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Monsoonal effects on meiofaunal assemblages in Pulau Tuba Mangroves, Langkawi, Malaysia

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Abstract. *Ramli R, Zulkifli NFD, Ismail A, Pardi F. 2025. Monsoonal effects on meiofaunal assemblages in Pulau Tuba Mangroves, Langkawi, Malaysia. Biodiversitas 26: 4694-4705.* Mangrove ecosystems are dynamic coastal habitats that support diverse and functionally important benthic communities, including meiofauna. This study investigates the spatial and temporal patterns of meiofaunal assemblages in the mangrove sediments of Pulau Tuba, Langkawi, Malaysia, in relation to monsoonal-driven environmental changes. Sediment and porewater samples were collected from four stations (MG1-MG4) in June 2023 and November 2023 to represent the Southwest Monsoon and Northeast Monsoon, respectively. Meiofauna were collected and classified to major taxa, while various environmental parameters were quantified, including salinity, temperature, pH, dissolved oxygen, organic matter content, sediment grain size, and composition. A total of nine meiofaunal groups were recorded, namely Sarcomastigophora, Copepoda, Rotifera, Oligochaeta, Halacaroidea, Polychaeta, Ostracoda, Kinorhyncha, with Nematoda dominated (>90%) in both seasons. Meiofaunal density was significantly higher during the Southwest Monsoon (Paired t-test, $p<0.05$). Diversity indices showed low species diversity, with dominance by a few groups. Multivariate analyses revealed that seasonal variation had a greater influence on community structure than spatial differences. Principal Component Analysis and Distance-based redundancy analysis identified salinity, temperature, organic matter, and dissolved oxygen as the key environmental drivers structuring meiofaunal communities. These findings add to the limited body of research on Malaysian and tropical mangrove meiofauna and provide observational evidence that may inform conservation planning, sustainable management, and policy discussions aligned with SDGs 14 and 15.

Keywords: Benthic meiofauna, mangroves, monsoon

INTRODUCTION

Mangroves are halophytic woody plant communities that grow along tropical and subtropical coastlines, playing crucial ecological roles in estuarine and coastal ecosystems (Biswas and Biswas 2019; Azzahra et al. 2023; Wirabuana et al. 2025). They provide habitat for diverse organisms, including epibenthic and endobenthic species, juvenile fish, crustaceans, mollusks, and birds, serving as essential nursery grounds (Ahmad et al. 2021; Hasan et al. 2022; Valen et al. 2022; Rahim et al. 2025). Mangroves are also key to climate change mitigation through high rates of carbon sequestration (Friess et al. 2020; Alongi 2022). In addition, they buffer coastlines against storm surges and erosion (Nguyen et al. 2017), enhance fisheries productivity through elevated primary productivity (Qureshi et al. 2016), and contribute organic matter that sustains estuarine food webs (Nguyen et al. 2017; Islamy and Hasan 2020). These multiple ecological functions highlight their significance in supporting biodiversity and human livelihoods in tropical regions (Hasan et al. 2023; Isroni et al. 2023).

Meiofauna are small, diverse benthic metazoans ranging in size from 500 µm (or 1000 µm) to 44 µm (or 63 µm), depending on definitions (Giere 2009). They comprise several taxa, including small gastropods, bivalves, annelids, and recurring organisms such as nematodes, copepods, and foraminifera, which collectively enhance biodiversity in mangrove environments (Christine et al. 2015; Michelet et al. 2021; Song et al. 2022). Meiofauna play crucial roles in organic matter decomposition, nutrient cycling, and sediment reworking, directly influencing ecosystem productivity (Schratzberger and Ingels 2018; Bianchelli et al. 2020; Martínez et al. 2025). They are also highly sensitive to environmental change, which makes them valuable bioindicators for detecting ecological shifts in benthic habitats (Zeppilli et al. 2015; Michelet et al. 2021; Sharma 2023). Their responses to habitat disturbance, salinity fluctuations, and organic matter inputs underscore their importance in assessing ecosystem health, yet they remain less studied than other benthic groups in tropical mangroves.

Monsoonal cycles strongly influence tropical mangrove systems, especially in regions subject to the Southwest Monsoon (SWM) and Northeast Monsoon (NEM) (Komiyama et al. 2019). In Malaysia, the NEM or wet season occurs from November to March with strong northeasterly winds and high rainfall, while the SWM or dry season occurs from May to September with southwesterly winds (Malaysian Meteorological

Department 2024). Seasonal events alter hydrological regimes and in situ parameters such as temperature, salinity, Dissolved Oxygen (DO), and conductivity (Peralta and Yusoff 2014). These shifts affect organic matter input, sediment redox conditions, and grain size, which in turn influence benthic fauna (Barboza et al. 2024) Understanding meiofaunal responses to these dynamics is critical, as they can serve as early indicators of change in mangrove ecosystems that are sensitive to climatic variability.

Pulau Tuba, located southeast of Langkawi main island, spans about 20 km² and hosts diverse mangrove flora, including *Rhizophora apiculata* Blume, *Rhizophora mucronata* Lam., *Ceriops tagal* (Perr.) C.B.Rob., and *Xylocarpus granatum* J.Koenig. The island has become a focal point of research across disciplines. Studies have explored its demography (Omar and Yussof 2006), cultural heritage (Ghazali et al. 2016), geological features (Ali et al. 2017), tree diversity (Pardi et al. 2018), and environmental challenges such as microplastic contamination (Kamaruddin et al. 2020). Further work has investigated coastal erosion (Adnan et al. 2021), water quality (Kamaruddin et al. 2021; Muhamad et al. 2022), and phytoplankton diversity (Norman et al. 2022). Despite these contributions, studies on meiofauna remain scarce, leaving significant gaps in understanding their roles in ecosystem functioning, resilience, and responses to seasonal variability.

This lack of knowledge hampers conservation planning and effective ecosystem management. Meiofauna, given their ecological roles and sensitivity, can serve as a model group to evaluate how monsoonal cycles and environmental parameters affect benthic community dynamics. Their study is particularly relevant amid climate change, coastal development, and habitat degradation, all of which may alter ecosystem processes in mangrove environments. Bridging this gap is necessary to strengthen ecological knowledge and to inform conservation strategies aimed at sustaining biodiversity and ecosystem services.

Thus, this study aims to identify variations in meiofauna abundance and diversity between the southwest and northeast monsoon seasons in the Pulau Tuba mangrove ecosystem, and to investigate key environmental parameters (e.g., salinity, temperature, pH, DO, and sediment characteristics) that influence meiofaunal distribution patterns.

MATERIALS AND METHODS

Study area

The study area is situated along the Pulau Tuba Strait in Langkawi Island, a narrow waterway between Pulau Tuba and Pulau Dayang Bunting, which is characterized by dense mangrove coverage (Figure 1). Langkawi Island experiences the typical monsoonal pattern observed throughout Malaysia, comprising the NEM, SWM, and two inter-monsoon periods each year (April and October) (Aziz et al. 2023). Located on the west coast of Peninsular Malaysia, Langkawi Island lies in the rain shadow of the Main Range (Banjaran Titiwangsa) and is therefore relatively sheltered from the direct influence of the NEM, which predominantly affects the east coast (Suhaila et al. 2010). Thus, over 80% of annual rainfall occurs in SWM (From May to September) rather than in NEM (Malaysian Meteorological Department 2024).

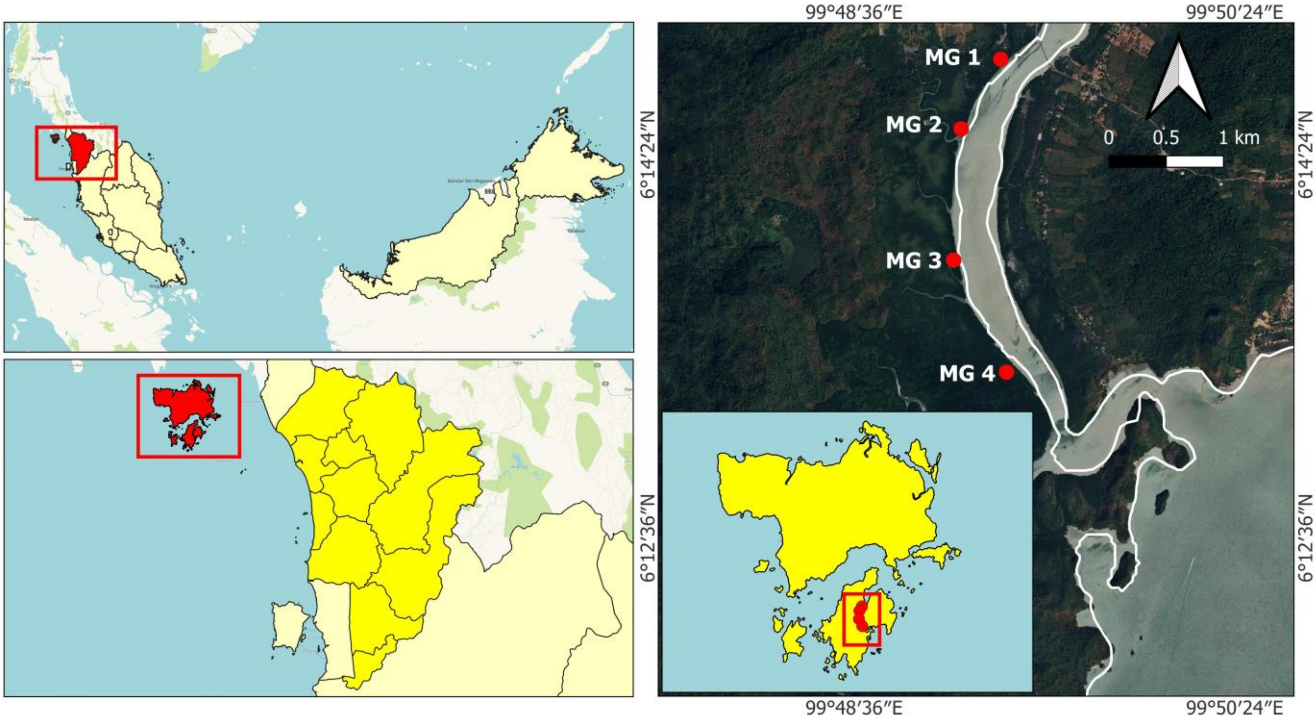

Figure 1. The map shows the location of each station (MG1-MG4) in Pulau Tuba Strait, Langkawi, Kedah, Malaysia

Procedures

Sampling protocol

Field sampling was conducted in June 2023 and November 2023, which represent SWM and NEM, respectively. The sampling site was marked by a handheld GPS on the sampling site. The details of the sampling locations are provided in Table 1. Five replicates of sediment samples (10 cm depth) were collected by using a metal corer (3.5 cm diameter). Each core sample was placed in a plastic bag, preserved with 10% buffered formalin. Additional sediment cores were also obtained for Organic Matter (OM) and particle grain size analysis. Porewater parameters have been measured in situ with handheld devices to measure salinity (ppt), temperature (°C), DO (mg/L), and pH. All the sediment samples were collected during low tide for accessibility purposes.

Meiofauna extraction

In the laboratory, meiofauna were extracted from the sediment samples by the decantation process with the addition of Ludox® HS 40 (Sigma-Aldrich) (Burgess 2001). The supernatant was passed through a set of 500 µm and 38 µm fraction sieves to retain the meiofauna (Castro et al. 2021). Meiofauna that was retained on the 38 µm sieve was fixed with 4% buffered formalin and stained with Rose Bengal to facilitate visualization during sorting and identification. They were identified to major taxonomic groups under a stereomicroscope, following standard references including Higgins and Thiel (1988) and Giere (2009).

Total organic matter analysis

Total organic matter was determined using the Loss on Ignition (LOI) method, which is based on the difference between the dry weight of each sample after oven-drying at 60°C until the weight of the dried soils was constant (Fourqurean et al. 2014), and the weight obtained after combustion at 450°C for 4 hours and expressed as percentage of the total weight.

Particle size analysis

The dried sediment samples were sieved in a 2000 µm mesh size and treated with 15 mL of 30% Hydrogen Peroxide (H_2O_2) to remove the organic matter. The suspension was kept on a heating plate at 50 °C for one hour, and the clear supernatant was removed with a pipette (Abdulkarim et al. 2021). Five mL of Calgon solution was added before being introduced into the dispersion unit device of the laser particle analyzer (Laser Diffraction Particle Size Analyzer, Malvern Mastersizer 2000) for particle size measurement. The composition of sand, silt, and clay fraction were analyzed by using Microsoft Excel, and the sediment Mean Grain Size (MGS) was converted to units of phi (ϕ).

Data analysis

The density of total meiofauna and individual major taxa was calculated and expressed as individuals per 10 cm^2 (Ind./10 cm^2±standard deviation) for each station and sampling occasion. Differences in meiofaunal density, diversity indices, and physicochemical parameters between stations were tested using One-Way Analysis of Variance (ANOVA), while Paired t-tests were used to assess seasonal differences (SWM vs. NEM). Pearson correlation analysis was applied to examine relationships between biological and physicochemical variables. All univariate statistical tests were performed using SPSS (Statistical Package for the Social Sciences) version 29 (IBM Corp., Armonk, NY, USA). Diversity indices calculated included total Species Richness (S), Shannon-Wiener Diversity Index (H′) (Shannon and Weaver 1963), Margalef's Species Richness (d) (Margalef 1958), Pielou's Evenness (J′), and Simpson's Diversity Index ($1-\lambda'$). Meiofaunal abundance data were square-root transformed to reduce the influence of dominant taxa (Clarke and Warwick 1994), and Bray-Curtis similarity matrices were generated (Bray and Curtis 1957). Two-way PERMANOVA (Permutational Multivariate Analysis of Variance) was applied to test for differences in community structure based on season (SWM vs. NEM) and station (MG1-MG4), using 9999 permutations. Analysis of Similarities (ANOSIM) was used to assess the strength of group separations, while hierarchical cluster analysis and Similarity Percentages (SIMPER) were performed to visualize community patterns and identify taxa contributing to group differences. Principal Component Analysis (PCA) was conducted on normalized environmental data using Euclidean distance to examine the influence of environmental variables on community patterns. Environmental parameters, including temperature, salinity, DO, pH, OM, MGS, and sediment composition (sand, silt, and clay), were square root transformed prior to normalization. Distance-based Redundancy Analysis (dbRDA) based on DistLM (Distance-based Linear Modeling) was performed to identify environmental variables that best explained variation in meiofaunal community composition. The proportion of variation explained by each dbRDA axis was reported, and the significance of environmental vectors was assessed using permutation tests (9999 permutations). All the multivariate analyses were conducted using PRIMER (Plymouth Routines in Multivariate Ecological Research) version 7 with the PERMANOVA+ add-on (Anderson et al. 2008; Clarke and Gorley 2015).

Table 1. Geographic location of the sampling stations in the mangrove area of Pulau Tuba Strait, Langkawi, Malaysia

Station	**Longitude (E)**	**Latitude (N)**	**Mangrove vegetation**
MG1	099° 49’ 16.90’’	06° 14’ 48.40’’	*Rhizophora mucronata* Lam.
MG2	099° 49’ 04.60’’	06° 14’ 23.50’’	*Ceriops tagal* (Perr.) C.B.Rob.
MG3	099° 49’ 06.18’’	06° 13’ 50.80’’	*Ceriops tagal* (Perr.) C.B.Rob.
MG4	099° 49’ 21.09’’	06° 13’ 23.60’’	*Rhizophora apiculata* Blume, and *Xylocarpus granatum* J.Koenig.

RESULTS AND DISCUSSION

The influence of monsoon seasons on the meiofauna assemblages in mangrove sediment in Pulau Tuba was discussed. The current spatio-temporal variation and the possible factors affecting the trends were further justified.

Environmental variables

The environmental parameters measured from the porewater showed significant variations between the seasons, except for the temperature (Paired t-test, $p>0.05$). During SWM, the temperature was highest at MG2 (29.87°C), while MG4 showed the lowest temperature (28.60°C) (Table 2). The salinity levels varied significantly among stations, with the lowest recorded at MG1 (25.73 ppt) and the highest at MG3 (31.77 ppt). pH values ranged from 6.33 (MG4) to 7.03 (MG1) while DO values ranged from 6.11 mg/L at MG4 to 6.65 mg/L at MG3. While in NEM, most of the water parameters show an increasing value. The lowest temperature was detected at MG2 (28.13°C) while MG4 exhibited the highest temperature (29.37°C). The salinity rose, ranging from 32.73 ppt (MG2) to 33.70 ppt (MG3). The pH peaked at MG3 (7.87) and dropped to 6.37 at MG2. DO was highest at MG2 (8.34 mg/L) and lowest at MG1 (7.62 mg/L). One-way ANOVA revealed significant differences across all water parameters among stations in both monsoon seasons ($p<0.05$).

The sedimentary parameters showed significant variations between the seasons, except for the silt content (Paired t-test, $p>0.05$). In the SWM, the sediment was dominated by the fine silt category, ranging from 6.17 ϕ to 6.67 ϕ, except for the sediment MGS at MG3 (5.94 ϕ; medium silt category) (Table 3). A similar trend was observed in the NEM, where fine silt sediment (ranging from 6.50 ϕ to 6.68 ϕ) dominated most of the sampling areas. The mean of sand content in SWM was higher than in the NEM, accounting for 13.13% and 7.38%, respectively. In contrast, the mean of silt and clay was higher in NEM than in SWM. The mean of silt and clay content was recorded as 63.62% and 23.43%, respectively, in the SWM and increased to 65.01% and 29.25%, respectively, in the NEM. The OM content in SWM ranged from 16.42% to 17.79%, notably higher than NEM, which ranged from 10.68% to 16.29%. According to the One-way ANOVA analysis, there were significant spatial differences in all sedimentary parameters among stations in both monsoon seasons, except for the OM content during SWM ($p>0.05$).

PCA of environmental parameters explained 66.3% of the total variation on the first two axes (Figure 2). PC1 separated NEM and SWM samples, with NEM stations aligning with higher salinity and DO, while SWM stations were associated with higher sand and OM content, and temperature.

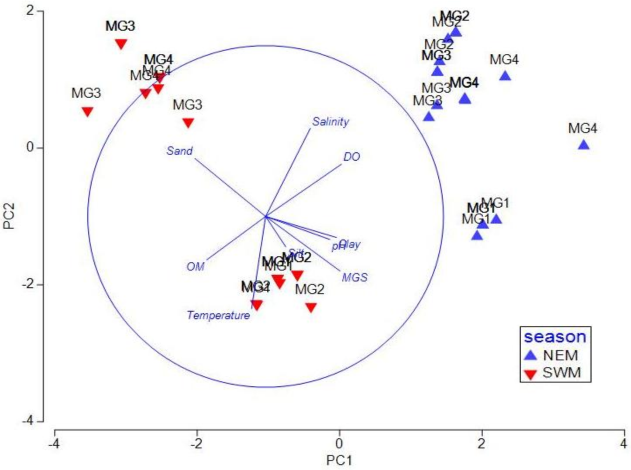

Figure 2. Principal Component Analysis (PCA) based on environmental variables in different stations (MG1-MG4) in SWM (inverted triangles) and NEM (triangles) seasons

Table 2. Mean (range) of water parameters measured during the SWM and NEM seasons

Stations	Temperature (°C)		Salinity (ppt)		pH		DO (mg/L)	
	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM
MG1	29.53 (29.40-29.70)	29.30 (29.20-29.40)	25.73 (25.60-25.80)	32.87 (32.80-32.90)	7.03 (7.00-7.04)	7.75 (7.74-7.75)	6.55 (6.53-6.56)	7.62 (7.61-7.63)
MG2	29.87 (29.70-30.00)	28.13 (28.10-28.30)	26.37 26.20-26.60)	32.73 (32.60-32.90)	6.68 (6.69-6.70)	6.37 (6.35-6.39))	6.25 (6.24-6.26)	8.34 (8.32-8.35)
MG3	29.40 (29.10-29.60)	28.67 (28.30-28.90)	31.77 (31.70-31.80)	33.70 (33.60-33.80)	6.37 (6.36-6.39)	7.87 (7.87-7.88)	6.65 (6.63-6.66)	8.11 (8.08-8.13)
MG4	28.60 (28.50-28.70)	29.37 (28.20-28.40)	30.57 (29.40-31.30)	33.57 (33.40-33.70)	6.33 (6.27-6.42)	7.84 (7.96-7.99)	6.11 (6.10-6.13)	7.97 (7.96-7.99)

Table 3. Sedimentary parameters measured during the SWM and NEM seasons

Stations	MGS (ϕ)		Sand (%)		Silt (%)		Clay (%)		OM (%)	
	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM
MG1	6.47	6.68	8.30	2.94	68.30	68.40	23.41	28.65	17.07	16.29
MG2	6.67	6.56	9.36	8.35	60.90	64.71	30.09	32.09	16.42	13.70
MG3	5.94	6.50	17.60	8.70	64.55	66.09	17.84	25.13	17.38	15.72
MG4	6.17	6.70	17.24	9.54	60.73	60.94	22.36	31.13	17.79	10.68

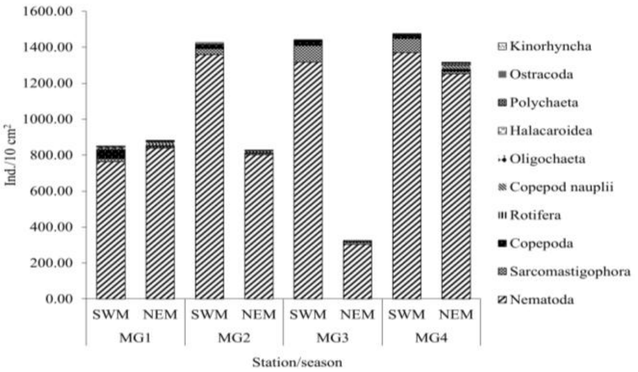

Figure 3. Abundance (Ind./10 cm^2) of meiofauna observed at all stations (MG1-MG4) along the Pulau Tuba Strait, Langkawi, Malaysia, during SWM and NEM

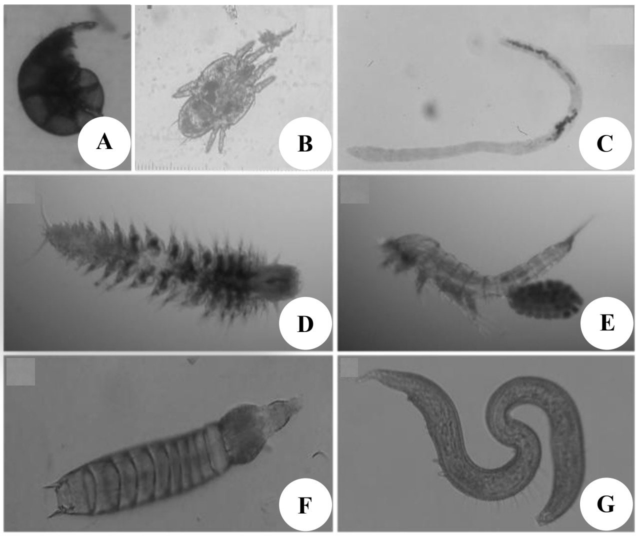

Figure 4. Representatives of the meiofaunal taxa: A. Sarcomastigophora, B. Halacaroidea, C. Oligochaeta, D. Polychaeta, E. Copepoda, F. Kinorhyncha, and G. Nematoda. Not to scale

Meiobenthic assemblages

Nine major meiofaunal taxa were found in both seasons, namely Nematoda, Sarcomastigophora, Copepoda, Rotifera, Oligochaeta, Halacaroidea, Polychaeta, Ostracoda, and Kinorhyncha (Table 4). Nematoda was the dominant taxon for both seasons, accounted for 93% and 95% during the SWM and NEM, respectively (Figure 3). Total meiofauna density was significantly higher in SWM (5195.01±2441.82 ind./10 cm^2) than in NEM (3353.64±2502.01 ind./10 cm^2), primarily driven by nematode abundance. In SWM, total meiofaunal density was highest at MG4 (1475.47 ind./10 cm^2), followed by MG3 (1442.41 ind./10 cm^2) and MG2 (1426.40 ind./10 cm^2), while the lowest density occurred at MG1 (850.73 ind./10 cm^2). Total nematode abundance was markedly high at 4813.10±2196.03 ind./10 cm^2, followed by the Sarcomastigophora group (220.58±131.30 ind./10 cm^2).

Copepods contributed 124.12±73.08 ind./10 cm^2, while the remaining meiofaunal density was minimally represented by Rotifera, Oligochaeta, Halacaroidea, Polychaeta, Ostracoda, and Kinorhyncha. During NEM, densities peaked at MG4 (1316.84 ind./10 cm^2), followed by MG1 (882.12 ind./10 cm^2) and MG2 (829.11 ind./10 cm^2), with the lowest density recorded at MG3 (325.57 ind./10 cm^2). Nematode abundance still remained high (3199.17±2324.64 ind./10 cm^2), while the other taxa were collectively accounted for only 154.47 ind./10 cm^2. Paired t-test analysis revealed significant seasonal differences in the density of most meiofaunal groups, except for Ostracoda and Kinorhyncha (p>0.05). However, spatial variation across stations was not significant for most of the meiofaunal density in either season (One-way ANOVA, p>0.05), except for Sarcomastigophora and Oligochaeta during SWM. The representatives of the meiofaunal taxa observed in this study are illustrated in Figure 4.

Changes in the meiofaunal community structure

The PERMANOVA analysis revealed significant effects of both season and station on the community composition of meiofauna. Specifically, meiofaunal composition was significantly different between the two monsoons (SWM and NEM) and across the stations (MG1-MG4) (p<0.05) (Table 5). However, the interaction between season and station was not significant (p>0.05), suggesting that the spatial effect of station on meiofaunal composition remains consistent across both monsoon periods. The hierarchical cluster analysis revealed a clear seasonal separation of meiofaunal communities, with most SWM samples grouping together and most NEM samples forming a distinct cluster at ~75-80% similarity (Figure 5). This visual separation was supported by ANOSIM, which showed a moderate but highly significant difference between seasons (R = 0.558, p = 0.001). SIMPER analysis indicated that the high within-group similarity for SWM (88.42%) and NEM (86.46%) was driven by the dominance of Nematoda, contributing 74.55% and 78.62% to similarity, respectively. Although average dissimilarity between seasons was relatively low (17.70%), secondary taxa, including Sarcomastigophora (21.27%), Copepoda (17.30%), and Oligochaeta (8.84%), were more abundant during SWM, while Polychaeta (14.59%) and copepod nauplii (13.84%) were more prevalent during NEM. These results demonstrate that while nematodes dominate year-round, seasonal monsoon shifts influence the composition and relative abundance of secondary taxa, contributing to moderate but significant differences in community structure.

Table 4. Taxonomic classification of the nine major meiofaunal groups recorded across both monsoon seasons in the study area

Kingdom	Phylum	Class/group
Animalia	Nematoda	Nematoda
Protista	Sarcomastigophora	Sarcomastigophora
Animalia	Arthropoda	Copepoda
Animalia	Rotifera	Rotifera
Animalia	Annelida	Oligochaeta
Animalia	Arthropoda	Halacaroidea
Animalia	Annelida	Polychaeta
Animalia	Arthropoda	Ostracoda
Animalia	Kinorhyncha	Kinorhyncha

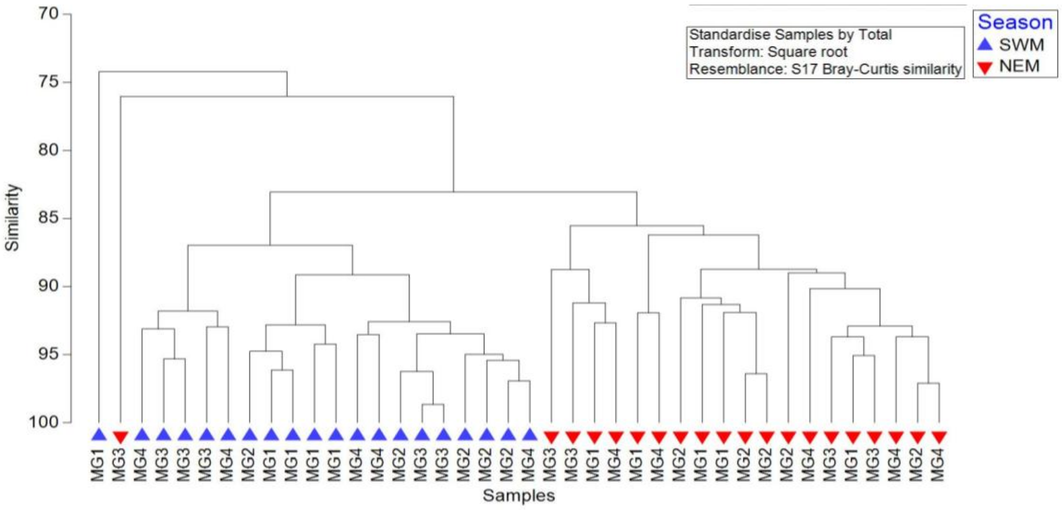

Figure 5. Cluster plot based on Bray-Curtis similarity coefficient of meiofaunal community from four stations (MG1-MG4) in SWM (triangles) and NEM (inverted triangles)

Table 5. Results of two-factor PERMANOVA analysis (“station” and “season” as fixed factors) for community composition for total meiofauna

Variable	Df	Sum of squares	Mean square	Pseudo-F	P(perm)
Season (Se)	1	3469.5	3469.5	9.3288	0.0003
Station (St)	3	2540.6	846.86	2.277	0.0182
Season x Station (Se x St)	3	1706.7	568.9	1.5297	0.1256
Residual (Res)	32	11901	371.91		
Total	39	19618			

Meiofauna diversity

Diversity indices showed no significant differences across stations (One-way ANOVA, p>0.05) or between monsoonal seasons (Paired t-test, p>0.05). Margalef’s Species Richness (d) shows moderate species richness, ranging from 0.97 to 1.34 and 0.87 to 1.26 during SWM and NEM, respectively. Pielou’s Evenness (J′) values exhibited little variation across all stations, ranging from 0.09 to 0.20 in both seasons, showing that the community is dominated by a few species, with other species being rare. Shannon-Wiener Diversity Index (H′) ranged between 0.31 and 0.46 in SWM and 0.19 and 0.32 in NEM, indicating low diversity with uneven distribution of individual taxa. The result of Simpson’s Index (1-λ) recorded the mean of 0.14 in SWM and 0.10 in NEM, demonstrating dominance by one or a few species (Table 6).

Relationship of the meiofaunal community with environmental variables

The dbRDA ordination revealed a clear seasonal separation of meiofaunal communities along the dbRDA1 axis (76.3% of fitted variation) (Figure 6). Assemblages during the SWM aligned with the salinity vector, indicating that interspace variability in salinity exerted a disproportionately strong influence on the community. In contrast, NEM assemblages were positioned towards higher DO and moderate OM values, reflecting a seasonal shift in environmental control whereby DO and OM were the predominant drivers of community differentiation. These patterns underscore a temporal shift in the relative importance of environmental variables, with salinity dominating in SWM, while DO and OM interactions exerting greater influence during NEM.

The correlation between each meiofaunal taxon and environmental variables was analyzed using Pearson correlation analysis. During SWM, the Sarcomastigophora group showed a very strong positive correlation with sand (r = 0.641), and strong negative correlations with both MGS (r = -0.590) and clay (r = -0.471) (Table 7). Similarly, Polychaeta exhibited strong positive correlations with sand (r = 0.502), while being negatively correlated with MGS (r = -0.451), suggesting a preference for coarser, sand-dominated sediments. In contrast, Oligochaeta showed a strong positive correlation with MGS (r = 0.688) and clay (r = 0.517), while strongly negatively correlated with sand (r = -0.716), suggesting a preference for finer, clay-rich sediments. This pattern is also reflected in Copepoda, whose distribution was associated with finer sediment fractions, as indicated by a strong positive correlation with silt content (r = 0.537). Sarcomastigophora, Polychaeta, and Copepoda showed the tolerance to the organic-rich sediment, as demonstrated by the positive correlations with OM content (r = 0.615, 0.711, and 0.541, respectively). Meanwhile, in NEM, only Nematoda and Ostracoda showed a negative correlation with Organic Matter (OM) (r = -0.478 and r = -0.492, respectively), suggesting lower abundance in organically enriched sediments.

Table 6. Variation in benthic community indices for all stations during SWM and NEM

Stations	Richness (S)		Margalef's Index (d)		Pielou's Evenness (J')		Shannon-Wiener Index (H')		Simpson's Index (1−λ′)	
	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM
MG1	10	9	1.34	1.19	0.20	0.13	0.46	0.28	0.19	0.09
MG2	8	9	0.97	1.20	0.12	0.09	0.24	0.19	0.09	0.06
MG3	9	6	1.11	0.87	0.17	0.18	0.37	0.32	0.16	0.13
MG4	9	10	1.10	1.26	0.14	0.12	0.31	0.28	0.13	0.10

Note: S: Total number of species, d: Species richness (Margalef), J′: Pielou's Evenness, H′: Shannon-Wiener Index, 1−λ′: Simpson Index

Table 7. Pearson correlation coefficients (r) between meiofaunal groups and sedimentary parameters (OM, MGS, sand, silt, and clay) during the SWM and NEM

Meiofauna Taxa	OM		MGS		Sand		Silt		Clay	
	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM
Nematoda	0.340	-0.478*	-0.193	0.427	0.336	0.0306	-0.372	-0.274	-0.074	0.363
Sarcomastigophora	0.615*	-0.201	-0.590**	0.144	0.641**	0.192	-0.241	-0.160	-0.471*	-0.096
Copepoda	0.541*	-0.438	0.163	0.212	-0.360	0.102	0.537*	-0.334	-0.063	0.187
Rotifera	0.414	-0.357	0.594	0.222	-0.261	0.024	0.399	-0.235	-0.039	0.137
Copepod Nauplii	0.347	-0.357	0.078	0.222	-0.186	0.024	0.320	-0.235	-0.049	0.137
Oligochaeta	-0.144	-0.255	0.688**	0.199	-0.716**	-0.001	0.264	-0.130	0.517*	0.019
Halacaroidea	0.147	-0.046	0.126	0.025	-0.248	-0.050	0.378	0.002	-0.033	0.415
Polychaeta	0.711**	-0.440	-0.451*	0.121	0.502*	0.288	-0.165	-0.394	-0.385	-0.053
Ostracoda	0.038	-0.492*	0.176	0.098	-0.326	0.257	0.411	-0.395	0.015	0.139
Kinorhyncha	-0.229	-0.118	0.004	0.113	-0.025	-0.269	0.138	0.017	-0.055	0.020

Note: Significant at the *p<0.05 and **p<0.01 level (2 tailed)

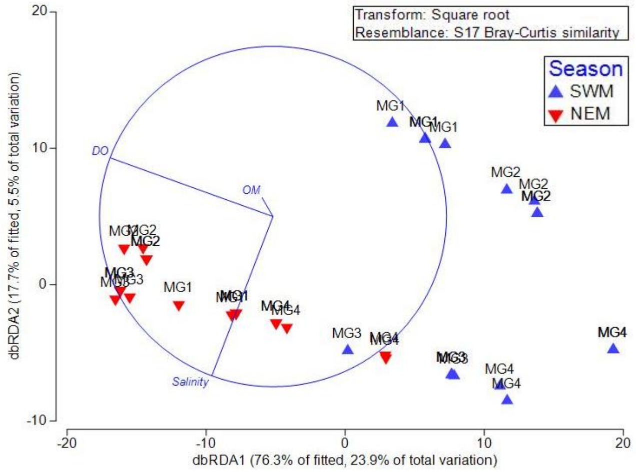

Figure 6. dbRDA ordination of meiofaunal communities during the SWM (triangles) and NEM (inverted triangles), with environmental vectors based on DistLM

For water quality, during SWM, the Sarcomastigophora group showed a strong negative correlation with pH (r = -0.590); in contrast, Copepoda, Oligochaeta, and Ostracoda showed positive correlations with pH (r = 0.580, 0.717, and 0.455, respectively), indicating a different tolerance in pH ranges. For salinity, Sarcomastigophora and Polychaeta displayed positive correlations (r = 0.728 and 0.566, respectively), while Oligochaeta showed a strong negative correlation (r = -0.775), suggesting a preference for less saline conditions. Meanwhile, in NEM, Halacaroidea showed a moderate negative correlation with pH (r = -0.497), suggesting a preference for more acidic conditions. Kinorhyncha exhibited a moderate negative correlation with DO (r = -0.449), indicating possible tolerance for lower oxygen levels. For the other taxa, Sarcomastigophora, Copepoda, Rotifera, Copepod nauplii, Oligochaeta, and Polychaeta, displayed weak and non-significant correlations with all measured environmental parameters, suggesting no strong relationship between their distribution and these factors (Table 8).

Table 8. Pearson correlation coefficients (r) between meiofaunal groups and water quality parameters (temperature, salinity, pH, and DO) in SWM and NEM

Meiofauna Taxa	pH		Salinity		DO		Temperature	
	SWM	NEM	SWM	NEM	SWM	NEM	SWM	NEM
Nematoda	-0.336	-0.200	0.314	-0.05	-0.204	-0.109	-0.123	0.243
Sarcomastigophora	-0.590**	0.260	0.728**	0.433	-0.003	-0.006	-0.380	0.298
Copepoda	0.580**	0.081	-0.339	0.044	0.354	-0.153	0.358	0.262
Rotifera	0.312	-0.027	-0.256	-0.374	0.192	-0.350	0.249	0.141
Copepod Nauplii	0.254	0.086	-0.198	0.024	0.165	-0.183	0.200	0.222
Oligochaeta	0.717**	0.129	-0.775**	0.117	-0.031	-0.163	0.430	0.181
Halacaroidea	0.372	-0.497*	-0.300	-0.365	0.152	0.211	0.115	-0.286
Polychaeta	-0.432	0.270	0.566**	0.355	-0.126	-0.063	-0.346	0.255
Ostracoda	0.455*	0.081	-0.317	0.206	0.215	0.003	0.07	0.140
Kinorhyncha	0.078	0.251	-0.121	-0.045	-0.108	-0.449*	-0.173	0.240

Note: Significant at the *p<0.05 and **p<0.01 level (2 tailed)

Discussion

In the intricate web of mangrove ecosystems, meiofauna play a crucial role in the process of nutrient remineralization. Meiofauna enhance prokaryotic activity, hence facilitating the breakdown and recycling of organic matter, significantly contributing to ecosystem health and ensuring nutrient availability for larger organisms while promoting a balanced habitat (Carugati et al. 2018). Mangrove ecosystems under tropical monsoon climates experience changes in environmental factors, through fluctuating salinity, nutrient availability, and physical disturbances (Hongwiset et al. 2021). Such disturbances have been known to regulate and control the seasonal distribution of biological communities (Qureshi et al. 2016). The present study reveals significant spatial and temporal variations in meiofaunal abundance within mangrove ecosystems during the SWM and NEM. The analysis showed clear spatial and seasonal differences in meiofaunal distribution, primarily influenced by the presence and distribution of nematodes. Muddy sediments in mangrove ecosystems provide essential habitats for benthic meiofauna communities, where nematodes comprise over 80% of the population, highlighting their ecological importance (Portnova et al. 2017). In the present study, nematodes accounted for more than 90% of the total densities, consistent with findings from other mangrove ecosystems, where they comprised 73.69-96.2% in Ca Mau province (Tran et al. 2017) and 98.35% in the mangrove tidal flat of Futian, Shenzhen, China (Song et al. 2022). Similarly, Hu et al. (2023) reported nematodes contributing 85.92-92.91% of meiofaunal abundance with the presence and absence of *Spartina alterniflora* Loisel., while Mutua et al. (2013) observed nematodes dominating over 90% of meiofaunal densities in both natural and reforested mangrove stands. Nematodes were also found abundantly in Australian mangroves (Della Patrona et al. 2016; Abdullah and Lee 2017), India (Ghosh et al. 2018; Ghosh and Mandal 2019), Sudan (Khalil 2019), Saudi Arabia (Al-Sofyani and El-Sherbiny 2018), Africa (Ihinmikaiye and Roberts 2025), Brazil (Netto and Galucci 2003), and Taiwan (Cai et al. 2020). Their high abundance has often been associated with low Shannon-Wiener and Simpson's Diversity Index values. Other taxa, such as Sarcomastigophora, Copepoda, Rotifera, Oligochaeta, Halacaroidea, Polychaeta, Ostracoda, and Kinorhyncha, occur in low densities. The low evenness observed further suggests niche specialization or competitive exclusion by dominant nematodes, restricting the distribution of other groups.

Physicochemical factors play a key role in shaping meiofaunal distribution patterns, with seasonal variation exerting a pronounced influence on both water variables (salinity, pH, temperature, and DO) (de Souza Sampaio et al. 2020; Merit and Smith 2023) and sedimentary properties such as organic matter content (Kathiresan et al. 2014). The PCA of environmental parameters revealed a clear seasonal separation, with SWM stations associated with higher temperature, sand, and OM content, while NEM stations aligned with higher salinity and DO. The dbRDA further confirmed that DO, OM, and salinity were the key environmental drivers structuring meiofaunal communities. The dominance of nematodes, with no significant associations to environmental variables other than a negative correlation with OM in NEM, indicates their adaptability and versatility in exploiting available food resources in mangrove sediments. Similarly, Ansari et al. (2013) reported higher nematode densities in lower organic carbon sediment, where epigrowth feeders prevailed under conditions of organic enrichment in surface sediments. The comparatively patchy and low distribution of other meiofaunal taxa in the present study is consistent with patterns reported in other mangrove systems (Abdullah and Lee 2017; Du et al. 2018; Khalil 2019; Sharma et al. 2021). High freshwater influx during rainfall in SWM may benefit meiofaunal species tolerant of lower salinity, as only euryhaline organisms can survive and continually recruit during the monsoon season (Desai et al. 2018). Salinity fluctuations can also stipulate ambient pH, substantially important for benthic foraminiferal tests (Saraswat et al. 2015). These conditions in SWM, together with higher sand content, may explain the elevated abundance of Sarcomastigophora, reflecting substrate preferences associated with habitat stability (Winanto et al. 2022).

Polychaeta abundance in the present study was strongly correlated with OM and positively associated with sand content. The higher silt-clay content can hold greater OM (Wafula et al. 2019), likely providing enriched food resources that supported higher Polychaeta densities during the SWM. As noted by Putro et al. (2025), both organic carbon and coarse sand fraction are key abiotic factors influencing polychaete distribution in mangrove sediments, with sandy areas offering optimal feeding conditions. Sandy substrates not only influence nutrient availability but also promote higher oxygen penetration, as indicated by the positive correlations between Polychaeta abundance, salinity, and DO. This preference for oxygenated conditions aligns with their known behavior of enhancing oxygen availability within burrows (Musale et al. 2015; Fang et al. 2022). Copepods ranked third in abundance during the SWM and showed positive correlations with silt content, higher OM, and more alkaline conditions. Although microcrustacean species are generally associated with coarser sediment fractions containing free or labile OM (De Souza Silva-Camacho et al. 2013), and such substrates generate well-oxygenated interstitial microhabitats that facilitate copepods' locomotion, foraging efficiency, and niche diversification (De Souza Silva-Camacho et al. 2013; Ramli et al. 2018), our findings indicate that copepods in this mangrove system were instead linked to finer sediments. Similar patterns were reported by Stringer et al. (2012), where *Robertsonia propinqua* (Scott T., 1894) and *Quinquelaophonte* sp. were positively associated with sediment particles smaller than 500 μm, with *R. propinqua* responding positively to organic content. This suggests that certain copepod species can exploit finer, organic-rich substrates, possibly due to greater detrital food availability. Furthermore, the positive correlation of *Quinquelaophonte* sp. with pH indicates a preference for more alkaline conditions, potentially reflecting an avoidance of acidic sediments that could impair physiological processes. This preference aligns with observations of *Bryocamptus* (*Limocamptus*) *echinatus* (Mrázek, 1893), a harpacticoid species that thrives in higher-pH environments, where conditions meet its ecological requirements and support essential biological activities such as foraging and reproduction (Zhai et al. 2015).

In the present study, Oligochaeta showed a clear preference for finer sediments, as indicated by their positive correlation with the MGS and clay content, and negative correlation with sand fraction. Their higher abundance likely contributes to the decomposition and remineralization of organic material, thereby supporting production at higher trophic levels in mangrove ecosystems (Chen et al. 2017). This finding aligns with Chen et al. (2017), who reported significant correlations of oligochaete density and biomass with silt content in both *Aegiceras corniculatum* (L.) Blanco and *Kandelia obovata* Sheue, H.Y.Liu & J.W.H.Yong habitats, where most species were brackish, soft mud forms in the Quanzhou Bay, China. Such associations with fine, cohesive sediments suggest a similar functional role to that observed in salt marshes, where bioturbation by oligochaetes enhances oxygen penetration, modifies sediment stability, and influences vegetation establishment, thereby contributing to habitat development and expansion (Van Regteren et al. 2017). Moreover, oligochaetes were also found to be correlated with pH and salinity, as shown by Sowa and Krodkiewska (2020), who found that high salinity can affect their distribution and lead to significant losses in diversity. In contrast, fewer significant correlations between meiofaunal abundance with environmental variables in NEM. Ostracoda were more abundant in less organic sediments, while Halacaroidea and Kinorhyncha were associated with lower pH and DO conditions, respectively, suggesting that the drier season altered environmental conditions and consequently induced notable shifts in meiofaunal abundance.

PERMANOVA, ANOSIM, and cluster analysis results demonstrated that seasonal variation exerted a stronger influence on meiofaunal community composition than spatial variation across stations. This suggests seasonal hydrological shifts exhibit greater effects than microhabitat within the mangrove sediment, as also noted in previous studies of estuarine meiofauna (Sharma et al. 2021). However, significant spatial variation, although less pronounced, reflects localized environmental heterogeneity that may influence specific taxa distributions (El-Serehy et al. 2016; Qureshi et al. 2016). Such dynamics underscore the critical role of environmental factors in shaping meiofaunal communities within tropical mangrove habitats. These findings suggest that understanding the specific environmental variables at play can enhance our ability to predict meiofaunal responses to changing conditions in tropical mangroves.

In conclusion, this study presents a pioneering investigation of meiofaunal communities within the Pulau Tuba mangrove ecosystem in Langkawi, providing crucial baseline information that is vital for understanding their ecological functions and guiding future research efforts in the area. The results show that seasonal monsoon changes play a major role in shaping meiofaunal abundance and composition, with nematodes being the dominant group in both monsoon seasons. The consistent prevalence of nematodes across environmental conditions highlights their value as bioindicators, with taxon-specific responses, diverse feeding strategies, and sensitivity to pollutants making them effective for detecting ecological shifts and assessing habitat quality (Schratzberger and Ingels 2018; Spedicato et al. 2023). Among the environmental factors, i.e., salinity and sediment characteristics, were the most significant influences on meiofaunal distribution, surpassing the impact of spatial differences between sampling stations. These findings add to the limited body of research on Malaysian and tropical mangrove meiofauna, and provide observational evidence that may inform conservation planning, sustainable management, and policy discussions aligned with SDGs 14 and 15. Further taxonomic identification of dominant meiofaunal groups, particularly nematodes, could help reveal their specific functional roles in mangrove sediment ecosystems and enhance understanding of ecosystem-based management approaches.

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