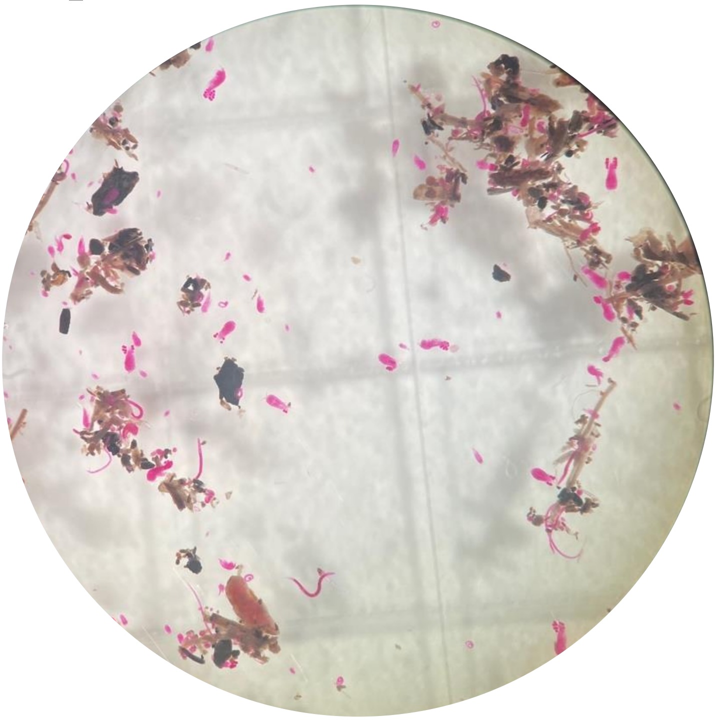
INSTITUTIONEN FÖR BIOLOGI OCH MILJÖVETENSKAP

THE IMPACT OF POLLUTION ON SEDIMENT MEIOFAUNA

Föroreningars inverkan på meiofauna i sediment



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Abstract

The decline of biodiversity due to anthropogenic pressures poses a significant threat to ecosystem stability and functionality. Pollution, such as eutrophication and contaminants, emerges as a critical factor disrupting the balance of particularly aquatic sediment habitats. Meiofauna, microscopic organisms inhabiting sediment, serve as valuable bioindicators due to their sensitivity to environmental changes. This study investigates the impact of sediment pollution on meiofaunal diversity and abundance in the Espírito Santo estuary, Maputo, Mozambique. By analyzing sediment samples from locations with varying levels of anthropogenic and natural contamination, the findings reveal that highly polluted areas exhibit reduced meiofaunal diversity and abundance. Dominance by opportunistic taxa, such as Nematoda, in polluted sites contrasts with the balanced communities observed in less impacted areas. These results underscore the potential of meiofaunal analysis as an effective tool for assessing ecosystem health and highlight the need for integrated strategies to mitigate contamination and preserve biodiversity in estuarine environments.

Abstrakt

Den biologiska mångfaldens nedgång till följd av antropogena påfrestningar utgör ett betydande hot mot ekosystemens stabilitet och funktionalitet. Föroreningar, såsom eutrofiering och föroreningar med olika kontaminanter, framstår som en kritisk faktor som stör balansen, särskilt i akvatiska sedimentära livsmiljöer. Meiofauna, mikroskopiska organismer som lever i sediment, fungerar som värdefulla bioindikatorer på grund av deras känslighet för miljöförändringar. Denna studie undersöker påverkan av sedimentföroreningar på meiofaunans mångfald och abundans i Espírito Santo-estuariet, Maputo, Moçambique. Genom att analysera sedimentprover från områden med varierande nivåer av antropogen och naturlig kontaminering visar resultaten att högt förorenade områden uppvisar minskad meiofaunal mångfald och abundans. Dominans av opportunistiska taxa, såsom Nematoda, i förorenade områden står i kontrast till de balanserade samhällena som observeras i mindre påverkade områden. Dessa resultat understryker potentialen för meiofaunala analyser som ett effektivt verktyg för att bedöma ekosystemhälsa och belyser behovet av integrerade strategier för att minska kontaminering och bevara biologisk mångfald i estuarina miljöer.

Glossary

Bioindicator – An organism or group of organisms used to monitor the health of an environment or ecosystem, often by indicating the presence of pollutants.

Bioturbation – The reworking of sediments by living organisms, which affects sediment properties and biogeochemical processes.

Bray-Curtis dissimilarity – A statistical measure used to compare differences in community composition between two ecological sites.

Chlorophyll-a (Chl-a) – A pigment used to measure the presence of phytoplankton or algae in sediment or water, serving as an indicator of primary productivity.

Density – Measured as individuals per square centimeter (ind./cm^2).

Dominant taxa – Species or groups that are most prevalent in an ecosystem and have significant influence on its structure.

Eutrophication – The process by which a water body becomes overly enriched with nutrients, leading to excessive growth of algae and depletion of oxygen, which can harm aquatic organisms.

Evenness – A measure of how evenly individuals are distributed among species in an ecosystem.

Meiofauna – Refers to a classification of organism within the size range of 63 – 1,000 µm. In this study, the focus is on benthic meiofauna, also known as meiobenthos (Giere, 2009).

Non-metric Multidimensional Scaling (nMDS) – A statistical technique used to visualize differences in community structure based on ecological data, such as species composition.

Opportunistic species – Species that rapidly colonize and able to dominate environments under high stress, such as polluted areas.

Organic matter (OM) – Decomposed material of biological origin present in sediments, influencing nutrient cycling and meiofaunal communities.

Practical Salinity Units (PSU) – A unit for measuring the salinity of water, based on its electrical conductivity.

Richness – The number of species present in a specific area or sample.

Sediment granulometry – The distribution of particle sizes in sediments, which influences habitat characteristics and the sediment's capacity to retain pollutants.

Shannon-Weaver index – A biodiversity measure that combines species richness and the evenness of their distribution.

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Acknowledgments

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CONTENT

1. INTRODUCTION

Human activities have driven the Earth beyond six of nine planetary boundaries, compromising the safe operating space necessary for long-term human survival and planetary stability (Richardson et al., 2023). Among the most pressing consequences of these transgressions is the loss of biodiversity, a key component of ecosystem functionality and stability (Barnosky et al., 2011). Biological diversity encompasses the variation among living organisms from all sources, including within species, between species, and across ecosystems (CBD, 1992). This diversity underpins ecosystem resilience, yet it faces accelerating threats from species extinctions driven by human activities and global changes (Barnosky et al., 2011). Species loss disrupts the delicate balance between extinction and speciation, amplifying the risk of ecosystem collapse under stress (Barnosky et al., 2011).

Water pollution is the degradation of water quality due to physical, biological, or chemical changes that harm living organisms or make the water unsuitable for use (Cunningham, 2020). Recognized as one of the five main global threats to biodiversity, pollution is significantly altering ecosystem structure, stability, and the services they provide (Backhaus et al., 2012). Eutrophication, a major consequence of water pollution from excess nutrients like nitrogen and phosphorus, causes algal blooms and oxygen depletion (Kennish, 2002; Breitbug, 2002). Chemical pollutants, particularly from diffuse sources, pose long-term challenges to organisms and ecosystems, making accurate risk assessments complex. To address these challenges, it is critical to integrate chemical and biological analyses to understand ecosystem changes and improve regulatory frameworks for sustainable chemical management (Backhaus et al., 2012). While pollution can occur naturally, this study focuses on human-caused factors impacting water quality.

Given the documented presence of pollutants in local water and fauna around Maputo Bay, this research focuses on the pollution of sediments, which serve as long-term repositories for pollutants and reveal historical exposure as well as trends over time (Balsamo et al., 2014). This study will analyze meiofauna diversity within sediment samples from sites with varying pollution levels, integrating chemical and biological sediment analyses to assess their combined impact on ecosystem health and functionality. By quantifying different meiofauna groups and correlating their presence with pollutant levels, the aims is to identify critical threats to biodiversity in the Espírito Santo estuary, Maputo, Mozambique.

2. BACKGROUND

2.1 What is meiofauna?

The term "meiofauna," was introduced by the marine biologist Molly F. Mare in 1942 to define a group of benthic metazoans characterized by their intermediate size between microfauna and macrofauna, typically ranging from 63 to 1,000 µm (Giere, 2009). These organisms may either spend their entire life cycle within the meiofaunal size range (permanent meiofauna) or occupy this size class temporarily as juveniles (temporary meiofauna), making the classification remarkably diverse, encompassing 24 of the 35 recognized animal phyla (Giere, 2009; Zeppilli et al., 2015).

2.2 The Ecological Importance of Meiofauna in Sediment Processes

Found in and on soft sediments as well as hard surfaces in both marine and freshwater environments, meiofaunal communities form complex and integral networks within the surrounding biological environment, underscoring their critical role in maintaining ecosystem function and stability (Giere, 2009; Zeppilli et al., 2015). As meiofauna accumulate and redistribute contaminants, contribute to the breakdown of organic material, and facilitate energy flow within the ecosystem, they influence microbial degradation processes and overall ecosystem function (Schratzberger & Ingels, 2018; Mohammad et al., 2024). Acting as intermediaries between microbiota—such as bacteria and microalgae—and higher trophic levels, meiofauna support energy transfer within benthic ecosystems. For example, copepods function as grazers, predators, and prey, shaping trophic interactions and organic matter cycling through bidirectional control, while other groups, such as turbellarians, act as specialized predators feeding on meiofaunal organisms (Coull, 1999; Giere, 2009; Schratzberger & Ingels, 2018).

The activity and distribution of meiofauna are strongly influenced by the physical and chemical properties of sediments (Schratzberger & Ingels, 2018). In muddy sediments, meiofauna are typically restricted to the upper layer, 2–3 cm, (Coull, 1999) whereas coarse-grained sediments provide larger interstitial spaces, improving gas and water exchange, making it possible to inhabit deeper sediment layers and host a higher abundance (Mohammad et al., 2024).

Meiofaunal mobility reshapes sediment structure, creating a dynamic feedback loop where alterations in sediment layers influence meiofaunal community composition. Their bioturbation also contributes to changes in sediment porosity and oxygen flow, mobilizing sediment-bound pollutants and enhancing their bioavailability for microbial degradation (Schratzberger & Ingels, 2018).

These roles within the ecosystem underscore the critical importance of meiofaunal resilience in stabilizing key processes and maintaining functionality, even under stressful and unfavorable conditions. (Schratzberger & Ingels, 2018).

2.3 Pollution Impacts and Meiofaunal Indicators

Sediments are considered a relatively stable medium due to limited fluctuations in factors such as pH and salinity compared to water. However, different habitats are better suited to specific taxa, and it is essential to account for both natural and anthropogenic pollution when analyzing meiofaunal communities. Meiofauna’s close association with sediments and their limited mobility enable them to accurately reflect localized environmental conditions (Giere, 2009). Additionally, taxonomic classification provides deeper insights into ecological patterns and stress factors, further supporting their utility in environmental monitoring (Chertoprud & Novichkova, 2023; Rao et al., 2023).

Meiofauna are characterized by short life cycles ranging from 3 days up to a year, making them highly sensitive to environmental changes. Factors such as temperature, salinity, and pollution can rapidly impact their populations and community structures. At the same time, their high reproductive capacity and dietary flexibility enable them to adapt quickly to disturbances and habitat changes (Schratzberger & Ingels, 2018; Zeppilli et al., 2015). A comprehensive understanding of meiofaunal survival strategies enhances their effective application as bioindicators.

Meiofaunal communities, characterized by their small size and rapid generational turnover, exhibit lower structural complexity than macrofauna (Zeppilli et al., 2015). Despite this simplicity, their ability to persist in environments inhospitable to larger organisms highlights their value as bioindicators in disturbed ecosystems (Schratzberger & Ingels, 2018). Furthermore, their limited mobility and sensitivity to physical and chemical variations make them particularly effective for assessing localized habitat conditions (Zeppilli et al., 2015).

Persistent pollutants, such as heavy metals, accumulate in muddy sediments and exert prolonged environmental stress, particularly in estuarine areas (Coull, 1999; Rao et al., 2023). These contaminants significantly alter meiofaunal communities by reducing taxa richness and evenness. Nematodes, for instance, bioaccumulate heavy metals and organic pollutants, which isolates contaminants within sedimentary matrices but also induces physiological stress, potentially impacting their survival and functionality (Schratzberger & Ingels, 2018).

Reduced oxygen levels, exacerbated by high organic enrichment, significantly reduce populations of predatory and omnivorous nematodes, disrupting trophic interactions and altering community stability (Mohammad et al., 2024; Sautya et al., 2025). Simultaneously, high organic enrichment shifts community composition favoring opportunistic species, such as deposit-feeding nematodes and platyhelminthes, which thrive in nutrient-rich or extreme habitats (Mohammad et al., 2024; Giere, 2009). Similarly, low oxygen concentrations lead to a reduction in copepod densities, further highlighting the vulnerability of meiofauna to environmental stressors (De Troch et al., 2013).

2.3.1 Overview of Bioindicator Taxa

Certain meiofauna taxa, such as Nematodes, Copepods, and Ostracods, are commonly acknowledge for their effectiveness as bioindicators due to their district ecological role. Their biological characteristics, including life cycles and reproductive strategies, also contribute to their ability to respond to environmental stressors (Schratzberger & Ingels, 2018; Zeppilli et al,, 2015; Waweru et al., 2024).

Nematodes, characterized by their high abundance ecological diversity, and ability to bioaccumulate contaminants, are often used to assess pollution impacts, especially in sediments with high organic enrichment or heavy metal contamination (Giere, 2009; Schratzberger & Ingels, 2018). Copepods, on the other hand, are sensitive to environmental changes such as salinity fluctuations and pollution, making them valuable indicators of localized habitat degradation (De Troch et al., 2013). Ostracods, with their calcified shells, proved unique insights into long-term environmental changes, such as sedimentation rates and shifts in water chemistry. As highlighted by McCormack et al. (2019), their role in reconstructing salinity variations in lake environments provides critical insights into past environmental conditions.

Waweru et al. (2024) emphasized meiofauna's sensitivity to both organic and inorganic pollutants, demonstrating their comprehensive role in reflecting ecosystem health. These taxa, through their physiological adaptations and ecological roles, provide critical information for effective environmental monitoring.

2.3.2 The Nematode/Copepod Index as a Tool

The Nematode/Copepod ratio (N/C index) offers a practical approach to quantifying these impacts. This ratio leverages the contrasting ecological responses of nematodes and copepods: nematodes, being resilient to environmental stressors such as organic pollution, often thrive in contaminated environments, while copepods, which are more sensitive to pollution, typically decline under similar conditions (Giere, 2009). By quantifying the balance between these two taxa, the N/C index complements traditional approaches like direct observations, indicator species analyses and habitat assessments. It provides a straightforward and rapid indication of organic load and environmental stress. (Giere, 2009; Raffaelli & Mason, 1981) This index has shown helpful in detecting pollution of mercury and petroleum hydrocarbons, with low N/C-ratios correlating with high contamination levels (Sautya et al., 2025).

2.3.3 Biodiversity Monitoring Approaches

Traditional biodiversity monitoring methods have long been pivotal in ecological research and conservation. Tools like the N/C index complement these methods by providing specific metrics to assess stress factors in ecosystems. These approaches enable detailed taxonomic identification and ecosystem health analysis, often employing statistical tools such as the Shannon-Wiener Index and Bray-Curtis dissimilarity to quantify biodiversity and compare ecological patterns over time and space (Beever, 2006; Zeppillin et al., 2015). However, these methods depend on specialized taxonomic expertise, leading to high costs and difficulties in analyzing cryptic species, remote habitats, as well as posing challenges for large-scale studies (Leasi et al., 2018; Chertoprud & Novichkova, 2023). Furthermore, a lack of standardization across studies can introduce biases and limit comparability (Zeppillin et al., 2015).

Despite these limitations, traditional approaches remain indispensable in biodiversity research. Methods like direct observations and taxonomic analyses offers robust baseline data, which indexed like the N/C index build upon to create a framework for analyzing large-scale trends and localized stressors (Zeppilli et al., 2015). For example, salinity gradients and organic carbon content were shown to significantly affect meiofaunal communities, underscoring the need for a holistic approach to ecological assessments (Sautya et al., 2025).

2.3.4 Integration into Environmental Management

Research on meiofauna offers significant potential for integration into environmental management and the restoration of benthic ecosystems, given their role as indicators of ecological health and sediment quality. By monitoring the impacts of human activities, meiofauna can provide critical data for restoration projects and contribute to evidence-based policies aimed at protecting estuarine habitats (Schratzberger & Ingels, 2018)

2.4 Area description

2.4.1 Hydrology and Biodiversity

The Espírito Santo estuary, with an area of 52.53 km², is a subtropical coastal ecosystem characterized by brackish waters resulting from freshwater inflows from the Tembe, Umbeluzi, Matola, and Infulene rivers, combined with tidal exchanges from Maputo Bay. It experiences a warm, rainy season and a cool, dry season, shaping its hydrodynamic and ecological features (Scarlet, 2015).

Tidal fluctuations significantly influence salt transport and groundwater flow in estuarine ecosystems, shaping their physical and chemical properties through interactions between tides, freshwater inputs, and human activities (Lenkopane et al., 2009). With shallow depths, rarely exceeding 5 meters, the estuary's waters are well-mixed by strong tidal action, preventing vertical stratification (Canhanga & Dias, 2005). Fine sediments, influenced by riverine processes and dredging, sustain benthic life but turbidity reduces light penetration, harming vegetation like seagrass and mangroves. Tidal ranges from 80 to 300 cm drive sediment transport, while dredging amplifies turbidity, disrupting habitats (Scarlet & Bandeira, 2014).

The estuary's unique salinity gradients foster biodiversity, supporting freshwater and marine species adapted to transitional conditions (Elliott & Whitefield, 2011). This biodiversity underpins ecosystem functions such as nutrient cycling and services like water purification and carbon storage (Backhaus et al., 2012).

2.4.2 Environmental Challenges in the Area

The rivers of the Maputo region—Infulene, Matola, Umbeluzi, Tembe, and Maputo—play a crucial role in biodiversity and local livelihoods but are severely affected by human impacts (Table 1, shows example on contaminations and its origins) (Nhantumbo et al., 2023; Scarlet & Bandeira, 2014). Nutrient runoff from untreated sewage and agriculture drives eutrophication, while heavy metals accumulate in sediment, degrading habitats and threating wildlife. Additionally, climate change and coastal development exacerbate habitat fragmentation and biodiversity loss (Mahoney & Bishop, 2017; Inteca et al., 2023).

Biomarkers such as "Scope for Growth" (SFG) reveal elevated stress levels in the estuary's organisms, with low SFG values indicating the detrimental impact of pollution (Scarlet et al., 2015). The release of untreated wastewater from rapidly urbanizing areas, including Maputo and Matola, further compounds these issues, intensifying water and sediment contamination and accelerating ecological decline (Scarlet & Bandeira, 2014).

The Infulene River provides essential support for agriculture in the Infulene Valley, supplying water for irrigation and contributing to local food production. However, the river is heavily impacted by untreated domestic wastewater, industrial effluents, and agricultural runoff, leading to severe microbial contamination and the presence of high pesticide levels, including malathion (Niquice-Janeiro et al., 2024; Scarlet, 2015; Nhantumbo et al., 2023).

The Umbeluzi River originates in Swaziland and provides irrigation and freshwater, particularly to sugar plantations, but pollution affects its delta's ecological functions (Scarlet, 2015; Scarlet & Bandeira, 2014). The Tembe River, originating in South Africa and known for its extensive mangroves, is crucial for sediment transport and coastal biodiversity (Scarlet, 2015; Ferreira & Bandeira, 2014). Finally, the estuarine habitats of the Maputo River, essential for aquatic species, are similarly degraded by pollutants, further straining the region's ecological resilience (Canhanga & Dias, 2014).

2.4.3 Historical Change in the Area

The Matola and Infulene rivers have shown consistent chemical and ecological deterioration over time. In 2015, the Infulene River showed moderate heavy metal contamination in sediments, while pesticide analysis revealed early signs of ecological stress, such as reduced acetylcholinesterase (AChE) activity in aquatic organisms (Scarlet, 2015; Sturve et al., 2016). By 2021, pesticide concentrations far exceeded safety thresholds, driven by agricultural runoff, untreated wastewater, and industrial effluents (Sturve et al., 2021).

Similarly, in 2015, Matola River's sediments contained elevated levels of cadmium, nickel, and copper from industrial discharges and urban runoff (Scarlet, 2015). By 2016, pesticide residues, including organophosphates, were detected, indicating anthropogenic impacts (Sturve et al., 2016). By 2021, both pesticide and heavy metal levels had increased further, exacerbated by ongoing industrial and urban development (Sturve et al., 2021).

TABLE 1 – AN OVERVIEW OF KNOWN POLLUTION TYPES AND THEIR SOURCES

Origin	Infulene	Matola	Umbeluzi	Tembe	Maputo	Contaminants
Agriculture	✓[1,2,5] *Irrigated agriculture*	✓[4,3]	✓[1,5] *Sugar plantations*	✓[3]	✓[1,5]	Pesticides, fertilizers, eutrophication
Aluminum industry		✓[2]				Heavy metals (Pb, Cd, Ni, Zn), accumulation in sediment
Brewery	✓[3]					Organic pollutants, nutrients, salt
Cement production		✓[3]			✓[7]	Heavy metals, organic pollutants
Harbor activity	✓[3]	✓[2,4]	✓[7]	✓[7]		Heavy metals, PAH
Heavy metals	✓[2,4,5]	✓[2,4,5]			✓[4,5]	Lead (Pb), cadmium (Cd) and zinc (Zn)
Paper industry	✓[1,3]					Organic pollutants, heavy metals
Pesticide	✓[4,5]	✓	✓[4,5]	✓[3,5]	✓[2,3,5]	Organophosphates, carbamates, herbicides, accumulation in sediments
Salt production	✓[3]	✓[6]	✓[6]			Untreated sewage with high salt content
Solid waste	✓[1,5]	✓[5]	✓[5]	✓[3]	✓[5]	From urban, suburban areas and marine litter
Treated sewage	✓[3,5]	✓[3,5]				Nutrients, microbial contamination (E. coli, total coliforms)
Untreated sewage	✓[1,3,4,5]	✓[1,5]	✓[1,2,3,5]	✓[3,5]	✓[3,5]	Nutrients, microbial contamination (E. coli, total coliforms), organic pollutants
Unspec. industrial runoff	✓	✓[1,2,4]	✓[4,5]	✓	✓	Heavy metals (Pb, Cd, Ni, Cu), bioaccumulation

[1]Nhantumbo et al., 2023; [2]Sturve et al., 2016; [3]Scarlet & Bandeira, 2014; [4]Sturve et al., 2021; [5]Mutatisse et al., 2022; [6]Nhabinde et al., 2014; [7]maps.google.com, accessed [2024-10-01]

3. AIM

The biodiversity and community structure of meiofauna serve as key indicators of ecosystem health. Anthropogenic contamination degrades critical habitats, reduces biodiversity, and poses significant risks to communities reliant on estuarine systems for fishing and agriculture (Nhantumbo et al., 2023; Scarlet & Bandeira, 2014). Addressing these challenges requires improved wastewater management, sustainable agricultural practices, stricter industrial regulations, and ecosystem restoration.

This pilot study investigates the impact of sediment pollution on meiofauna diversity in the Espírito Santo estuary, Maputo, Mozambique. Specifically, it aims to assess how varying pollution levels and environmental variables influence meiofauna communities by analyzing sediment samples from five locations with three replicates each. Given the documented presence of pollution in local waters and fauna, the study will focus on the accumulation of pollutants in sediments, which reflect long-term exposure and potential ecological risks. By integrating chemical and biological sediment analyses, the research seeks to identify threats to ecosystem health and provide insights into pollution trends over time. To address this, the following research question was posed:

How does the diversity of meiofauna in the sediments of estuaries in Maputo Bay vary in relation to levels and types of pollution?

4. MATERIALS AND METHODS

4.1 Study area and sampling

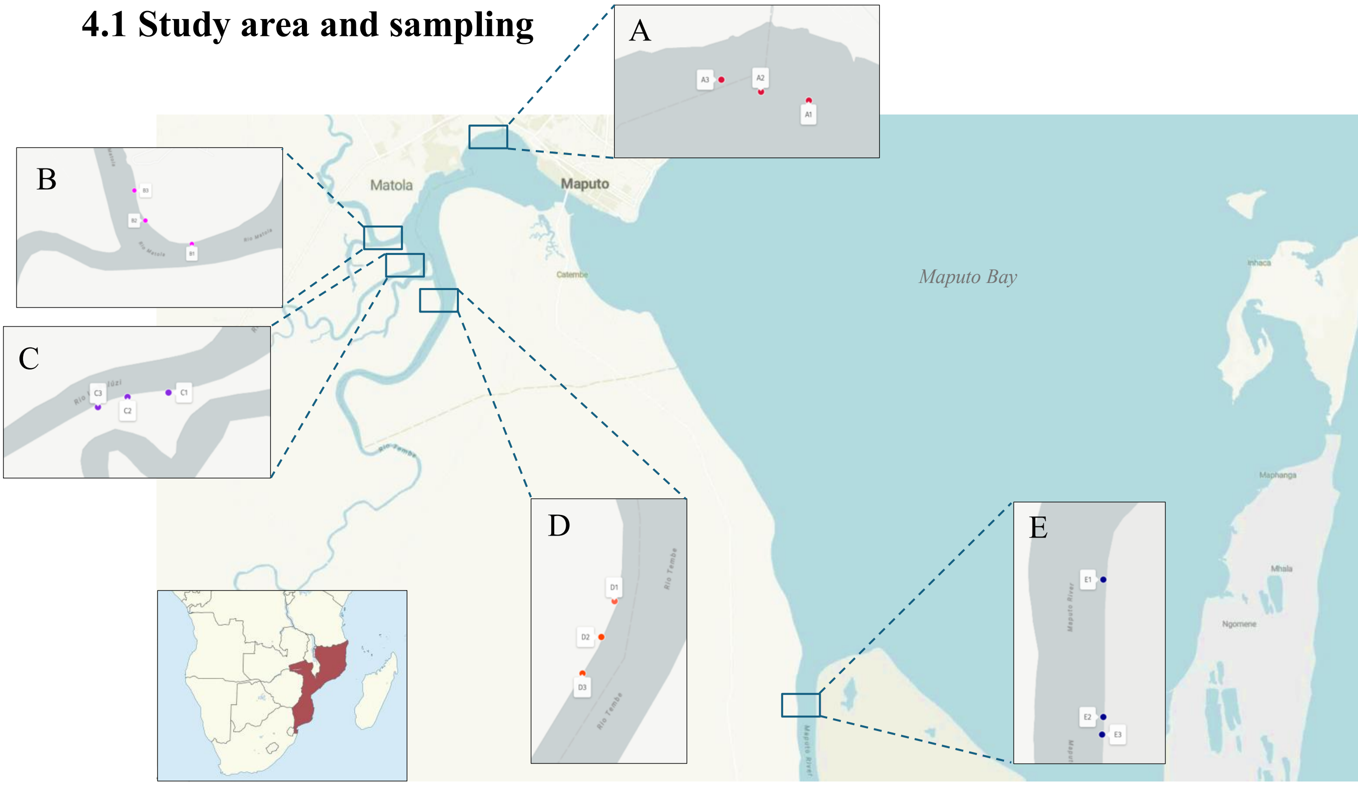


FIGURE 1 – POSITIONS OF SAMPLING LOCATIONS IN THE STUDY ESTUARIES.
Locations (A): Infulene River, Location (B): Matola River, Location (C): Umbeluzi River, Location (D): Tembe River and Location (E): Tembe River

This figure is adapted from "Mozambique in Africa (mini map, rivers)" by TUBS (2018), retrieved from Wikipedia (https://en.m.wikipedia.org/wiki/File:Mozambique_in_Africa_%28-mini_map_-rivers%29.svg). Map data © OpenStreetMap contributors under ODbL. Tiles courtesy of CartoDB. Licensed under CC-BY-SA 4.0

Sediment samples were collected from four locations in Espirito Santo estuary (A – D) and one from Maputo Bay (E), Mozambique (Fig. 1), on the morning of 26th September 2024. Each location included three replicates, spaced approximately 250–500 meters apart. Six sediment cores were pooled for each replicate to ensure adequate sampling volume. A 2-meter-long PVC tube with a diameter of 5 cm (same equipment use by de Abreu, et al., 2017) was used, yielding a sampling area of 19.63 cm^2.

The cores were divided into separate containers based on their intended analysis. For meiofauna analysis, three subsamples of 30 mL were taken from the upper 1.5–2 cm of the sediment. These samples were preserved in an ethanol-glycerol solution (95:5) containing Rose Bengal. This stain is widely used in biological research to selectively stain organic material, such as living or recently deceased cells, distinguish them from detritus or sediment particles. Its chemical composition enables interactions with proteins and other biological components, providing a distinct contrast that facilitates microscopic analysis. (Giere, 2009) The samples remained in this solution from the time of collection until the extraction process, stored in sealable plastic jars.

Two samples (approximately 100 g each) were collected for chemical analysis and stored in sealable glass jars, which had been pre-treated at 550°C for 8 hours for disinfection. The last sediment core was divided into three segments for analysis: chlorophyll (approximately 5 g from the upper layer), organic material (approximately 50 g), and grain size analysis (approximately 50 g). Each segment was then placed in three separate marked zip lock-bags. The chlorophyll sample was scraped from the upper layer of the core, specifically the green-colored sediment

4.1.1 Environmental Conditions During Sampling

October is the end of the dry season, meaning days with rain in the area vary between 0-5 days per month. The last day with rain before sampling was on 21st September.

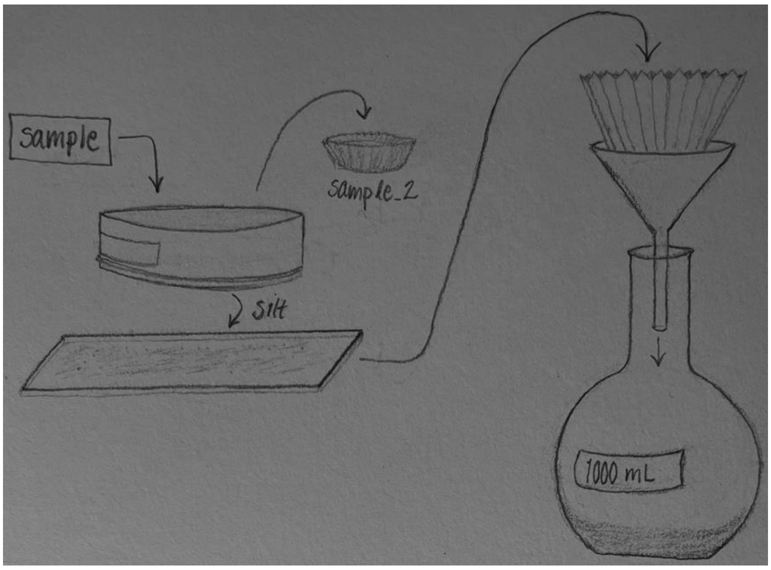
The lowest tidal level in September was -0.9 m (Table S1), which occurred on September 19 during low tide. Other days with very low tidal levels were September 17–20, ranging between -0.6 m and -0.9 m. The shallowest depth observed during sampling was 0.2 m (e.g., Matola River and Tembe River, see Table S2), indicating that these locations were likely exposed during the lowest tidal levels in September (around September 19, approximately one week before sampling). At locations with greater depths (0.4 m or more), it is less likely that the sediment was exposed.

During the sampling day, the tide was slowly rising (Table S1), and its influence was likely minimal on the sampling day, as measurements indicate stable temperature conditions (Table S2).

4.2 Environmental variables

Chlorophyll, granulometric composition, dry weight, and organic matter were prepared and analyzed at the Department of Biological Science, Universidade Eduardo Mondlane, Maputo, Mozambique. Chlorophyll was analyzed using a spectrophotometer and calculated according to the method described by Jeffrey and Humphrey (1975). The sediment samples for granulometric composition, dry weight, and organic matter were dried to prevent particle clumping. It was then sieved through a series of mesh screens with decreasing mesh sizes (2 mm, 0.9 mm, 0.55 mm, 0.125 mm and 0.07 mm). The material retained on each screen was weighed to determine the amount of sediment in each grain size category. The analysis is outlined in Figure 2.

Containers with samples for heavy metal and chemical analysis were sent to the IAEA Marine Environment Laboratories, Monaco for further analysis.



← *FIGURE 2A*

↓ *FIGURE 2B*

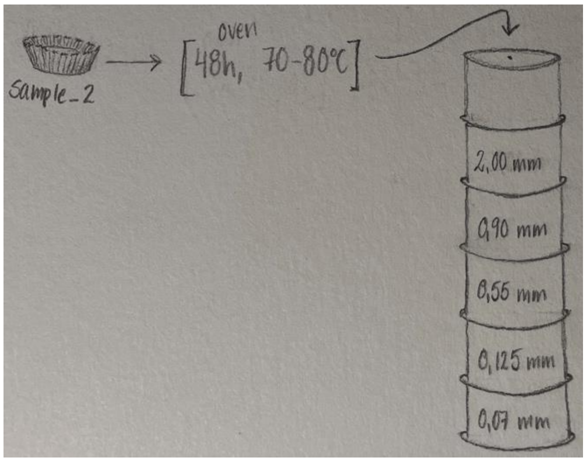


FIGURE 2 – A SCHEMATIC FIGURE OF THE EQUIPMENT USED FOR DETERMINING GRAIN SIZE.

Figure 2A shows Step 1: The sample was poured through a sieve. The portion that landed on the tray was weighed and added to the rest of the silt. The sample that remained in the sieve was then poured into pre-weighed aluminum tin. Figure 2B shows Step 2: The sample from aluminum tin was poured into sieves that separated the grain based on size.

4.3 Meiofaunal extraction

The meiofauna extraction was performed at Kristineberg marine research station, Sweden, using a combination of the methods described by Lindgren et al. (2013) and Burgess, R. (2001).

The dyed sediment samples were rinsed with seawater and sieved through a 1 mm coarse sieve followed by a 63 µm sieve, to remove macrofauna and larger organic material. The samples were rinsed again with seawater (15.9°C, 34 PSU) to remove Rose Bengal dye and the ethanol solution. They were then rinsed with tap water to eliminate salt residues before being transferred to Falcon tubes. The samples were centrifuged at 900 rpm for 5 minutes to separate the sediment from the water column, whereupon 30 mL of Ludox HS-40 (a colloidal silica solution with a density of 1.31 g cm^{-3}) was added to facilitate isopycnic separation. The mixture was then thoroughly vortexed at high speed for 30 seconds to break up the sediment while preserving delicate meiofauna. Following this, the mixture was fluidized by vortexing at low speed for 4 minutes to maintain sediment particles in suspension and allow the lighter meiofauna to rise to the surface of the Ludox solution. The sample was centrifuged again at 900 rpm for 5 minutes, enabling heavier particles (silt and clay) to settle at the bottom of the tube while meiofauna and the Ludox solution remained at the surface. The top 2 ml of the solution, containing the meiofauna, was carefully pipetted into new containers.

The extracted material was rinsed with tap water through a 63 μm sieve to remove Ludox residues and subsequently preserved in an ethanol-glycerol solution (95:5), each replicate in its own container, marked with pencil (pen ink would be dissolved be ethanol)

4.4 Meiofaunal identification

To ensure thorough analysis, only one replicate was processed per day. Each sample was diluted with seawater (34 PSU) to a total volume of 100 mL. From this, 5 mL at a time was pipetted into a petri dish to minimize organism overlap during counting, until 200 individuals had been counted. The total abundance of organisms in the sample was estimated using a volumetric extrapolation method, where the total number of individuals in the entire volume was calculated as:

$$Total\ individuals\ in\ the\ sample = (Counted\ individuals \times \frac{Dilution\ volume}{Analyzed\ volume})$$

This method, often referred to as subsampling with volumetric upscaling, ensures that the entire sample is represented proportionally based on the analyzed subsample (Begon, & Townsend, 2021).

Organisms were identified morphologically using stereo microscope (Leica MZ12 and Heerbrugg M5-64571). Since some individuals were hard to identify, every new organism with a different morphology than the last was sketched and/or photographed, for later comparison with taxonomic literature (Fig. 3; Fig. A1).

FIGURE 3A ***FIGURE 3B*** ***FIGURE 3C***

FIGURE 3 – EXAMPLES OF TOOLS USED FOR IDENTIFYING MEIOFAUNA PHYLA.

Unspecified species of the phylum Kinorhyncha presented in three different ways. Fig. 3A: Photo with camera phone through a microscope, Fig. 3B: Sketches made during counting, and Fig. 3C: Photo from electron micrograph.

This approach facilitated accurate identification and allowed for systematic documentation. Unidentified specimens were labeled "Unknown_X" to maintain consistent tracking.

4.5 Statistical data analysis

To describe the meiofauna community, univariate measures such as Density (N) and Abundance were used. Additionally, diversity metrics included Richness (S), Evenness (J'), and Shannon-Weaver Diversity Index (H'). Differences in species composition among locations were analyzed using Bray-Curtis dissimilarities, a multivariate approach based on the abundance of individual species.

ANOSIM and perMANOVA tests were performed to evaluate significant differences between groups based on Bray-Curtis dissimilarities, while SIMPER analyses identified the species contributing most to observed patterns. Community structure was further examined using nMDS (non-metric multidimensional scaling) to visualize differences across locations.

To link the structure of meiofaunal communities to environmental factors, a BEST test (BIOENV procedure) was performed, as described by Clarke and Ainsworth (1993). This method uses rank correlations to optimize the correlation between community patterns and combinations of environmental variables, enabling identification of the factors best explaining the observed biological data. The analysis compared Bray-Curtis dissimilarities in faunal composition with environmental variables using Euclidean distances. Key environmental variables included in the analysis were sediment grain size, organic matter, pH, temperature, salinity, dry weight, and chlorophyll concentration. Prior to statistical analysis, environmental variables were transformed following Clark and Warwick (1994) to improve normality and comparability. Transformations such as logarithmic and square root adjustments were applied to address skewness, and all variables were standardized to eliminate unit-based differences. Similarly, square root transformations were applied to abundance data to reduce the influence of dominant species and meet multivariate analysis assumptions. (Clark and Warwick, 1994)

All statistical analyses were performed using PRIMER (version 7.0.21), Microsoft Excel (version 16.92), and RStudio (version 2023.09.0+463). Various supplementary packages were utilized to enhance statistical analysis and data visualization, including dplyr, tidyr, ggplot2, vegan, pairwiseAdonis, cluster, and pheatmap.

5. RESULT

5.1 Environmental variables

Sampling depths at the studied locations ranged between 0.7 and 0.9 meters, with the shallowest depths recorded in Matola and Maputo Rivers and the deepest in Tembe (*Fig. 4*; *Table S1*).

Relatively stable temperatures (22.3–22.5°C) were observed in Infulene and Tembe, while higher values were recorded in Matola and Umbeluzi (up to 23.8°C). The lowest temperature was noted in Maputo (20.8°C). Salinity levels exhibited significant variation among the rivers, with the highest value observed in the Infulene River (65.0 PSU) and the lowest in Umbeluzi (25.4 PSU). The Matola and Tembe Rivers also demonstrated elevated salinity levels, measuring 63.9 PSU and 62.7 PSU, respectively. The Maputo River showed intermediate salinity, with a recorded value of 33.2 PSU.

The rivers' pH values spanned from neutral to slightly alkaline (7.8–8.1), with Infulene, Matola and Umbeluzi showing stable levels around 7.9. Slight deviations were noted in Tembe (7.8) and Maputo (8.1).

Chlorophyll-a (Chl-a) concentrations varied significantly, peaking in Infulene (3.2 µg/g DW) and reaching a minimum in Maputo (0.9 µg/g DW). Intermediate levels were recorded in Matola (1.8 µg/g DW) and Tembe (2.1 µg/g DW), while Umbeluzi displayed slightly lower concentrations (1.4 µg/g DW). Organic matter (OM) concentrations were highest in Infulene (262.1 mg/g) and relatively high in Tembe (142.5 mg/g). Moderate levels were recorded in Matola (99.1 mg/g) and Umbeluzi (70.7 mg/g), while Maputo had the lowest OM concentration (45.7 mg/g).

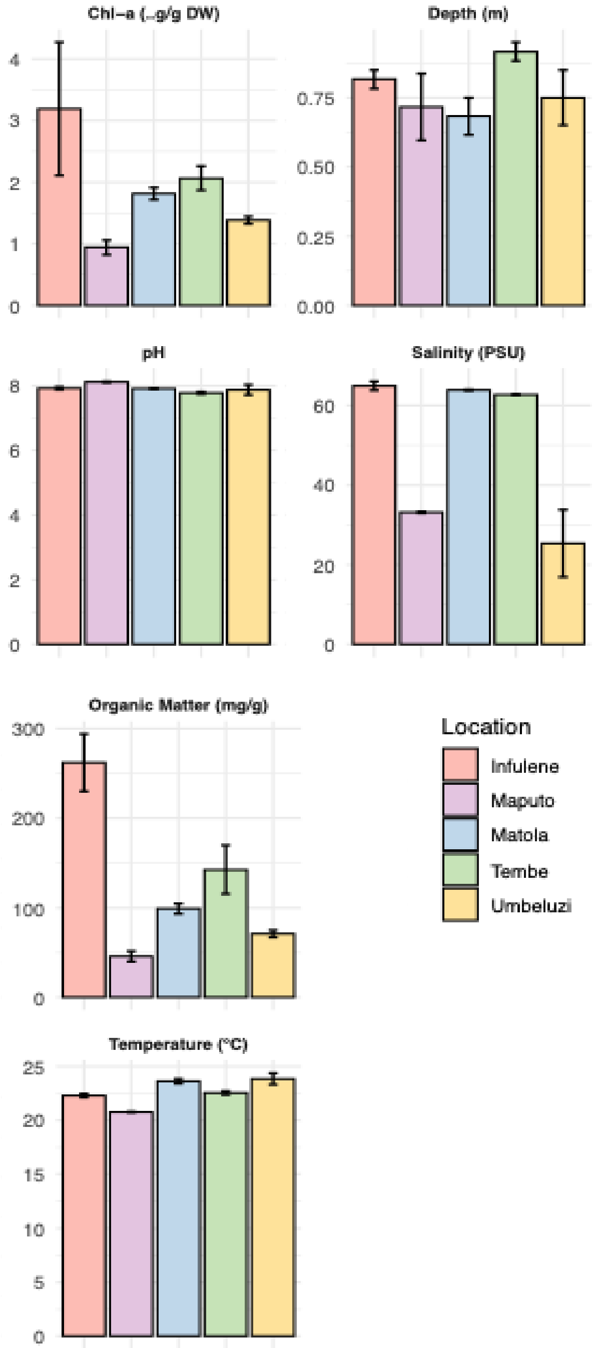


FIGURE 4 – MEAN ENVIRONMENTAL VARIABLES ± SE.

Variables presented are Chl-a, chlorophyll, presented in µg/g Dry weight. OM, organic matter in mg/g dry weight. Temp., temperature, measured in °C. Salinity, measured in PSU. Depth in m, measured from water surface.

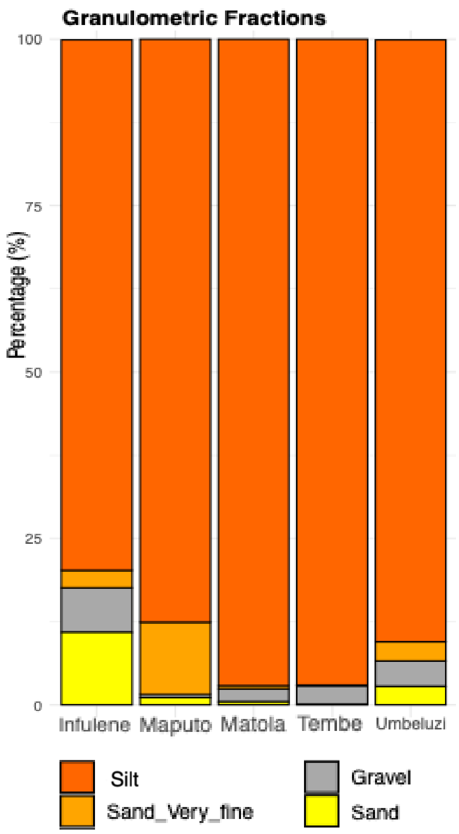


FIGURE 5 – GRANULOMETRIC FRACTIONS AT THE FIVE LOCATIONS.

Sand is here a general term for a collection of sizes (very coarse=1-2 mm, coarse=0.5-1 mm, medium=0.25-0.5 mm and fine=0.125-0.25 mm). Gravel is in the size range of 2-4 mm, Sand (Very fine) 0.063 – 0.125 mm and Silt <0.063mm

The granulometric composition of sediments exhibits significant variability, reflecting differences in hydrological processes, pollution sources, and anthropogenic activities (Fig. 5; Table S3).

Silt (<0.063 mm) dominates the sediments across all rivers, with the highest proportions observed in Tembe (96.7%) and Matola (95.6%). In contrast, Infulene (60.1%) and Umbeluzi (83.4%) show a more mixed granulometric composition, while Maputo has an intermediate silt content at 84.8%. Statistical analysis revealed significant differences in coarse sand ($p = 0.038$) and very fine sand ($p = 0.002$). Tembe and Matola are nearly entirely composed of silt, whereas Umbeluzi and Infulene exhibit a more varied sediment profile. Maputo also contains the highest proportion of very fine sand at 10.4%, highlighting its distinct granulometric composition.

5.2 Meiofauna diversity

5.2.1 Abundance and composition of meiofauna

A total meiofaunal abundance of 25,997 individuals was recorded, representing at least 67 species across 12 phyla. Among the meiofaunal groups, Nematoda dominated the communities in Matola (47.1%), Umbeluzi (32.1%), Tembe (50.3%), and Maputo (50.2%). In contrast, Copepoda was the dominant phylum in Infulene, comprising 34.5% of the total abundance. Other notable taxa included Platyhelminthes, Rotifera, and Ostracoda, which contributed to local variations in community composition (Fig. 6).

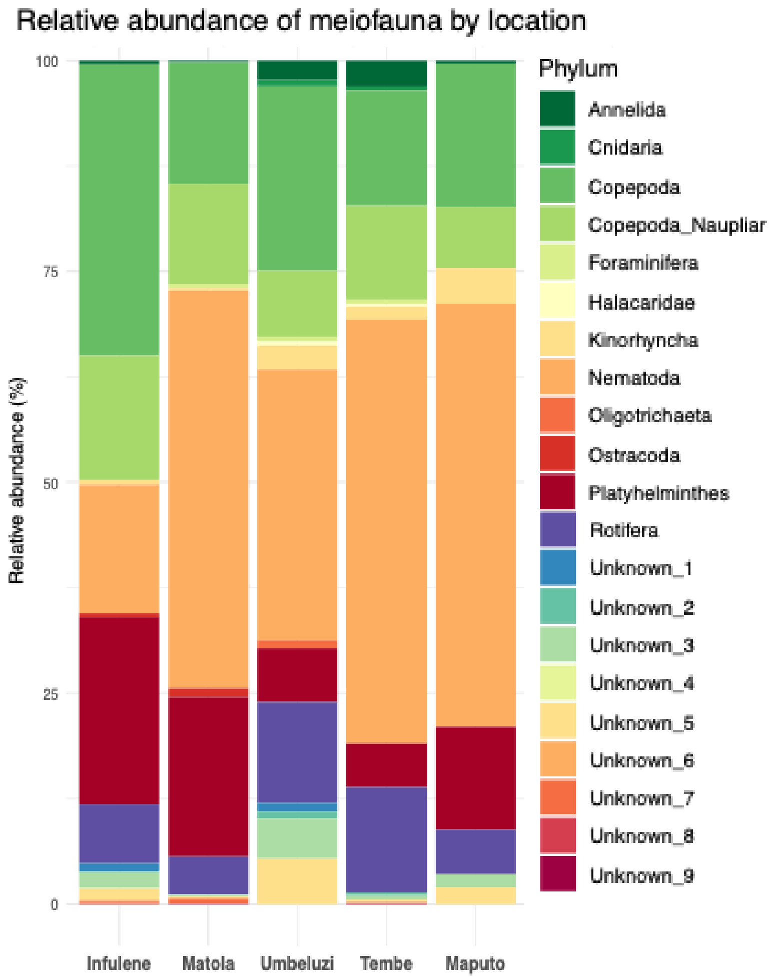


FIGURE 6 – RELATIVE ABUNDANCE (%) OF MEIOFAUNAL PHYLA ACROSS THE FIVE LOCATIONS (INFULENE, MATOLA, UMBELUZI, TEMBE AND MAPUTO).

The graph illustrates the meiofaunal community composition at each site, highlighting variations in phylum distribution.

Meiofaunal density (ind./cm²) varied significantly across locations (*p < 0.001;* Fig. 7; Table S5). The highest mean density was observed in Maputo (204.0 ± 0.0 ind./cm²), followed by Infulene (135.0 ± 11.8 ind./cm²) and Matola (79.7 ± 12.7 ind./cm²). Lower densities were recorded in Umbeluzi (13.0 ± 0.28 ind./cm²) and Tembe (10.4 ± 0.18 ind./cm²). These differences were primarily driven by the dominance of Nematoda and Copepoda at high-density sites (Fig. A2).

Species richness (S) followed a similar pattern, with significant differences observed between locations (*p = 0.047*; Table S5). Infulene exhibited the highest mean richness (14.0 ± 0.58 species), followed by Umbeluzi (13.0 ± 0.0 species), Tembe (10.3 ± 0.67 species) and Matola (10.0 ± 2.52 species). The lowest richness was observed in Maputo (8.33 ± 0.33 species), highlighting a gradient in community complexity across the study area.

Evenness (J') remained relatively stable across all locations (*p = 0.185*), ranging from 0.64 ± 0.02 in Infulene, Matola, and Tembe to 0.77 ± 0.01 in Umbeluzi.

Diversity metrics integrating species richness and evenness, revealed further variability between locations. The Shannon-Weaver diversity index (H') ranged from 1.43 ± 0.16 in Matola to 1.98 ± 0.03 in Umbeluzi. While these differences approached significance (*p = 0.067*), they underline the higher diversity at sites like Umbeluzi and Infulene compared to Matola and Maputo.

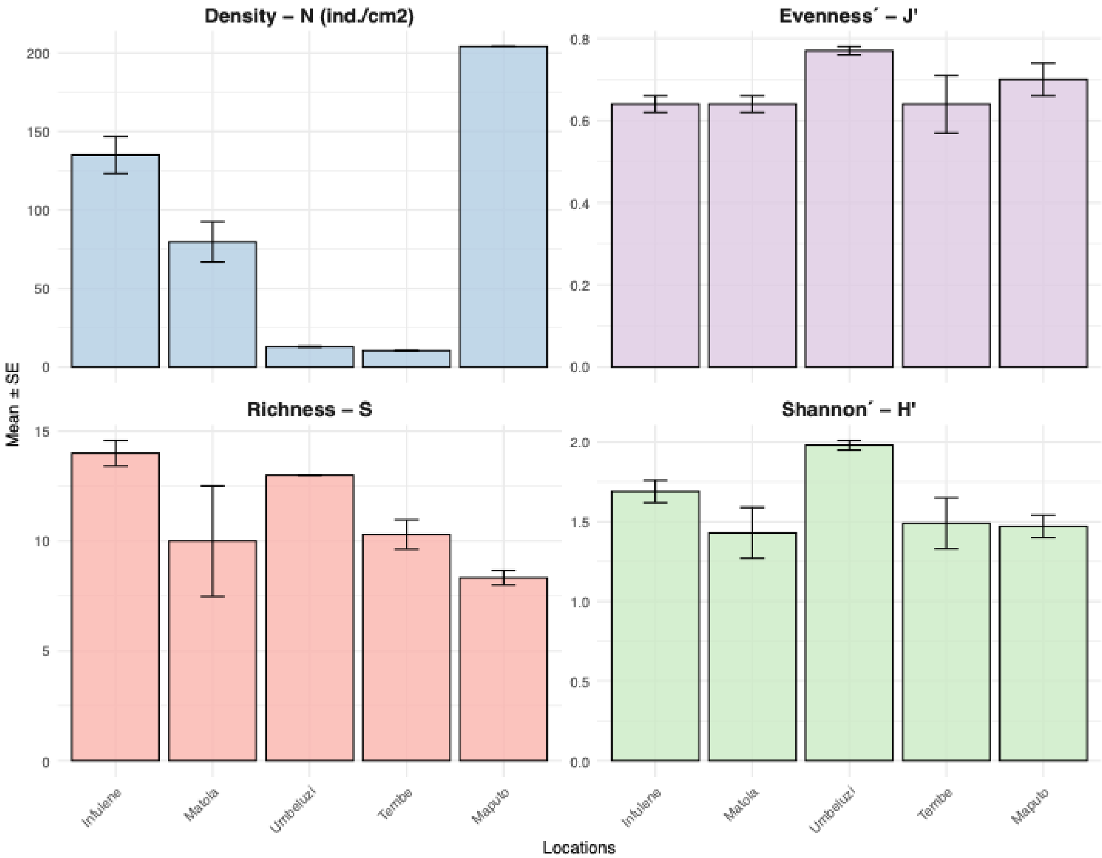


FIGURE 7 – MEAN ± SE FOR DENSITY, EVENNESS, RICHNESS AND SHANNON-WINER INDEX.

Bar plots showing mean values (± standard error) for meiofauna density (N, ind./cm^2), evenness (J'), richness (S), and Shannon-Wiener diversity index (H') across different sites. The x-axis represents the sampling location, while the y-axis represents the corresponding metric values. Error bars indicate variability within each site.

5.2.2 Species Contribution to Similarity and Dissimilarity Between Locations

There were significant differences in meiofaunal community composition between the five locations based on Bray-Curtis dissimilarities (ANOSIM, p = 0.001; R = 0.86), supported by a perMANOVA (F = 16.52, p = 0.001). The reported p = 0.001 reflects the smallest achievable significance level based on 999 permutations, highlighting strong evidence for differences while acknowledging that p-values in permutation tests are constrained by the number of permutations performed. Pairwise comparisons revealed clear separation between most location pairs, with p-values consistently at 0.1 due to the limited permutations. Notable examples of less pronounced differences include Umbeluzi vs Tembe (R = 0.444), Infulene vs Maputo (R = 0.593), and Matola vs Maputo (R = 0.704).

The SIMPER one-way analysis revealed patterns of species contributions to both within-locations similarity and between-location dissimilarity.

Within locations, Umbeluzi exhibited the highest average similarity at 84.12%, where dominant taxa such as Nematoda (20.74%), Copepoda (17.96%), and Rotifera (12.09%) collectively contributed to 50.79% of the group similarity (Table S6). Maputo and Infulene also showed high levels of similarity, at 82.67%, and 82.36% respectively. In Infulene, Copepoda (23.97%) and Platyhelminthes (19.87%) were the primary contributors, while in Maputo, similarity was largely driven by Nematoda (33.75%) and Copepoda (19.03%). Tembe presented a moderately high similarity of 75.98%, with Nematoda (33.57%) and Rotifera (17.55%) together explaining 51.12% of the observed similarity. Matola displayed the lowest average similarity at 69.21%, where Nematoda (33.29%) and Platyhelminthes (19.83%) dominated, resulting in a cumulative contribution of 53.12%.

The analysis of dissimilarity between locations revealed notable variations in species contributions (Table S7; Fig. 8). The highest dissimilarity was observed between Tembe and Maputo (65.93%), while the lowest occurred between Umbeluzi and Tembe (25.14%). Intermediate dissimilarities were recorded for pairs such as Matola and Tembe (52.56%), Matola and Umbeluzi (50.69%), and Infulene and Umbeluzi (54.04%). The lowest dissimilarity between Infulene and Matola (33.12%) highlights similarities in community composition

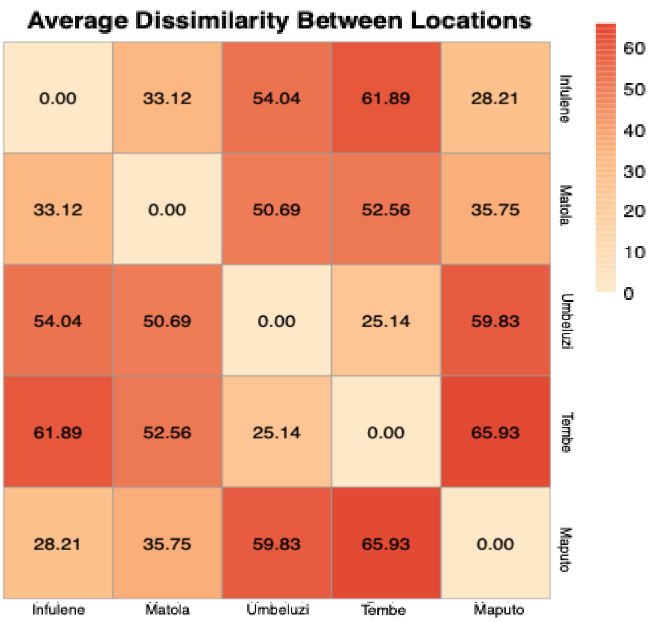


FIGURE 8 – AVERAGE DISSIMILARITY BETWEEN LOCATIONS.

The heatmap illustrates pairwise average dissimilarity values between locations, with higher values indicating greater differences in community composition. Darker shades represent higher dissimilarity, while lighter shades correspond to more similar locations. The diagonal shows a value of 0, representing self-comparison. Among the locations, the greatest dissimilarity is observed between Tembe and Maputo (65.93), while the lowest dissimilarity is found between Infulene and Matola (33.12). This pattern highlights variability in environmental conditions or biological communities across the sampled areas.

between these moderately impacted sites. Umbeluzi and Maputo showed a relatively high dissimilarity of 59.83%, indicating distinct community structures.

These patterns are further illustrated by the non-metric multidimensional scaling (nMDS) plot (Fig. 9), which shows a clear separation of communities in polluted locations such as Maputo and Infulene from those in less impacted areas like Tembe and Umbeluzi. Tembe exhibits partial overlap with Umbeluzi, as shown by their closer grouping in the nMDS plot.

Taxonomic contributions varied across locations (Table S7; Fig. 9). In Maputo, Nematoda accounted for 62.7% of meiofaunal communities, whereas in Infulene, the dominant groups were Copepoda (23.97%) and Platyhelminthes (19.87%). In Umbeluzi, Copepoda (40.5%) and Rotifera (23.1%) were key contributors, while in Tembe, Nematoda (33.57%) and Rotifera (17.55%) played a major role. In Matola, Nematoda (33.29%) and Platyhelminthes (19.83%) dominated the meiofaunal communities.

Taxa contributing to dissimilarity between pairs of locations include Nematoda and Copepoda, which drove differences between Tembe and Maputo, while Platyhelminthes were more prominent in comparisons involving Matola. These taxa also contributed to the separation observed in the nMDS plot, where the vectors highlight key drivers of dissimilarity.

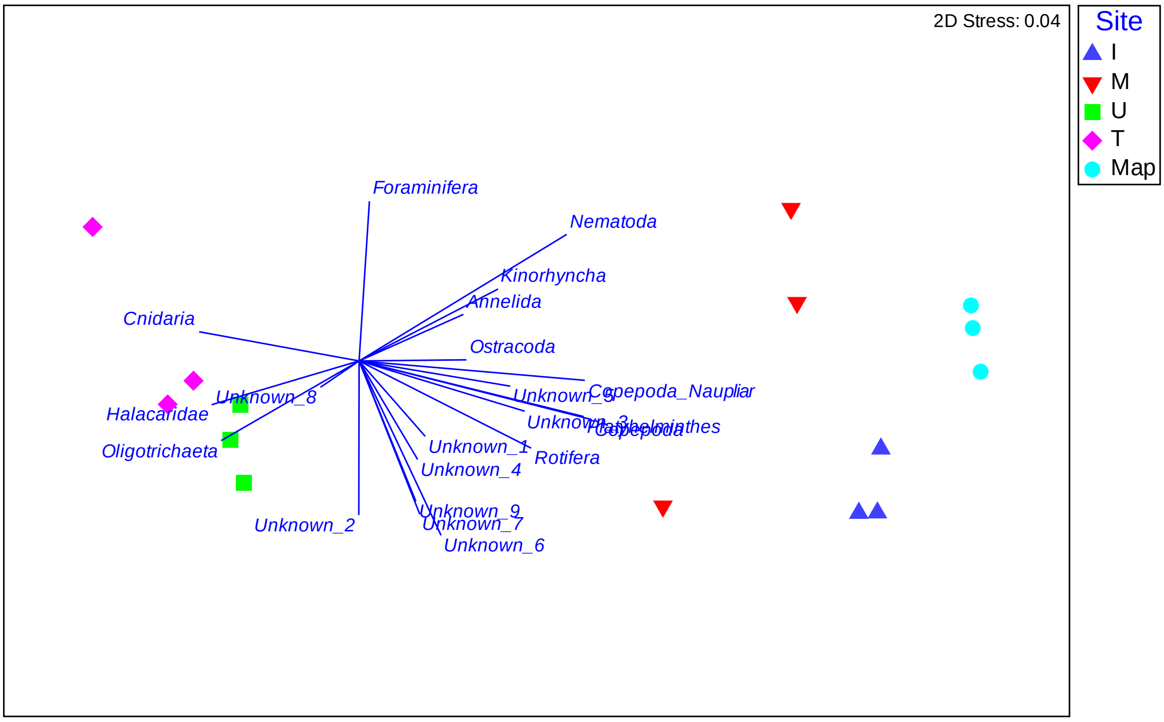


FIGURE 9 – NON-METRIC MDS PLOT.
Transform: Square root. Resemblance: S17 Bray-Curtis similarity

The nMDS plot shows the variation in meiofaunal community composition across sites. Polluted locations, such as Maputo (red triangles) and Infulene (green squares), are clearly separated, driven by opportunistic taxa like Nematoda. Less disturbed sites, such as Tembe (purple diamonds) and Umbeluzi (blue circles), cluster together, reflecting more balanced communities with sensitive taxa. Vectors indicate key taxa contributing to dissimilarity, highlighting the influence of pollution gradients and sediment conditions.

5.2.3 N/C-ratio

The measured N/C ratios display variations across the studied locations, with results that are not fully consistent. Low ratios suggest a dominance of Copepoda, which is indicative of less stressed environmental conditions, whereas high ratios point towards greater environmental stress or impact. As shown in Table 2, Infulene and Umbeluzi consistently exhibit low ratios, suggesting relatively stable and less disturbed environments. In contrast, Tembe displays high ratios across all measures, indicating more stressed environmental conditions. Meanwhile, Matola and Maputo show significant variability; depending on the method of calculation, these locations alternate between having the highest and moderate ratios. This variability underscores the sensitivity of the N/C ratio to the inclusion of different copepod developmental stages in the analysis.

TABLE 2 – N/C-RATIO

$N/C_{Naupliar}$: This ratio includes all copepods, regardless of their developmental stage, including those in the naupliar stage.
N/C: This ratio considers only copepods in their adult stage, excluding juveniles and nauplii.

	Infulene	Matola	Umbeluzi	Tembe	Maputo
$N/C_{Naupliar}$	0.3	1.8	1.1	2.0	2.1
N/C	0.4	3.3	1.5	3.7	3.0

5.3 Correlation between meiofauna and environmental variables

The primary BIOENV-Best analysis was conducted under two scenarios: one including both water column and sediment variables (Combined Analysis; Table 3) and a second limited to sediment variables alone (Sediment-Only Analysis; Table 4). Both analyses yielded non-significant results (*p = 0.13 respectively p=0.35*), indicating that the tested environmental parameters do not sufficiently explain meiofaunal community variation.

In Combined Analysis, the highest correlation coefficient (*Rho = 0.322*) was achieved using three variables: *Sediment granulometry 0.5 mm, Temperature,* and *pH*. Adding additional variables, such as salinity (*PSU*) or other *Sediment granulometry* fractions, slightly decreased the explanatory power, highlighting the limited contribution of these factors beyond the most influential variables (*Rho=0.296* for four variables and *Rho=0.263* for five). Among the tested environmental parameters, the most influential variables identified were *pH* (Rho = 0.236), *Temperature* and *pH* combined (Rho = 0.306). *pH* and *Temperature* consistently emerged as the most influential factors across models, followed by *Sediment granulometry*, particularly the *0.5 mm* fraction. In contrast, organic matter (OM) content and salinity (PSU) contributed less to the models, indicating weaker relationships with meiofaunal distributions.

TABLE 3 – BEST RESULTS FOR EACH NUMBER OF VARIABLES IN THE COMBINED ANALYSIS.

Variables: *Ch = Chl-a (µg/gDW), DW = DW %, OM = OM%, PS = PSU T = Temperature and pH = pH*
Granulometric variables are presented as: *2 = 2 mm (%) (Gravel), 1 = 1 mm (%) (Sand, very coarse), 0.5 = 0.5 mm (%) (Sand, coarse), 0.2 = 0.25 mm (%) (Sand, medium), 0.1 = 0.125 mm (%) (Sand, fine), 0.0 = 0.063 mm (%) (Sand, very fine), >0 = >0.063 mm (%) (Silt).*

No. of Variables	Correlation (Rho)	Selections (Variables)
1	0.236	pH
2	0.306	T, pH
3	**0.322**	**0.5, T, pH**
4	0.296	0.5, PS, T, pH
5	0.263	0.5, 0.0, PS, T, pH

Figure 10 illustrates the Principal Component Analysis (PCA) for all variables included in the Combined Analysis. This plot visualizes the relationships between meiofaunal community variation and the tested environmental parameters. The vectors for *pH* and *Temperature* are prominent, while *Sediment granulometry* fractions such as *0.5 mm* contribute less distinctly. The clustering of sites reflects the variation observed in the dataset.

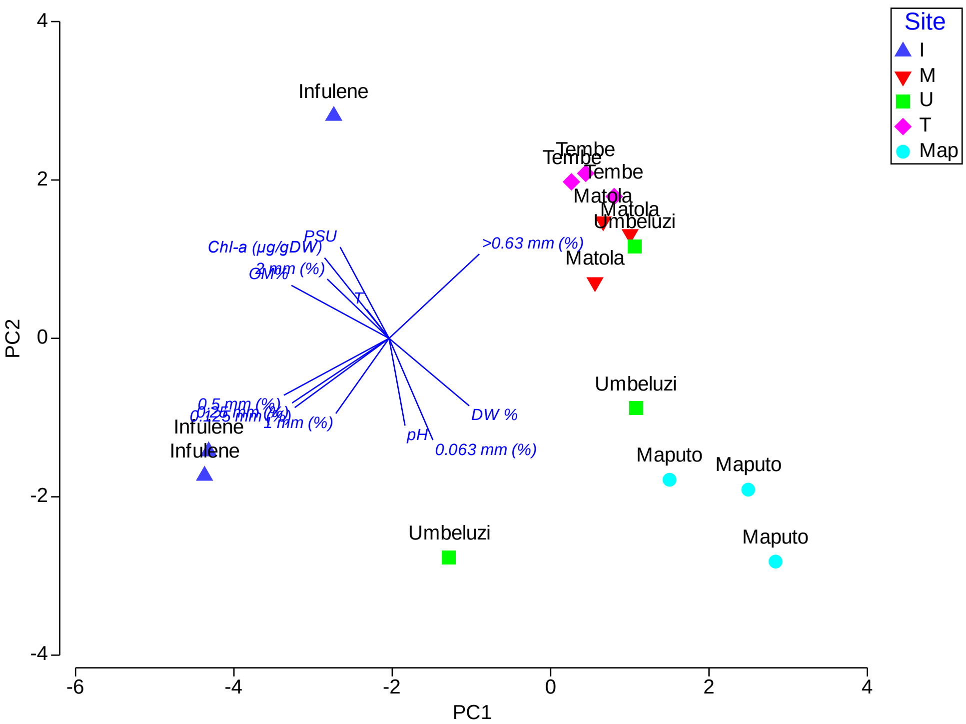


FIGURE 10 – PCA FOR THE RESULT FROM THE COMBINED ANALYSIS.

Principal Component Analysis (PCA) plot for the Combined Analysis, including all sediment and water column variables. The vector for pH and Temperature are the most prominent, suggesting their potential influence on meiofaunal community structure. Sediment granulometry fractions, such as 0.5 mm, contribute to a lesser extent but remain notable.

In Sediment-Only Analysis, the highest correlation coefficient (*Rho=0.181*) was achieved with three variables: *Organic matter* (*OM*), *Sediment granulometry 2 mm,* and *0.063 mm*. Similarly, as in the Combined Analysis, increasing the number of variables reduced the correlation with *Rho=0.175* for four variables and to *Rho=0.165* for five. However, *OM* and *Sediment granulometry 0.063 mm* consistently emerge as the most influential factors across models, followed by *Sediment granulometry 0.5 mm.* In contrast, Chlorophyll-a concentration (*Chl-a)* and other *Sediment granulometry* fractions exhibited weaker correlations with meiofaunal distributions, indicating a limited influence on the observed patterns.

TABLE 4 – BEST RESULTS FOR EACH NUMBER OF VARIABLES IN THE SEDIMENT-ONLY ANALYSIS.

Variables: *Ch = Chl-a (µg/gDW), DW = DW % and OM = OM%*
Granulometric variables are presented as: *2 = 2 mm (%) (Gravel), 1 = 1 mm (%) (Sand, very coarse), 0.5 = 0.5 mm (%) (Sand, coarse), 0.2 = 0.25 mm (%) (Sand, medium), 0.1 = 0.125 mm (%) (Sand, fine), 0.0 = 0.063 mm (%) (Sand, very fine), >0 = >0.063 mm (%) (Silt).*

No. of Variables	Correlation (Rho)	Selections (Variables)
1	0.093	2
2	0.164	OM, 0.0
3	**0.181**	**OM, 2, 0.0**
4	0.175	DW, 2, 0.5, 0.0
5	0.165	DW, OM, 2, 0.5, 0.0

Figure 11 illustrates the PCA restricted to sediment variables, providing a visual representation of meiofaunal community and sediment characteristics. *OM* and finer *Sediment granulometry* fractions, particularly *0.063 mm*, emerge as notables variables. The reduced clustering compared to Figure 10 reflects the limited explanatory power of Sediment-Only parameters.

These non-significant results, with low correlations, indicate that measured variables have limited explanatory power. Pending chemical analyses, which will assess hazardous substances such as heavy metals and hydrocarbons, are expected to address this gap and complement the current findings.

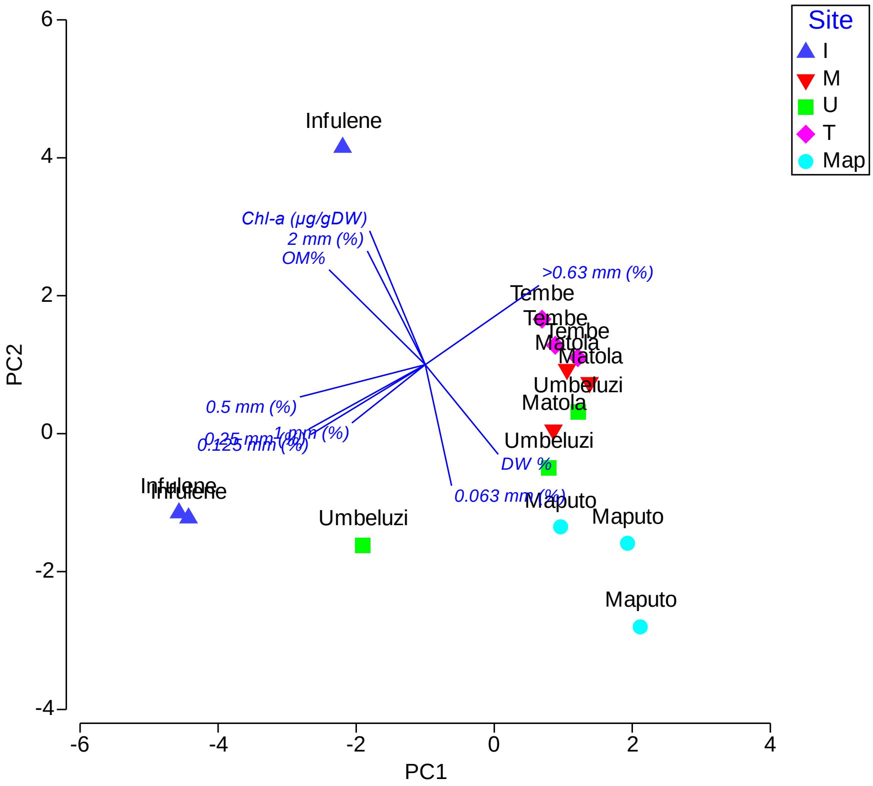


FIGURE 11 – PCA FOR THE RESULTS FROM THE SEDIMENT-ONLY ANALYSIS.

Principal Competent Analysis (PCA) plot for the Sediment Only Analysis, restricted to sediment variables. OM and Finer sediment granulometry fractions, particularly 0.063 mm, emerges as primary drivers. The reduced clustering compared to Fig. 1 reflects the limited explanatory power of sediment variables alone.

5.4 Chemical contamination

This data is not yet available; however, once it is obtained, a BIOENV-Best analysis will be conducted, as above, to complement and enhance the current results.

6. DISCUSSION

6.1 Opportunistic Taxa and Ecosystem Impacts

Nematoda consistently dominated community composition across all sites, except Infulene, highlighting their adaptability to diverse environmental conditions and underscoring the potential functional consequences of ecological simplification (Fig. 6). This is consistent with findings from Yusal et al. (2019), where meiofaunal taxa such as Nematoda showed resilience in polluted environments due to their adaptability to environmental changes. As opportunistic taxa thrive, the roles of sensitive taxa like Copepoda and Rotifera—critical for nutrient cycling and sediment stability—may diminish. This shift could reduce the functional redundancy of the ecosystem, making it less resilient to further disturbances. For example, the suppression of Nematoda, which facilitate organic matter decomposition, might slow nutrient turnover, while the decline of Copepoda, signals worsening sediment quality (Zeppilli et al., 2015; Schratzberger & Ingels, 2018). These findings directly relate to the study's aim of evaluating the impacts of pollution on biodiversity, as the loss of sensitive taxa exemplifies how anthropogenic pressures reshapes the ecological balance.

This pattern is reflected in the SIMPER results for Matola (Table S6), where Nematoda and Platyhelminthes were identified as dominant taxa. These findings suggest that the meiofaunal community structure in Matola is heavily influenced by opportunistic taxa, potentially as a response to local environmental pressures. Elevated chlorophyll-a (Chl-a) levels in Matola (Table S2), along with high organic matter (OM) content, indicate substantial nutrient inputs from fertilizers, pesticides, and urban runoff. Similar patterns have been observed in polluted estuaries, where anthropogenic inputs significantly alter meiofaunal communities (Yusal et al., 2019). These enriched conditions likely enhance microbial activity while depleting sediment oxygen levels, a process that, as Zhao et al. (2024) emphasize, not only exacerbates hypoxia but also mobilizes heavy metals, further stressing meiofaunal communities through changes in sediment chemistry. The dominance of silt in Matola (Table S3) exacerbates these issues by acting as a sink for contaminants and creating localized contamination hotspots (Ma et al., 2016).

However, focusing solely on opportunistic taxa is insufficient for a comprehensive understanding of meiofaunal community dynamics. In Maputo, opportunistic taxa such as Nematoda dominate, but the presence of sensitive taxa like Copepoda suggests that the system is not severely degraded. Furthermore, this meiofaunal community is characterized by high density and evenness, yet it exhibits low Shannon-Weaver index and species richness (Table S5). These patterns highlight a moderately polluted environment rather than one heavily impacted by pollution. The low levels of Chl-a and OM further support this classification, indicating that the site is not heavily eutrophic or burdened by organic enrichment. While ecological stress is evident, likely driven by anthropogenic factors (Table 1), the relatively balanced community structure and meiofaunal density suggest that Maputo retains some functional stability. That said, a more comprehensive evaluation of its health requires the inclusion of additional variables.

6.2 Meiofaunal Correlations with Environmental Factors

Analysis of meiofaunal community structure in Maputo Bay revealed modest correlations with environmental variables. Among the sediment-only variables analyzed in the Bioenv-Best analysis (Table 4 and Table S9), OM, gravel, and fine sand showed the highest correlations with meiofaunal pattens. However, the weak correlations suggest that the dataset lacks sufficient explanatory power, emphasizing the need for additional data, such as hazardous substance measurements. For instance, elevated pollutant loads associated with fine sediment, particularly in Matola, act as unmeasured stressors shaping meiofaunal patterns, reinforcing the need for targeted chemical analyses (da Silva et al., 2022). In contrast, highly variable factors like Chl-a and OM exhibited weak correlations with meiofaunal distribution, further pointing to the role of unmeasured stressors such as heavy metals and pesticides (Zeppilli et al., 2015; Schratzberger & Ingels, 2018; Nhantumbo et al., 2023). The PCA pot (Fig. 11) illustrates this, with less distinct site clustering and limited explanatory powers, reinforcing the need for complementary analyses.

The combined Bioenv-Best analysis (Table 3 and Table S8), which integrates water column and sediment variables, identified pH, coarse sand, and temperature as the variables most correlated with meiofaunal distributions. While fluctuations in these variables can directly impact meiofaunal species composition and survival rates (Schratzberger & Ingels, 2018), such effects are only relevant when they occur within the meiofaunal habitat itself. However, collecting pH, temperature, and salinity measurements from the water column rather than the sediment limits their applicability to meiofaunal communities. For instance, elevated temperatures in the Matola River (Fig. 4; Table S2), may amplify pollution impacts by intensifying hypoxic conditions, highlighting the need for sediment-specific temperature analyses to assess thermal impacts on meiofaunal communities (França et al., 2024).

Even though the combined Bioenv-Best analysis yielded slightly higher correlations than the sediment-only analysis, significant gaps in the data remain. As mentioned above, uncovering the underlying drivers requires additional data—possibly hazardous substances or other stressors. Ongoing chemical analyses are expected to provide critical insights needed to identify these stressors and explain community differences.

6.3 Sediment and Pollution in Meiofaunal Distribution

Taken together, these findings underline the complex interplay of environmental factors and dynamic stressors, emphasizing the importance of sediment-specific analyses to fully capture meiofaunal responses to pollution. Understanding these interactions is crucial for predicting ecosystem resilience and informing targeted management strategies to mitigate anthropogenic impacts on biodiversity.

Interestingly, Infulene, which is recognized as a highly polluted site (Table 1), is dominated by Copepoda—a sensitive taxon—but also Platyhelminthes, an opportunistic group. This atypical composition suggests that local environmental factors, such as sediment grain size (Fig. 5), may mediate the responses of meiofaunal communities to pollution. Due to physical constraints—the river being to shallow for the boat to navigate—sampling in Infulene was conducted just outside the river's mouth, meaning that some pollutants had already dispersed at this point. While the sample is representative of the site, it may not fully capture conditions closer to the river's interior.

Furthermore, the findings highlight the importance of environmental factors, such as sediment grain size. As shown in Fig. 5 and Table S3, Infulene has the lowest silt content and the highest proportion of gravel and sand among the sampled locations. Granulometry shapes meiofaunal habitats and pollutant dynamics, where finer sediments enhance heavy metal retention and fosters hypoxic microenvironments that stress meiofaunal communities (Spedicato et al., 2024). Conversely, in the Infulene River, its higher gravel and sand content limits pollutant retention but reduces meiofaunal habitat stability (Ma et al., 2016).

At the same time, Infulene exhibits the highest Chl-a and OM content (Table S2), reflecting significant organic enrichment from untreated sewage, which threatens the local ecosystem by intensifying oxygen depletion and meiofaunal stress (Zhao et al., 2024). Despite these challenges, the granulometry of Infulene appears to mitigate some negative effects of pollution by providing an environment that supports Copepoda. This suggests that the coarse sediment composition contributes to a relatively stable meiofaunal community, despite the contamination which we would expect to reduce stability.

In Tembe and Umbeluzi, characterized by variations in nutrient levels and sediment granulometry, exhibited distinct meiofaunal structures shaped by Rotifera and Nematoda. Sensitive taxa, such as Rotifera, serve as an indicator of ecological health in stable, low-impact environments (Giere, 2009). The prevalence of Rotifera in Tembe and Umbeluzi thus suggest that they are less disturbed ecosystems compared to the other locations studied. This aligns with Bielanska-Grajne et al. (2017), who highlight how Rotifera communities serve as reliable indicators of environmental stability and health, reflecting specific ecological conditions. However, when considering the broader picture, Tembe cannot be characterized as a healthy ecosystem. Its low density, moderate evenness, species richness, and Shannon-Weaver index (Table S5), combined with elevated Chl-a and OM content (Table S2), indicate a stressed environment. While its granulometry includes both gravel and silt, the silt component appears to exert a significant negative impact, as previously noted in the case of Matola.

Copepoda, which is sensitive to oxygen depletion, decline in heavily polluted regions but are prevalent in areas with favorable sediment oxygenation (Mohammad et al., 2024; Zeppilli et al., 2015). The SIMPER result showed a significant abundance of Copepoda in Umbeluzi (Table S6), suggesting that the location may have such favorable sediment oxygenation. However, this variable was not measured in this study.

In contrast, Platyhelminthes is noted for its persistence in moderately impacted sites where it acts as an intermediate stress indicator, bridging pristine and degraded conditions (Balsamo et al., 2014). Its abundance in Infulene and Matola, which are such moderately impacted sites, suggests that contamination—outlined in Table 1—may influence meiofaunal communities more strongly than nutrient enrichment alone. For example, the dominance of Copepoda in Infulene could reflect its resilience to certain pollutants as compared to taxa like Rotifera, which, as noted above, are more abundant in less polluted environments.

At a broader scale, the patterns observed emphasize that meiofaunal community structures reflect an interplay of anthropogenic pressures and natural habitat conditions, requiring a more nuanced approach to fully understand their distributional changes.

6.4 N/C Ratio as an Indicator of Meiofaunal Community Dynamics

The N/C ratio, focusing on adult copepods, is the primary metric for this study due to its direct link to ecosystem functionality. Adult copepods, critical for nutrient cycling and sediment stability, are sensitive to stressors like hypoxia and pollutants (Mohammad et al., 2024; Sautya et al., 2025). Their responses make the N/C ratio a robust bioindicator of ecosystem health. Aligning this with adult nematode counts ensures consistency between taxa.

In contrast, the $N/C_{Naupliar}$ ratio, which includes all copepod life stages, offers broader insights into recruitment and population dynamics. However, nauplii's high abundance can dilute stressor impacts observed in adults, and their lower mobility risks underrepresentation in sediment samples, particularly in locations where they appear absent (Giere, 2009). This underrepresentation could also be a limitation of the sampling method, which might not fully capture less mobile nauplii in areas with strong sediment dynamics or variable conditions. Additionally, increasing the number of replicates or expanding the sampling area could help ensure a more comprehensive representation of nauplii across different locations.

While Sautya et al. (2025) used the N/C ratio to assess anthropogenic stress, they did not specify copepod developmental stages, creating ambiguities. Excluding nauplii in the N/C ratio clarifies meiofaunal responses but may miss early-life stress indicators. Despite this, the adult-focused N/C ratio strengthens correlations with ecosystem health.

In Infulene, the low N/C ratio (Table 2) indicates a relatively balanced community where both Nematoda and Copepoda contribute to ecosystem functionality and in contrast, Matola with a higher ratio exhibits the opposite, as previously discussed.

In Tembe, the highest N/C ratio indicates a system dominated by Nematoda, with Copepoda playing a minimal role which can also be seen in Table S4 and the SIMPER results in Table S6. This community structure is consistent with low species richness and Shannon-Weaver index values (Table S5), highlighting significant ecological stress. The dominance of silt in the sediment (Table S3) and moderately high OM levels suggest a sediment environment prone to hypoxia, likely exacerbating nematode dominance. Mohammad et al. (2024) emphasize that nematodes thrive in environments with high silt content and organic matter, as these conditions favor their resilience to hypoxia and other stressors, reinforcing their dominance in such habitats. While Chl-a levels remain moderate, indicating some primary production, the overall meiofaunal composition indicates a site experiencing substantial anthropogenic impact.

Umbeluzi, with a moderate N/C ratio, represents an intermediate state. While Nematoda is prominent, Copepoda remains a significant presence, reflecting a more balanced meiofaunal community than in Matola or Tembe. High evenness and a strong Shannon-Weaver index (Table S5) further support the interpretation of Umbeluzi as a less disturbed site. However, the high silt content (83.4%) and lower OM and Chl-a levels suggest a nutrient-poor environment with limited primary production (Table S2). These factors may limit meiofaunal density but contribute to community stability.

Finally, in Maputo, the N/C ratio reflects nematode dominance and shares similarities with Matola and Tembe in exhibiting nematode dominance. However, the high meiofaunal density and moderate evenness suggest that this community retains some functional stability despite signs of ecological stress. Low Chl-a and OM levels (Table S2) point to limited organic enrichment, while sediment composition dominated by silt supports the retention of contaminants (Table S3). Although Maputo reflects a moderately polluted environment, the presence of Copepoda, even in low numbers, indicates that the system is not yet severely degraded.

6.5 Taxonomic Dissimilarities Across Pollution Gradients

The SIMPER analysis further demonstrates how the differences in pollution influence taxonomic composition and dissimilarity between sites. Copepoda and Platyhelminthes, for instance, contribute significantly to the lower dissimilarity between Infulene and Matola (Table S7). Meanwhile, the higher dissimilarity between Infulene and Tembe was driven by Copepoda and Platyhelminthes, which may reflect differences in granulometry (Table S3).

The dominance of Nematoda in Maputo, as previously highlighted, underscores the impact of heavy pollution. This contrasts sharply with the more balanced contributions of Copepoda in Umbeluzi, where the measurements indicated a less impacted, more stable environment. These findings align with previous research, Zeppilli et al. (2015); Giere (2009), which emphasizes the utility of meiofauna as indicators of localized environmental conditions.

The nMDS analysis (Fig. 9) further supports these observations by demonstrating clear differences in community structure across sites. As previously noted, polluted locations such as Maputo and Infulene cluster away from the less impacted location like Umbeluzi, reflecting the influence of pollution gradients and sediment characteristics. Vectors for taxa such as Nematoda point toward polluted locations, indicating their prevalence in these environments, while taxa like Copepoda align with less disturbed sites, suggesting a preference for more oxygenated, balanced conditions (Mohammad et al., 2024; Zeppilli et al., 2015). These results illustrate not only the separations between locations but also how sediment composition and contaminant levels actively drive distinct ecological assemblages.

The findings in Matola emphasize the interplay between nutrient enrichment, sediment characteristics, and meiofaunal community responses. Elevated Chl-a levels and high OM content, likely stemming from agricultural runoff and untreated wastewater, create conditions that enhance microbial activity but deplete sediment oxygen levels, favoring opportunistic taxa such as Nematoda and Platyhelminthes. Additionally, the fine sediment composition in Matola retains contaminants and exacerbates meiofaunal stress, while higher temperatures amplify hypoxic conditions. These enriched, low-oxygen environments illustrate how eutrophication and pollution synergistically shape meiofaunal patterns.

Interestingly, as noted earlier, Infulene represents an atypical case, where meiofaunal assemblages reflect a balance between pollution stress and sediment composition. Despite significant organic enrichment and high Chl-a content, the coarse sediment profile supports the persistence of Copepoda, a sensitive taxon, alongside opportunistic taxa like Platyhelminthes. This suggests that granulometry in Infulene mitigates some pollution effects, providing a relatively stable habitat for meiofaunal communities. However, as sampling was conducted just outside the river's mouth, rather than in the river itself, the data could potentially underrepresent localized stressors closer to the interior.

6.6 Implications for Ecosystem Management

As already discussed, meiofaunal communities act as sensitive bioindicators of estuarine health, reflecting cumulative environmental stressors. Locations dominated by opportunistic taxa highlight severe impacts from untreated sewage and industrial runoff, underscoring the need for targeted interventions. In contrast, balanced communities, such as Tembe and Umbeluzi, demonstrate resilience and their value as reference points for restoration efforts (Schratzberger & Ingels, 2018).

Long-term monitoring incorporating meiofaunal assessments and sediment analysis is crucial for effective estuarine management (Balsamo et al., 2014; Zeppilli et al., 2015). Proactive strategies should include stricter industrial regulations, improved wastewater treatment, and sustainable agricultural practices to reduce nutrient and pollutant inputs (Balsamo et al., 2014). Meiofaunal data in routine monitoring can enhance ecological models and provide early warnings of degradation (Zeppilli et al., 2015; Giere, 2009).

Restoration strategies in polluted areas should focus on reducing sediment contaminant loads, enhancing natural flushing processes, and restoring habitats. Integrating meiofaunal indicators with hydrodynamic and chemical data enables a more comprehensive restoration approach. Addressing knowledge gaps on chemical contamination and meiofaunal functional diversity is vital for refining conservation strategies (França et al., 2024; Balsamo et al., 2014).

6.7 Knowledge Gaps and Future Research

This study highlights several key knowledge gaps that warrant further exploration to deepen our understanding of meiofaunal dynamics and their ecological roles. A primary limitation is the absence of chemical data, such as heavy metal concentrations, nutrient levels, and contaminants like pesticides and hydrocarbons. These factors likely play critical roles in shaping meiofaunal communities, particularly in polluted locations like Infulene and Maputo, through direct toxic effects and indirect impacts from nutrient enrichment (Zeppilli et al., 2015; França et al., 2024). Incorporating chemical analyses in future research is essential to refine environmental gradients and clarify the stressors affecting meiofaunal diversity.

Additionally, the spatial and temporal scope of this study limits its ability to capture meiofaunal responses to seasonal and long-term changes. Investigating such dynamics, alongside geochemical analyses, could enhance understanding of pollution sources and sediment-organism interactions. Exploring meiofaunal functional diversity and its role in nutrient cycling would also provide critical insights into ecosystem resilience in estuarine environments under anthropogenic pressure. The exclusion of diatom analyses due to technical challenges represents another gap; future studies should include diatoms, as they are key indicators of water quality and productivity.

Detailed investigations into specific taxa, such as kinorhynchs, could yield insights into evolutionary biology and ecological specialization. As part of the clade Scalidophora, kinorhynchs share traits with Loricifera and Priapulida, making them a valuable subject for studying body plan evolution and ecological adaptation (Giere, 2009). Given Maputo's status as a growing urban center, collaboration with socio-economic sciences could illuminate the impact of pollution on communities reliant on estuarine systems for fishing and agriculture. Long-term monitoring of meiofaunal communities and sediment characteristics will be essential to evaluate conservation efforts and address emerging threats, contributing to sustainable management and the health of estuarine ecosystems.

7. CONCLUSION

This study demonstrates that meiofaunal diversity in the estuaries of Maputo Bay is significantly influenced by pollution. Polluted sites exhibit reduced diversity and ecological homogenization, dominated by opportunistic taxa, whereas less impacted areas support more balanced and diverse communities. Key environmental drivers, such as pH, temperature, and sediment granulometry, were identified, though their limited explanatory power highlights the need for a more integrative approach.

The findings emphasize the growing impacts of pollution exacerbated by climate change. Altered rainfall patterns and increased storm activity are expected to intensify pollutant transport and ecological strain. Comprehensive watershed management strategies, including improved wastewater treatment, riparian buffer zones, and sustainable agricultural practices, are critical to mitigate these stressors and restore ecosystem functionality.

Spatial heterogeneity in meiofaunal communities, as revealed by SIMPER analysis, underscores the importance of site-specific assessments. Distinct assemblages in locations such as Maputo and Tembe highlight meiofaunal taxa as valuable bioindicators for monitoring ecosystem health and pollution gradients.

The dominance of opportunistic taxa in polluted areas reflects the severe impacts of untreated sewage, industrial runoff, and agricultural pollution. Stricter industrial regulations, enhanced wastewater treatment, and reduced pesticide use are essential to preserve meiofaunal diversity and maintain ecological balance.

This study acknowledges the absence of chemical data, such as heavy metals, which limits understanding of meiofaunal dynamics. Future research should address this gap and explore taxonomic uncertainties and functional diversity to deepen insights into meiofaunal roles in ecosystem resilience.

Long-term monitoring is essential to evaluate management interventions and adapt to changing conditions. Integrating physical, chemical, and biological data will support targeted conservation strategies, restoring habitats and protecting biodiversity. This study reinforces the importance of addressing pollution in safeguarding Maputo Bay's estuarine ecosystems and highlights meiofaunal analyses as effective tools for ecosystem monitoring and management.

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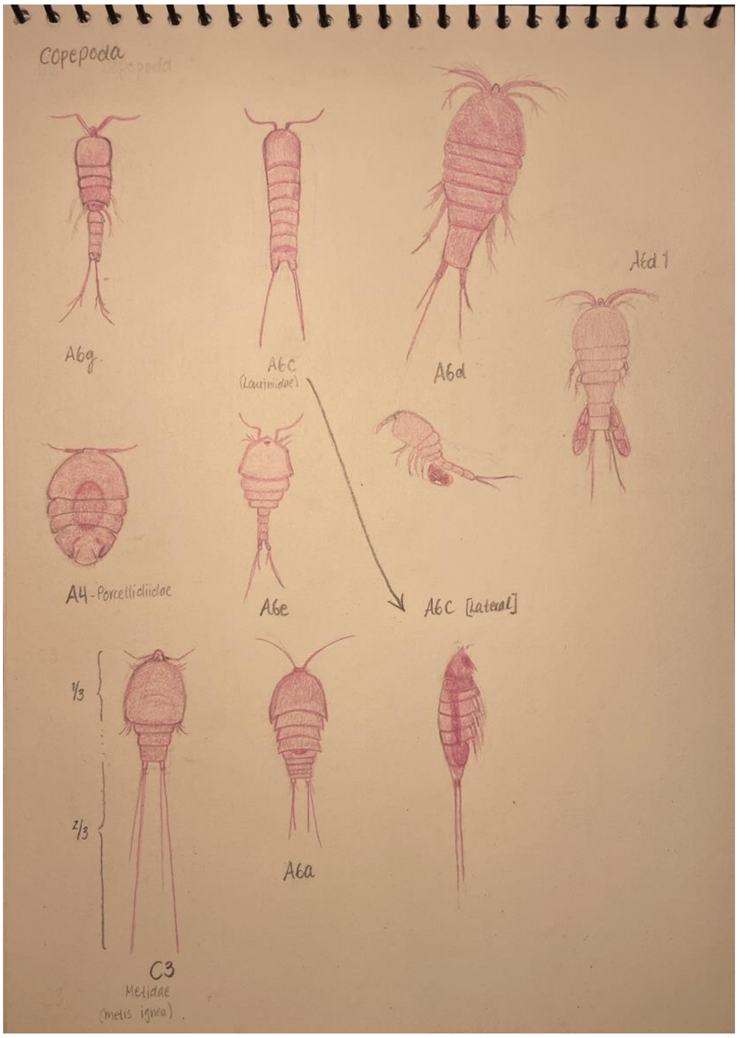
Map Data to Fig. 1:

TUBS. (2018). *Mozambique in Africa (mini map, rivers)* [Map]. Retrieved from https://en.m.wikipedia.org/wiki/File:Mozambique_in_Africa_%28-mini_map_-rivers%29.svg

OpenStreetMap contributors. (n.d.). *OpenStreetMap data*. Licensed under Open Database License (ODbL). Tiles courtesy of CartoDB. Retrieved from https://www.openstreetmap.org (https://umap.openstreetmap.fr/sv/map/provtagningsplatser_bt_1151889#17/-25.99125/32.46091)

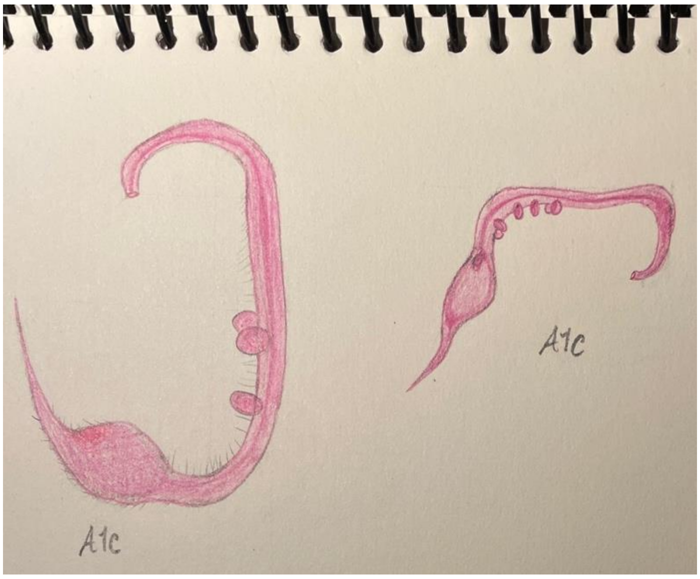
APPENDIX

A.



B.

C.



D.

FIGURE A1 – EXAMPLES OF TOOLS USED FOR IDENTIFYING MEIOFAUNA PHYLA:
A. Different types of *Copepoda*, labeled as A6a, A6b, ..., A6x; **B.** Various kinds of *Nematoda*; **C.** Sketch of "*Unknown_1*"; **D.** Microscope image of "*Unknown_1*"

APPENDIX

T*able S1 – Tide Table for Matola, September 2024.* *Sampling date is marked in bold*

	Low Tide				High Tide			
	AM		PM		AM		PM	
Day	Time	Height	Time	Height	Time	Height	Time	Height
01-sep	9:46am	-0.1m	10:02pm	-0.2m	3:32am	1.8m	3:46pm	2.0m
02-sep	10:13am	-0.3m	10:28pm	-0.3m	3:52am	2.0m	4:07pm	2.2m
03-sep	10:38am	-0.5m	10:54pm	-0.4m	4:13am	2.2m	4:29pm	2.3m
04-sep	11:04am	-0.5m	11:19pm	-0.5m	4:36am	2.3m	4:51pm	2.4m
05-sep	11:29am	-0.5m	11:45pm	-0.4m	4:59am	2.3m	5:15pm	2.4m
06-sep	11:54am	-0.5m	-	-	5:22am	2.3m	5:38pm	2.4m
07-sep	12:09am	-0.4m	12:18pm	-0.4m	5:45am	2.3m	6:00pm	2.2m
08-sep	12:33am	-0.2m	12:42pm	-0.2m	6:08am	2.1m	6:23pm	2.1m
09-sep	12:56am	-0.0m	1:05pm	0.0m	6:30am	2.0m	6:46pm	1.9m
10-sep	1:20am	0.2m	1:29pm	0.3m	6:54am	1.7m	7:11pm	1.7m
11-sep	1:47am	0.4m	1:59pm	0.5m	7:21am	1.5m	7:45pm	1.4m
12-sep	2:30am	0.7m	3:02pm	0.8m	8:04am	1.2m	10:05pm	1.1m
13-sep	6:04am	0.8m	7:25pm	0.7m	-	-	12:47pm	1.2m
14-sep	8:03am	0.5m	8:23pm	0.3m	1:30am	1.3m	1:59pm	1.5m
15-sep	8:41am	0.1m	9:01pm	-0.0m	2:16am	1.7m	2:37pm	1.8m
16-sep	9:15am	-0.2m	9:36pm	-0.4m	2:51am	2.0m	3:10pm	2.2m
17-sep	9:49am	-0.6m	10:11pm	-0.6m	3:23am	2.2m	3:42pm	2.5m
18-sep	10:24am	-0.8m	10:45pm	-0.8m	3:55am	2.5m	4:15pm	2.7m
19-sep	10:58am	-0.9m	11:20pm	-0.8m	4:27am	2.6m	4:47pm	2.8m
20-sep	11:33am	-0.8m	11:54pm	-0.7m	4:59am	2.6m	5:19pm	2.7m
21-sep	-	-	12:07pm	-0.7m	5:30am	2.5m	5:51pm	2.5m
22-sep	12:27am	-0.5m	12:41pm	-0.4m	6:02am	2.3m	6:21pm	2.2m
23-sep	1:00am	-0.2m	1:15pm	-0.1m	6:33am	2.0m	6:51pm	1.9m
24-sep	1:33am	0.2m	1:50pm	0.3m	7:04am	1.7m	7:22pm	1.5m
25-sep	2:09am	0.5m	2:36pm	0.7m	7:39am	1.4m	7:59pm	1.2m
26-sep	**3:20am**	**0.8m**	**7:18pm**	**0.8m**	**-**	**-**	**12:13pm**	**1.1m**
27-sep	7:51am	0.7m	8:19pm	0.6m	1:39am	1.2m	2:12pm	1.3m
28-sep	8:27am	0.4m	8:47pm	0.3m	2:25am	1.4m	2:41pm	1.6m
29-sep	8:54am	0.1m	9:11pm	0.0m	2:46am	1.6m	3:00pm	1.8m
30-sep	9:20am	-0.1m	9:37pm	-0.2m	3:05am	1.9m	3:18pm	2.0m

Source: *https://tidechecker.com/mozambique/maputo/matola/, accessed [2024-09-23]*

APPENDIX

TABLE S2 – AN OVERVIEW OF PHYSICAL AND CHEMICAL PARAMETERS BETWEEN THE FIVE LOCATIONS, VALUES EXPRESSED IN AVERAGE (± SE).

Chl-a, chlorophyll, presented in µg/g Dry weight. OM, organic matter in mg/g dry weight. Temp., temperature, measured in °C. Salinity, measured in PSU. Depth in m, measured from water surface.

Location	Depth m	Temp. °C	pH	Chl-a µg/gDW	OM mg/g	Salinity PSU
Infulene	0.8 ± 0.0	22.3 ± *0.2*	7.9 ± 0.0	3.2 ± 1.*1*	262.1 ± *31.9*	65.0 ± *1.1*
Matola	0.7 ± 0.1	23.6 ± *0.2*	7.9 ± 0.0	1.8 ± 0.1	99.1 ± *5.8*	63.9 ± *0.1*
Umbeluzi	0.8 ± 0.1	23.8 ± *0.5*	7.9 ± 0.2	1.4 ± 0.1	70.7 ± *4.0*	25.4 ± *8.4*
Tembe	0.9 ± 0.0	22.5 ± *0.2*	7.8 ± 0.0	2.1 ± 0.2	142.5 ± *27.2*	62.7 ± *0.1*
Maputo	0.7 ± 0.1	20.8 ± *0.0*	8.1 ± 0.0	0.9 ± 0.1	45.7 ± *5.9*	33.2 ± *0.2*

TABLE S3– COMPARISON OF GRANULOMETRIC FRACTIONS N EVERY LOCATIONS, VALUES EXPRESSED IN AVERAGE (SE).

Average values (±SE) of the granulometric fractions in the five locations.
Where Gravel is 2-4 mm, Sand (very coarse) is 1-2 mm, Sand (Coarse) 0.5-1 mm, Sand (Medium) 0.25-0.5 mm, Sand (Fine) is 0.125-0.25 mm, Sand (Very fine) 0.063 – 0.125 mm and Silt <0.063mm.
Result of PERMANOVA, PERMIDISP on the granulometric matrix of the locations.
p-vales < 0.05 are in bold.
The small cap (a and b) letters represent groups of significant differences between the study areas and each granulometric size.

Location	Gravel	Sand *Very coarse*	Sand *Coarse*	Sand *Medium*	Sand *Fine*	Sand *Very fine*	Silt
				%			
Infulene	5.1 ± 2.3	1.5 ± *0.3* [a]	2.5 ± 0.4	14.9 ± *7.4*	14.0 ± *7.0*	1.9 ± 1.0	60.1 ± *13.5* [b]
Matola	1.9 ± 0.5	0.4 ± *0.2* [a]	0.4 ± *0.0*	0.6 ± 0.5	0.6 ± 0.4	0.5 ± 0.3	95.6 ± *0.8*
Umbeluzi	3.5 ± 0.5	2.4 ± *1.2* [a]	0.9 ± 0.5	3.6 ± 3.0	3.5 ± 2.3	2.7 ± 1.0	83.4 ± *7.9* [b]
Tembe	2.8 ± 1.4	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	96.7± *1.3* [b]
Maputo	0.5 ± 0.2	0.7 ± 0.2	0.5 ± 0.1	1.2 ± 0.3	1.9 ± 0.3	10.4 ± *2.8*	84.8 ± *2.0* [b]
p-value	0.163	**0.038**	**0.011**	0.087	0.084	**0.002**	**0.031**
Pseudo-F	1.93	2.78	9.30	3.00	3.07	8.63	4.26
PermDisp	0.583	0.417	0.474	0.400	0.631	0.192	0.607

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Table S4 ***– THE TOTAL MEIOFAUNA DENSITY AT INFULENE, MATOLA, UMBELUZI, TEMBE AND MAPUTO.***

Phyla	Density (ind./cm^2)					
	Infulene	Matola	Umbeluzi	Tembe	Maputo	∑
Annelida	2	1	1	1	2	6
Cnidaria	0	-	-	-	-	0
Copepoda	139	34	9	4	104	291
Copepoda (*Naupliar*)	60	29	3	3	45	140
Foraminifera	-	1	-	-	-	1
Halacaridae	-	-	-	-	-	0
Kinorhyncha	2	1	1	-	25	30
Nematoda	62	113	13	16	307	509
Oligotrichaeta	-	-	-	-	-	0
Ostracoda	2	-	-	-	-	4
Platyhelminthes	90	45	2	2	74	213
Rotifera	28	11	5	4	33	80
Unknown	19	3	5	-	21	49
∑	404	239	39	31	611	1324

APPENDIX

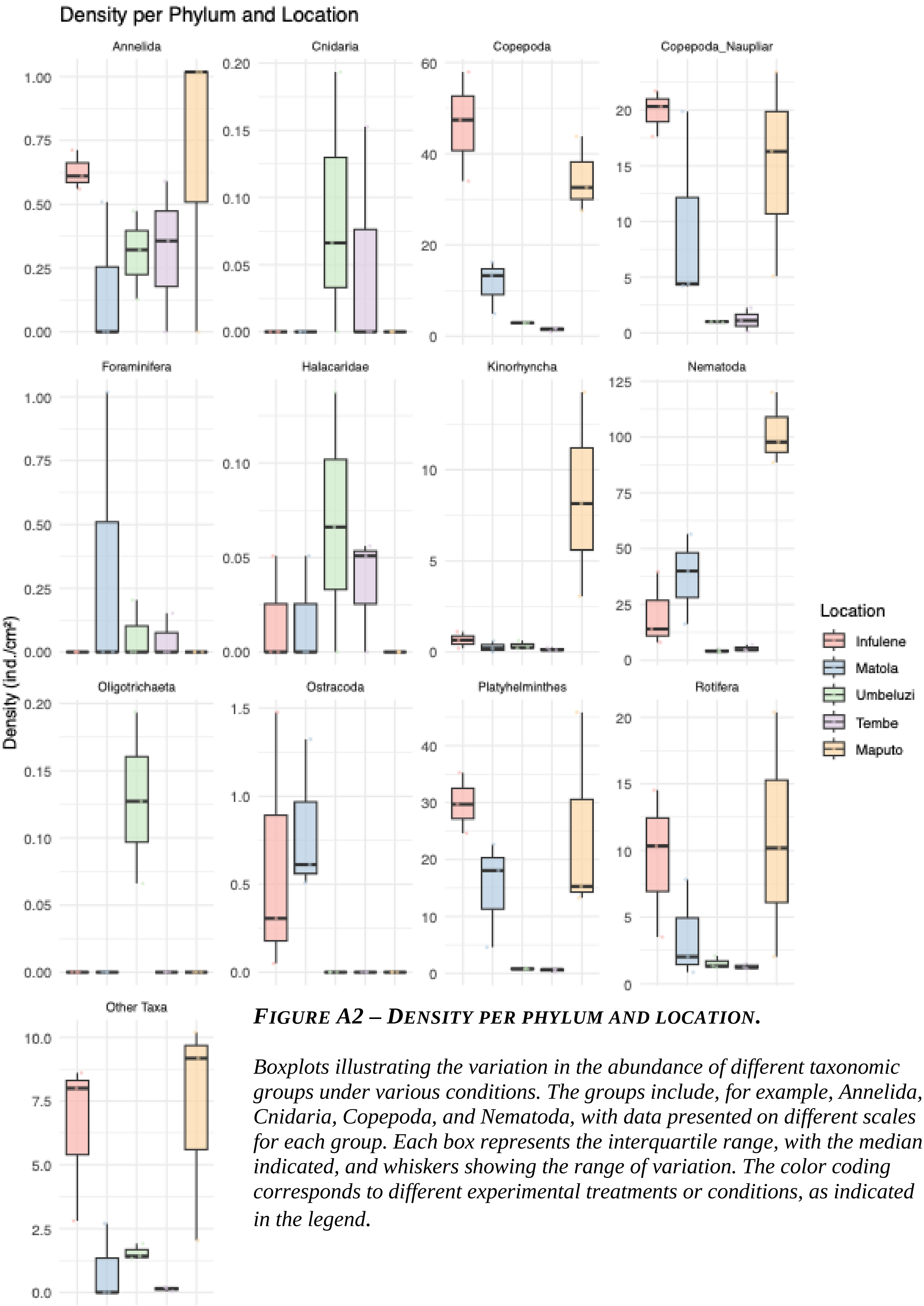

FIGURE A2 – DENSITY PER PHYLUM AND LOCATION.

Boxplots illustrating the variation in the abundance of different taxonomic groups under various conditions. The groups include, for example, Annelida, Cnidaria, Copepoda, and Nematoda, with data presented on different scales for each group. Each box represents the interquartile range, with the median indicated, and whiskers showing the range of variation. The color coding corresponds to different experimental treatments or conditions, as indicated in the legend.

APPENDIX

TABLE S5– COMPARISON AMONG ECOLOGICAL INDICES.

Mean ± se for Density, Evenness, Richness and Shannon-winer.
PERMANOVA and Pair-wise results for the ecological indices in the study Locations.
p-vales < 0.05 are in bold.

Location	Density – N (ind/cm^2)	Evenness’ – J	Richness – S	Shannon’ – H
Infulene	135.0 ± *11.8*	0.64 ± 0.02	14.0 ± 0.58	1.69 ± 0.07
Matola	79.7 ± 12.7	0.64 ± 0.02	10.0 ± 2.52	1.43 ± 0.16
Umbeluzi	13.0 ± 0.28	0.77 ± 0.01	13.0 ± *0.0*	1.98 ± 0.03
Tembe	10.4 ± 0.18	0.64 ± 0.07	10.3 ± 0.67	1.49 ± 0.16
Maputo	204.0 ± *0*	0.70 ± 0.04	8.33 ± 0.33	1.47 ± 0.07
p-value	**0.001**	0.185	**0.047**	0.067
Pseudo-F	119.96	1.83	3.91	3.40
R^2	0.98	0.42	0.61	0.58
PermDisp	8.45	5.23	12.76	10.15

TABLE S6 – RESULT SIMPER, ONE-WAY ANALYSIS.

This table summarizes the similarity percentages and species contributions to within-group similarities for meiofaunal communities across the five sampled locations. The analysis is based on Bray-Curtis similarity measures, with a cutoff for low contributions set at 40.00%.
For example, in Maputo, Nematoda contributed 33.75% to the total group similarity, followed by Copepoda with 19.03%, resulting in a cumulative contribution of 52.78%. This highlights the dominant role of specific taxa in structuring meiofaunal communities across locations.

Group	Av.Sim	Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Infulene	82.36	Copepoda	30.03	19.74	8.50	23.97	23.97
		Platyhelminthes	24.14	16.37	10.53	19.87	43.84
Matola	69.21	Nematoda	26.38	23.04	3.52	33.29	33.29
		Platyhelminthes	16.46	13.73	2.24	2.24	53.12
Umbeluzi	84.12	Nematoda	9.04	17.45	73.89	20.74	20.74
		Copepoda	7.49	15.11	38.77	17.96	38.79
		Rotifera	5.48	10.17	32.99	12.09	50.79
Tembe	75.98	Nematoda	10.04	25.51	11.84	33.57	33.57
		Rotifera	5.03	13.34	31.15	17.55	51.12
Maputo	82.67	Nematoda	44.70	27.90	24.38	33.75	33.75
		Copepoda	25.95	15.73	24.53	19.03	52.78

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TABLE S7 – DISSIMILARITY CONTRIBUTION OF MEIOFAUNAL TAXA BETWEEN LOCATION PAIRS.

The table summarizes the results of a SIMPER analysis (Similarity Percentage Analysis) for various taxa contributing to dissimilarity between pairs of locations. Each row represents a phylum, and the included columns are defined as follows:
Av.Abund: The average abundance of each taxon within the respective group.
Av.Diss: The average dissimilarity (contribution to the differences between groups).
Diss/SD: The ratio of average dissimilarity to standard deviation, indicating the stability of the contribution.
Contrib%: The percentage contribution of each taxon to the total dissimilarity.
Cum.%: The cumulative percentage, which aggregates each taxon's contribution to the total.

Group Pair	Species	Group 1 Av.Abund	Group 2 Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Infulene, Matola	Copepoda	30.03	14.61	6.66	3.16	20.11	20.11
	Nematoda	18.98	26.38	4.24	1.31	12.79	32.90
	Platyhelminthes	24.14	16.46	3.31	1.38	10.00	42.90
Average dissimilarity		*33.12*					
Infulene, Umbeluzi	Copepoda	30.03	7.49	12.02	6.54	22.23	22.23
	Platyhelminthes	24.14	4.02	10.75	8.24	19.90	42.13
Average dissimilarity		*54.04*					
Matola, Umbeluzi	Nematoda	26.38	9.04	12.29	2.57	24.24	24.24
	Platyhelminthes	16.46	4.02	8.89	2.25	17.54	41.78
Average dissimilarity		*50.69*					
Infulene, Tembe	Copepoda	30.03	5.23	14.23	6.77	22.99	22.99
	Platyhelminthes	24.14	3.15	12.08	7.65	19.51	42.51
Average dissimilarity		*61.89*					
Matola, Tembe	Nematoda	26.38	10.04	12.76	2.41	24.27	24.27
	Platyhelminthes	16.46	3.15	10.51	2.35	19.99	44.27
Average dissimilarity		*52.56*					
Umbeluzi, Tembe	Unknown_5	3.54	0.68	3.39	2.13	13.47	13.47
	Unknown_3	3.34	0.82	2.99	2.03	11.90	25.37
	Copepoda	7.49	5.23	2.68	2.78	10.67	36.04
Average dissimilarity		*25.14*					
Infulene, Maputo	Nematoda	18.98	44.70	8.92	3.09	31.64	31.64
	Kinorhyncha	3.43	12.38	3.08	2.17	10.94	42.57
Average dissimilarity		*28.21*					
Matola, Maputo	Nematoda	26.38	44.70	7.51	2.45	21.01	21.01
	Copepoda	14.61	25.95	4.62	2.58	12.93	33.94
Average dissimilarity		*35.75*					
Umbeluzi, Maputo	Nematoda	9.04	44.70	17.76	10.42	29.68	29.68
	Copepoda	7.49	25.95	9.17	7.79	15.32	45.00
Average dissimilarity		*59.83*					
Tembe, Maputo	Nematoda	10.04	44.70	18.47	9.95	28.01	28.01
	Copepoda	5.23	25.95	11.02	8.34	16.71	44.72
Average dissimilarity		*65.93*					

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TABLE S8 - BEST RESULTS FOR THE COMBINED ANALYSIS

Variables: *Ch = Chl-a (µg/gDW), DW = DW %, OM = OM%, PS = PSU T = Temperature and pH = pH*
Granulometric variables are presented as: *2 = 2 mm (%) (Gravel), 1 = 1 mm (%) (Sand, very coarse), 0.5 = 0.5 mm (%) (Sand, coarse), 0.2 = 0.25 mm (%) (Sand, medium), 0.1 = 0.125 mm (%) (Sand, fine), 0.0 = 0.063 mm (%) (Sand, very fine), >0 = >0.063 mm (%) (Silt).*

No. of Variables	Correlation (Rho)	Selections (Variables)
3	0.322	0.5, T, pH
2	0.306	T, pH
4	0.296	0.5, PS, T, pH
3	0.289	>0, T, pH
4	0.277	0.5, 0.0, T, pH
4	0.266	OM, 0.5, T, pH
5	0.263	0.5, 0.0, PS, T, pH
4	0.262	>0, PS, T, pH
3	0.262	OM, T, pH
3	0.258	PS, T, pH

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TABLE S9 - BEST RESULTS FOR THE SEDIMENT-ONLY ANALYSIS

Variables: *Ch = Chl-a (µg/gDW), DW = DW % and OM = OM%*
Granulometric variables are presented as: *2 = 2 mm (%) (Gravel), 1 = 1 mm (%) (Sand, very coarse), 0.5 = 0.5 mm (%) (Sand, coarse), 0.2 = 0.25 mm (%) (Sand, medium), 0.1 = 0.125 mm (%) (Sand, fine), 0.0 = 0.063 mm (%) (Sand, very fine), >0 = >0.063 mm (%) (Silt).*

No. of Variables	Correlation (Rho)	Selections (Variables)
3	0.181	OM, 2, 0.0
3	0.179	DW, 0.5, 0.0
4	0.175	DW, 2, 0.5, 0.0
4	0.168	DM, OM, 0.5, 0.0
5	0.165	DW, OW, 2, 0.5, 0.0
5	0.164	Ch, DW, 2, 0.5, 0.0
4	0.164	OM, 2, 0.5, 0.0
3	0.164	OM, 0.0
3	0.163	Ch, OM, 2
2	0.159	OM, 2