian mangroves are notable for their extensive and mature forests, which hold ecosystem carbon stocks two to ten times higher than those of adjacent upland forests (Kauffman et al., 2018). Mangroves deliver a wide range of essential ecosystem services (Tasneem & Ahsan, 2024) that sustain the livelihoods of countless traditional coastal populations who depend on these habitats for subsistence (Manesch, 1993, 1995; Fernandes et al., 2018; Owuor et al., 2024; Otieno et al., 2026).

Despite their critical importance, mangroves are globally recognized as one of the most threatened ecosystems, due to rapid coastal development and continuous population growth (Goldberg et al., 2020). Among the main drivers of mangrove degradation is aquaculture, which, over the past century, has profoundly altered the structure and functioning of coastal ecosystems by modifying nutrient fluxes and food webs (Price et al., 2015; Ferriss et al., 2016; Van der Linden et al., 2016; Lacoste et al., 2020). Bivalve cultivation, a key component of marine aquaculture, is often considered to have a lower environmental impact compared to finfish or shrimp farming, as it typically requires no external feed inputs (Dumbauld et al., 2009; Cranford et al., 2012). However, intensive farming can act as a localized stressor.

Cultured bivalves can also enhance ecosystem complexity by providing substrates for settlement of other species (Tallman & Forrester, 2007), generating novel energy

pathways (Kluger et al., 2017), and supporting meiofaunal communities through biodeposition (Huang et al., 2018). In addition, the accumulation of organic wastes, in estuarine sediments promotes organic enrichment, which can lead to reduced interstitial dissolved oxygen, eutrophication, and negative impacts on local benthic fauna (Diaz & Rosenberg, 2008). Understanding the complex interactions between aquaculture practices and mangrove ecosystems is therefore essential for promoting sustainable production and effective coastal management (Figueira et al., 2016).

Benthic fauna, particularly meiofauna, are widely used as bioindicators to assess environmental stress due to their ecological roles and sensitivity to pollutants. Benthic meiofauna (the assemblage of microscopic organisms inhabiting the sediment interstices) is widely employed to diagnose environmental stress due to their strong dependence on the sedimentary environment and its central role in nutrient cycling and energy transfer (Coull & Chandler, 1992; Giere, 2009). Meiofauna is particularly suitable for monitoring because of its high diversity, widespread distribution, and rapid, localized response to anthropogenic disturbances (Giere, 2009; Schratzberger & Ingels, 2018; T. M. T. Santos et al., 2025a).

In Brazil, oyster farming (ostreiculture) has expanded since the 1970s (Valenti et al., 2021), and in Pará State, production focuses on the cultivation of the native oyster species, *Crassostrea gasar* (Adanson, 1757), using fixed-table and long-line systems in intertidal areas characterized by a macrotidal regime (Hoshino, 2009; Lopes et al., 2013). This species naturally forms dense beds on rocky or muddy substrates along riverbeds (Nascimento, 1991; Rios, 1994). In mangrove environments, oysters represent an important fishery resource for coastal communities (Galvão et al., 2012) and the key municipalities involved in oyster cultivation in the Pará state include Augusto Corrêa, Curuçá, Maracanã, Salinópolis, and São Caetano de Odivelas (Hoshino, 2009).

In the northern region of Brazil, oyster farming systems are predominantly fixed-table types installed in macrotidal mangrove areas, which are daily subjected to

tidal emersion and submersion. When cultivated, they often exhibit faster growth rates than in natural environments due to seed selection and management practices (Pereira et al., 2003). In this context, *C. gasar* has been successfully farmed in the Amazon region (Lopes et al., 2013), and well-regulated oyster farming can help mitigate the environmental pressure caused by extractive harvesting on natural populations (Gardunho et al., 2012). Therefore, by understanding the interactions among oyster farming practices, benthic communities, and mangrove ecosystem functioning, sustainable management strategies can be developed to balance production with conservation of these highly valuable coastal habitats.

While the cultivation of *C. gasar* provides an important income source for communities and helps mitigate pressure on natural populations (Gardunho et al., 2012), information on its specific environmental impacts in the Amazonian region remains scarce. Given the imminent expansion of ostreiculture along the Pará coast, this study aimed to identify and assess the effects of the cultivation of mangrove oysters (*C. gasar*) in the meiofauna community in the Curuçá estuary. The following hypothesis was tested: Oyster farming of *C. gasar* in alters the composition and abundance of meiofaunal communities, such that cultivated areas exhibit significant differences in density, species richness, and diversity compared to non-cultivated areas.

MATERIAL AND METHODS

STUDY AREA

This study was carried out in Curuçá city (00° 43' 48" S, 47° 51' 06" W) located on the Northern Amazon coast of Brazil (Figure 1). It is a humid equatorial region (Amazon Rainforest equatorial climate-type Am), characterized by high temperatures (27 °C annual average), low thermal amplitude, and high precipitation of over 2,000 mm per year (Martorano et al., 1993). Curuçá city has over 40,000 residents and its economy is based on fishing, agriculture, and tourism in mangroves (IBGE, 2018). Salinity varies

from < 7 ‰ during rainy season to > 22 ‰ in the dry season (Pará, 2005).

The city is within a coastal extractive reserve (Lauro Sodré Community), which holds one of the largest protected areas on the Amazon coast with rich mangrove ecosystems so there is good representation for other reserves in the country. The reserve has nearly 60 traditional community settlements with approximately 3,000 families living on estuarine islands, tidal creeks, rivers, beaches, and mangroves (Figueiredo et al., 2009). The Curuçá estuary is formed by the confluence of the Curuçá and Muriá rivers (Paula et al., 2006).

FIELD PROCEDURES

Sampling was carried out in April 2019 within a cultivation area of *Crassostrea gasar* in the São João da Ponta village (00° 50' 59" S, 47° 55' 12" W). Two distinct areas were selected for sample collection: (I) the cultivation area, located directly beneath the oyster tables, and (II) the control area, positioned approximately 100 m away from the cultivation area. In each area, ten biological samples were collected using a 3 cm diameter corer inserted to a depth of 10 cm into the sediment (Figure 1C). Immediately after sampling, the material was fixed in 4% formaldehyde. Additionally, sediment samples were taken from each site for the analysis of grain size and organic matter content. Samples intended for organic matter determination were kept refrigerated during fieldwork and subsequently frozen in the laboratory until further processing. Seawater salinity was also determined in the water column with a manual refractometer.

LABORATORY PROCEDURES

Meiofauna was extracted from the sediment using colloidal silica at a specific density of 1.18 g/cm³ (Somerfield et al., 2005). The supernatant was washed through 0.3 and 0.045 mm meshes, and the organisms retained in the 0.045 mm mesh were placed on Dollfus plates and identified to the major taxonomic groups (phylum, class, or order, depending on the group) following Giere (2009) and Danovaro (2010).

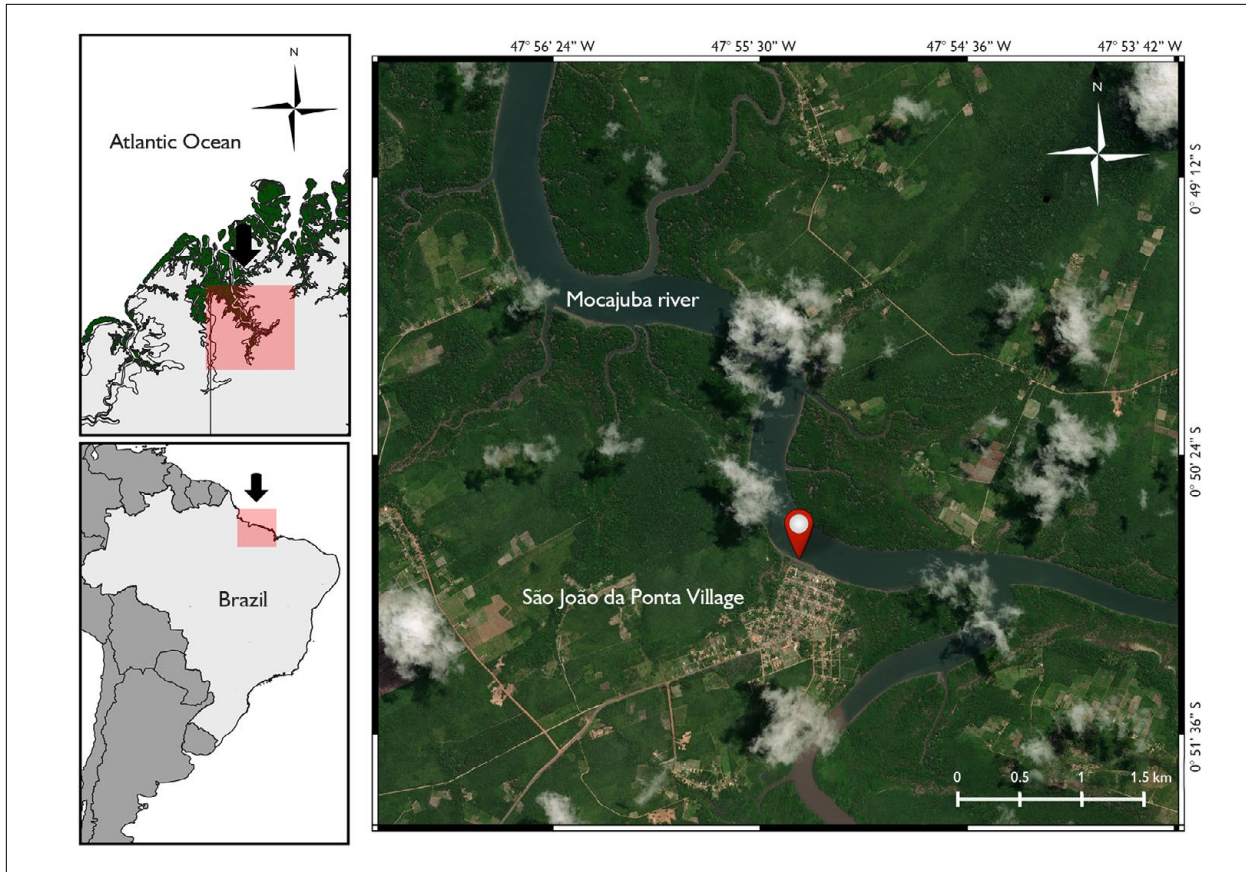


Figure 1. Map of the study area showing the location of the study areas. Map: Thuareag Monteiro Trindade dos Santos (2025).

The granulometric analysis was conducted by sieving out coarse sediments and pipetting fine sediments, as proposed by Suguio (1973). Textural parameters (mean grain size, sorting, % sand, and gravel) were calculated using the equations of Folk and Ward (1957). Grain sizes were determined by sieving the sediment in an automatic shaker and classifying the grains according to the Wentworth scale (Buchanan, 1984). Water content was determined as the percentage of mass loss after drying the sediment samples at 60 °C until constant weight and calculated according to the formula: water content (%) = $[(\text{wet mass} - \text{dry mass})/\text{wet mass}] \times 100$. Organic matter content was determined by loss on ignition (Dean, 1974). Sediment samples were dried at 60 °C until constant weight to obtain dry mass and then combusted at 550 °C for 4 h.

Organic matter was calculated as the percentage of mass loss relative to the initial dry mass, using the formula: %LOI = $[(\text{dry mass} - \text{ash mass})/\text{dry mass}] \times 100$.

STATISTICAL ANALYSIS

Meiofauna density (ind./10 cm²) and major taxonomic group richness were calculated for each biological sample; density was standardized to the corer surface area (10 cm²), and all samples were analyzed considering the entire sediment column (0–10 cm). Differences between study areas (*Crassostrea gasar* tables × control area) were tested using one-way analysis of variance (ANOVA) after verifying normality and homogeneity of variances with the Kolmogorov–Smirnov and Levene tests, respectively. When necessary, data were fourth-root transformed.

A Principal Coordinates Analysis (PCO) was run on a Bray-Curtis similarity matrix of the fourth root-transformed species to visualize the similarity between samples across areas. To identify the species that characterized each area, species that correlated (Spearman's coefficient) more than 60% with one of the first two axes were plotted in each PCO. Simultaneously, the same density matrices used for the PCO were analyzed using a one-way permutational ANOVA (PERMANOVA) designed using the same layout as the ANOVA. The contribution of each taxon to the dissimilarity found among the groups was assessed using the SIMPER (similarity percentage) routine.

For linking the meiofauna community biological descriptors with the sediment variables, a distance-based linear model (DistLM; Anderson, 2001) was performed. This technique analyzes and models the relationship between a multivariate data cloud, as described by a resemblance matrix and predictor variables. Resemblance matrices were calculated using Euclidean distance ($\log_{(x+1)}$ transformed data). The best models in DistLM were chosen using a forward routine with 9999 permutations based on AIC selection criteria (Anderson et al., 2008). A 5% significance level was considered in all analyses.

RESULTS

ENVIRONMENTAL VARIABLES

In the study area, seawater salinity was 11 ± 2 ‰. Overall, sediment temperature presented higher values in the control area in comparison with the *Crassostrea gasar* table (Table 1). The sediment H₂O content presented higher values in the Control area (Table 1). Organic matter (OM) did not varied between areas ($F_{(1,8)} = 7.03$, $p > 0.05$), however higher value was found in the *Crassostrea gasar* table (Table 1). The sediments were mostly very-well sorted muddy (silt + clay) however, some differences were found between the areas. In the *C. gasar* table the sediment varied from well-sorted coarse

silt to moderated-sorted medium sand, with presence of gravel, while in the Control area, the sediment was predominantly muddy (Table 1).

MEIOFAUNA COMMUNITY

Overall, ANOVA showed significant differences in density between areas ($F_{(1,18)} = 8.41$; $p < 0.01$), with higher values found at Control area (38.65 ± 29.16 ind/10 cm²) than in the *Crassostrea gasar* table (32.04 ± 22.05 ind/10cm²) (Figure 2A). On the other hand, richness did not varied significantly between areas ($F_{(1,18)} = 3.21$; $p > 0.05$), however, higher values were found in the control area (Figure 2B).

Meiofauna was comprised of 12 major groups and composition was similar in the study areas, however gastropods and bivalves were exclusively found at *C. gasar* table area (Table 2). Overall, Nematoda (77.5%) and Oligochaeta (15.8%) were the dominant groups; however, their contribution varied among areas. In the *C. gasar* table area, Nematoda (74.6%) and Oligochaeta (19.5%) were the dominant groups, in addition, the contribution of other major groups were higher. In the Area 2, a decrease in

Table 1. Mean values (\pm SD) of the sediment variables in the study areas.

Variable	Study areas	
	<i>Crassostrea gasar</i> table	Control area
Temperature (°C)	28.13 \pm 0.32	29.53 \pm 0.50
Organic matter (%)	5.08 \pm 1.44	4.67 \pm 1.02
H ₂ O content (%)	49.81 \pm 1.07	47.25 \pm 1.21
Mean grain size (Φ)	3.85 \pm 0.24	4.61 \pm 0.31
Sorting (Φ)	0.89 \pm 0.84	0.48 \pm 0.28
% Gravel	0.37 \pm 0.64	0
% Sand	27.29 \pm 21.06	0.99 \pm 0.32
% Mud (Silt + Clay)	72.34 \pm 21.4	99.01 \pm 0.24
Grain size classification	Coarse silt	Coarse silt
Sorting classification	Well sorted to Moderate sorted	Very-well sorted



the Oligochaeta (12%) contribution, with a proportional increase in Nematoda (80.2%) and of other major groups occurred dominance (Figure 3C).

The structure of the meiofauna community varied significantly between areas ($pseudo-F_{(1,18)} = 8.15$; $p_{(perm)} = 0.001$; $p_{(Monte Carlo)} = 0.001$), and the spatial configuration distinguished the meiofauna samples between the two study areas (Figure 3). Regarding major groups,

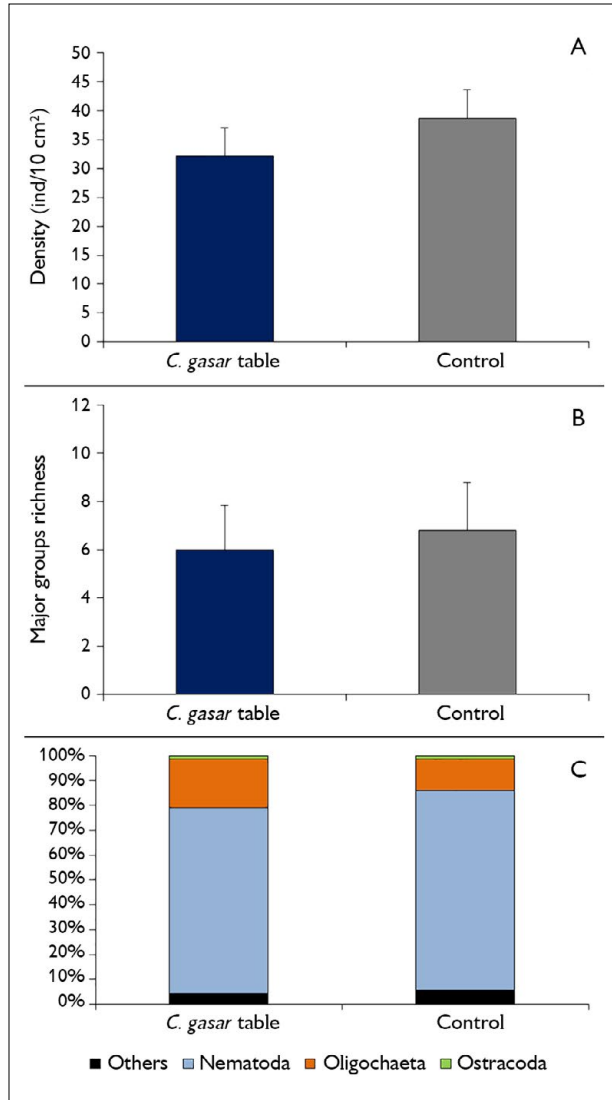


Figure 2. Mean density (\pm SE) (A), mean major groups richness (\pm SE) (B), and relative abundance (%) (C) of the meiobenthic major groups of the study areas.

Table 2. Mean density (\pm SE) of the meiofauna major groups found in the study areas.

Major groups	<i>Crassostrea gasar</i> table	Control area
Nematoda	28.7 \pm 2.9	34.1 \pm 4.65
Ostracoda	0.5 \pm 0.3	0.6 \pm 0.2
Oligochaeta	7.5 \pm 1.4	5.36 \pm 1.34
Acari	0.1 \pm 0.07	0.14 \pm 0.05
Kinorhyncha	0	0.35 \pm 0.06
Copepoda	0.3 \pm 0.1	0.53 \pm 0.16
Simpunculla	0.5 \pm 0.2	0.48 \pm 0.21
Tubertlaria	0.14 \pm 0.07	0.22 \pm 0.07
Gastthropoda	0.16 \pm 0.06	0
Bivalve	0.22 \pm 0.08	0
Polychaeta	0.05 \pm 0.05	0.63 \pm 0.14
Gastrothicha	0	0.02 \pm 0.01
Peracarida	0.02 \pm 0.01	0.05 \pm 0.01

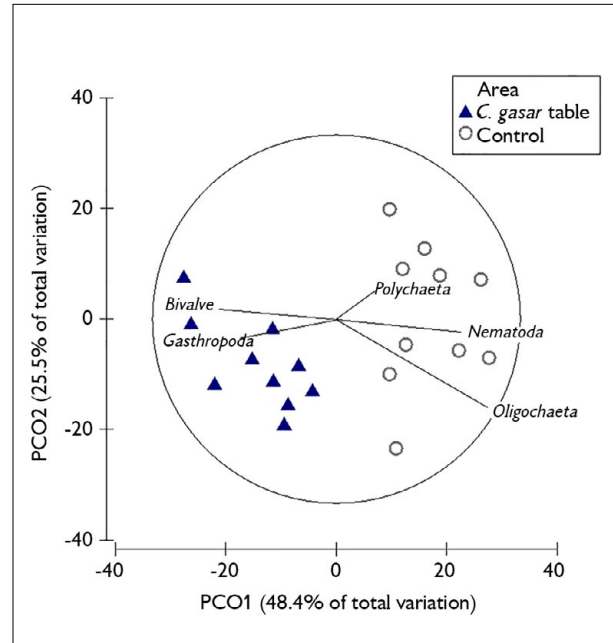


Figure 3. Principal Coordinates Analysis (PCO) of the samples of the meiobenthic major groups considering the taxonomic composition. The vectors represent species/groups correlating more than 60% (based on Spearman correlation coefficients) with one of the first two PCO axes.

axis 1 explained 48.4% of the variation in the data and was responsible for separating the two areas. The major groups most correlated with *C. gasar* tables samples were Gastropoda and Bivalve, whereas Nematoda, Oligochaeta and Polychaeta were most correlated with Control area. The SIMPER analysis indicated a mean dissimilarity of more than 80% between the study areas (Table 3). Comparing areas, most of the species indicated by SIMPER were more abundant in *C. gasar* tables, in particular Gastropoda and Bivalve (Table 3).

The best distance-based linear model (DistLM) explained 45% for density and 56% for richness variation of meiofauna community in the study areas. Sediment grain size, organic matter and % sandy were the principal environmental variables correlated with both descriptors, while H₂O content and % muddy were related principally with density and richness, respectively (Table 4).

DISCUSSION

Overall, the granulometric composition on both areas was characterized by predominantly muddy sediments (silt + clay). This sediment composition is typical of low-energy Amazonian estuaries (Silva et al., 2011; Mendes, 2023; Braga

et al., 2024; T. M. T. Santos et al., 2024, 2025b, 2026; Rocha et al., 2026) where fine fractions enhance organic matter retention and provide a food-rich microhabitat for benthic fauna (Giere, 2009). In contrast, the occurrence of coarser and poorly sorted particles in the *C. gasar* table indicates local hydrodynamic influence associated with the oyster-table structures and the deposition of fragmented shells. Fixed installations can modify near-bottom flow, generating micro-zones of turbulence, erosion, and selective deposition (Heery et al., 2017; T. M. T. Santos & Aviz, 2020). Similar patterns were reported by Chamberlain et al. (2001), who observed increased sand and gravel fractions beneath *Mytilus edulis* long-lines, and by Mendes (2023) in the Muriá Channel (Curuçá, Pará), where intermittent currents and microtopographic variations promoted heterogeneous accumulation of fine and coarse sediments around fixed structures.

Organic matter content was slightly higher in the *C. gasar* table, although the difference was not statistically significant. This pattern agrees with previous studies showing that the accumulation of bivalve biodeposits is the main source of organic enrichment beneath aquaculture structures (Dahlbäck & Gunnarsson, 1981; Chamberlain et al., 2001; Nizzoli et al., 2006; Zhao et al., 2022). Oyster biodeposits have high settling velocities

Table 3. Average dissimilarities between the samples from *Crassostrea gasar* table and control area, with the contribution from taxonomical groups.

Average dissimilarity = 82.64			
Major groups	Average dissimilarity	Dissimilarity/Standard deviation	Contribution %
Gastropoda	6.32	1.46	23.72
Bivalve	3.94	0.7	22.8
Oligochaeta	3.01	1.11	11.29
Nematoda	2.68	0.95	10.06

Table 4. Best distance-based linear models (DistLM) fitted for meiobenthic community descriptors against sediment variables in the study areas. Values in brackets: proportion of variability explained by each variable; * = significant differences ($p < 0.05$).

Descriptors	AIC	R ²	Variable included	p
Density	25.7	0.86	Grain size (15%), organic matter (12%), H ₂ O content (10%), % sand (8%)	< 0.05* (all)
Richness	19.4	0.81	Grain size (22%), organic matter (17%), % sand (10%), % muddy (7%)	< 0.05* (all)



and tend to accumulate directly beneath culture tables, locally increasing particulate organic carbon and altering decomposition dynamics (Callier et al., 2006). However, the magnitude of this accumulation depends strongly on hydrodynamic conditions. In macrotidal environments such as the Amazon coast, strong currents and tidal flushing disperse fine particles, mitigating excessive organic buildup (Sutherland et al., 2018). Therefore, the moderate increase in OM observed in the Curuçá estuary likely reflects a balance between organic input and dispersive forces, a condition typical of high-energy estuarine systems where hydrodynamics prevent anoxia but do not entirely remove deposited material (Souza-Filho et al., 2009; Asp et al., 2013).

The community descriptors (density and richness) differed between conditions, with lower density and richness at *C. gasar* table, as expected from previous studies (Mirto et al., 2000; Christensen et al., 2003; Callier et al., 2008). Overall, in organically enriched areas, meiofaunal density generally tends to decrease due to oxygen depletion and sediment compaction (La Rosa et al., 2001). In the Curuçá estuary, this pattern was consistent with those observations, as lower densities were recorded in the *C. gasar* table area, while higher values occurred in the Control area.

Overall, the composition of the meiofauna on the study areas was similar. Furthermore, the taxonomic composition of these areas was similar to that of other soft bottom habitats on the Amazon coast (Paula et al., 2006; Gomes & Rosa Filho, 2009; Rosa Filho et al., 2011; Baia & Venekey, 2019; T. M. T. Santos et al., 2021, 2025a; Baia et al., 2021; T. B. Santos et al., 2023; Melo et al., 2024; Ferreira-Ramos et al., 2026; T. M. T. Santos & Aviz, 2026), as well as other estuarine areas worldwide, with Nematoda as the dominant group (see Giere, 2009 for review). This dominance of nematodes is associated with three main factors: i) their body shape (long, thin, and fusiform), which facilitates burrowing activities; ii) their high tolerance to environmental stress; and iii) their diversity of feeding habits, allowing them to utilize all

available food resources (Bouwman, 1983; Giere, 2009; T. M. T. Santos & Venekey, 2017). In addition, Nematodes are known bioindicators of anthropic impact (T. M. T. Santos et al., 2021, 2025a) and are highly tolerant to environmental variations, often dominating areas with organic enrichment (Schratzberger & Ingels, 2018).

Species richness is generally expected to decline in impacted areas, leading to increased dominance by opportunistic taxa (Clarke & Warwick, 2001), while more sensitive species decrease (Pearce et al., 1981). In this study, the high abundance of *Oligochaeta* beneath *C. gasar* tables indicates that oyster bio-deposition strongly shapes the benthic environment. It is well known that *Oligochaeta* is favored under organically enriched conditions (Pearson & Rosenberg, 1978; Giere, 2009). This bio-stimulatory effect is reinforced by the exclusive presence of *Gastropoda* and *Bivalvia* in the farming area, likely benefiting from increased detrital food and calcareous particles from shell fragments (Dahlbäck & Gunnarsson, 1981; Zhao et al., 2022). In contrast, the absence or reduction of the sensitive *Gastrotricha* highlights its susceptibility to micro-environmental changes such as sediment compaction and oxygen fluctuations (Kieneke & Schmidt-Rhaesa, 2015). The low abundance of *Copepoda* is consistent with the low-salinity conditions of the inner estuarine zone, where freshwater-associated copepod taxa are commonly recorded (Boxshall & Defaye, 2008). These selective shifts in meiofaunal composition underscore their value as early-warning indicators of low-level environmental impacts (Paula et al., 2006).

In the study region, the oyster production system that covers both juvenile and growth phases until the market-size adults (Funo et al., 2019). Therefore, the presence of adults tends to be lower in comparison to other cultivation areas, since the adults are collected regularly. The organic enrichment due to the presence of juvenile oysters is likely low compared with that of adult oysters, but the continuous exploitation of the area for farming may have modified community characteristics

compared with outside areas (Lacoste et al., 2020). However, despite the reduction in the *C. gasar* table, the densities remained within the range reported for other unpolluted tropical estuaries (Vasconcelos et al., 2004), suggesting that the level of organic enrichment in Curuçá has not yet reached a critical threshold capable of causing severe ecological degradation (Paula et al., 2006).

Aquaculture has become the primary solution for meeting the continuously rising global demand for aquatic products, in light of plateauing wild-capture fisheries. A major milestone was recently reached: according to the FAO's SOFIA 2024 report (FAO, 2024), aquaculture surpassed capture fisheries in 2022, contributing 51% of the total global production of aquatic animals for human consumption. This rapid and sustained growth underscores the sector's crucial role in global food security. However, this expansion demands a strict commitment to sustainability, particularly given the intense competition for resources (land, water, energy) and the imperative to minimize environmental impact.

In vulnerable ecosystems, such as Amazonian estuaries where aquaculture is often nascent, assessing environmental impacts from the outset is essential for adaptive management. We recommend that impact assessments move beyond isolated physical and chemical analyses and integrate farming-related factors (e.g., establishment time, occupied area, and production yield) with biological indicators. In this context, the meiofauna community is proposed as a highly effective monitoring tool (Giere, 2009).

Among meiofaunal groups, Nematoda deserve particular emphasis, as they are typically the most abundant and taxonomically diverse group and often respond to environmental changes before shifts become evident at broader taxonomic levels (Bongers & Ferris, 1999). Analyses at finer taxonomic resolution (e.g., family or genus level) can therefore provide a more sensitive and precise assessment of mariculture impacts (Mirto et al., 2014).

CONCLUSION

In conclusion, the sediment and meiofaunal patterns observed in the Curuçá estuary indicate that oyster farming induces moderate, localized environmental changes without exceeding ecological thresholds. The selective responses of meiofaunal taxa, particularly the dominance of tolerant groups and the reduction of sensitive taxa, underscore their utility as sensitive bioindicators. Nematoda, the most abundant meiofaunal group, comprises a high diversity of species whose abundance and composition are strongly influenced by environmental conditions, reinforcing the potential of finer taxonomic resolution to improve impact detection. Ongoing and future analyses at the genus level will provide additional insights into community responses to oyster farming. These findings highlight the importance of continuous monitoring and adaptive management to ensure sustainable oyster cultivation while preserving benthic ecosystem integrity in tropical estuaries.

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AUTHORS' CONTRIBUTION

A. B. M. Ferreira-Ramos contributed to formal analysis, methodology, investigation and writing (original draft); E. F. S. de Souza contributed to formal analysis and investigation; J. T. Lee contributed to project administration, methodology and visualization; and T. M. T. dos Santos contributed to supervision, conceptualization, data curation, validation and writing (review and editing).