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Spatial Dynamics of Macrobenthos Assemblages in Different Breakwater Systems in Kuala Nerus, Terengganu, Malaysia

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ABSTRACT

The Sultan Mahmud Airport runway extension in 2008 resulted in coastal erosion along the Kuala Nerus shorelines. In response, different breakwater systems were constructed to mitigate erosion. Despite previous reports highlighting the effects of breakwaters on marine organisms, the local impact remains uncertain. Therefore, this study investigates the spatial impact of different breakwater systems on macrobenthos composition in the Kuala Nerus coastal area. Samplings were conducted at 12 substations across five main stations, covering sheltered and exposed areas. Results revealed 27,137 macrobenthos individuals, with groyne exhibiting the highest macrobenthos composition (8448.79 ± 2813.73 ind./m^2). Gastropoda dominated (4971.01–41608.70 ind./m^2), followed by Bivalvia (2927.54–12391.20 ind./m^2) and Polychaeta (1000.00–4956.52 ind./m^2). Macrobenthos compositions in the sheltered and exposed stations differed significantly ($p < 0.05$). The coastal area is predominantly sandy (30.68%–77.32%) with relatively stable total organic matter (TOM) and heavy metal concentrations. Current speed and significant wave height (H_s) are lower in sheltered stations, while bathymetry is deeper in exposed stations (up to 8 m). The macrobenthos assemblages are influenced by soft-bottom characteristics and food availability, with the hydrodynamic stress from the breakwater system governing these two primary factors.

Keywords: Bathymetry, breakwater system, groyne, Kuala Nerus, macrobenthos

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INTRODUCTION

Macrobenthos composed of macroinvertebrates with sizes of 500 µm and above, including annelids, molluscs, crustaceans, and echinoderms, inhabit the soft-bottom substrates of marine and estuarine environments (Amfa et al., 2020). These communities play significant and diverse ecological roles, such as maintaining the sediment and water quality of the areas, serving as important food sources for fishes, larger invertebrates, and birds, and functioning as great bioindicator species (Araujo-Leyva et al., 2020; Ehrnsten et al., 2022). Benthic organisms with a significant relationship with sediments are highly susceptible to contaminants due to prolonged exposure and limited movement (Desrosiers et al., 2019). Therefore, changes in their composition could indicate an area's health status, including in modified coastal regions with breakwater systems (Costas, 2016).

Kuala Nerus district, encompassing an area of 40,000 hectares, has experienced rapid urbanisation driven by business activity, eco-tourism gateway, sports and recreational events, and educational hub, supporting its dense population of approximately 158,000 people in 2002 (Ahmad et al., 2014; Wahid, 2022). Naturally, the fishing and local villages along the Kuala Nerus northern coast have been highly vulnerable to intense wave action and erosion, particularly during the annual northeast monsoon season. The erosion worsened following the completion of the Sultan Mahmud Airport runway extension in 2010 (Zulfakar et al., 2020). In response to this erosion, different breakwater systems, including groyne, semi-enclosed jetty-type and parallel breakwaters, and revetments, were installed along the Kuala Nerus coastline to mitigate erosion.

The groyne in Teluk Ketapang was initially built for airport runway extension, marking the inception of coastal structures in the Kuala Nerus district (Ariffin et al., 2020). Following that, the semi-enclosed jetty-type breakwater in Tok Jembal, originally parallel, was later repurposed to sustain the local fishing community, providing a safer and calmer harbour and maintaining the navigation channel's depth (Ariffin et al., 2018). Additional groynes, revetments, and parallel breakwaters were constructed between December 2016 and December 2020 to enhance coastal protection further. They were strategically placed along the northern Kuala Nerus coast to defend against wave action and currents, ultimately reducing erosion in the affected areas.

Breakwater systems are coastal engineering structures designated to defend and protect shore areas, harbours, marinas and navigation channels from the effects of waves, currents and tides (Schoonees et al., 2019). Nonetheless, they pose significant negative impacts, such as affecting the coastal ecosystems' function, reducing shoreline resilience, influencing sediment transport, fragmenting the coastal space and disturbing macrobenthos habitat (Fitri et al., 2019; Jahangirzadeh et al., 2012). The sediment compositions (organic matter and contaminants) determine the macrobenthos habitats, food sources, health and reproductive success (Matthiessen & Law, 2002). The hydrodynamic condition influences sediment transport, resulted in burying and exposing benthic organisms, affecting their survival and distribution (Wiesebron et al., 2021).

In Malaysia, breakwater systems are expected to increase due to the growing coastal populations, expanding coastal cities, and climate change threats (Siegel, 2020). However, despite its increasing prevalence, limited studies examine its environmental impacts, particularly concerning coastal ecosystems' ecological perspective, biodiversity, and productivity. In addition, the breakwater systems' research is often overlooked and given less priority by the scientific community, funding agencies, and policymakers, likely due to its multidisciplinary nature. This lack of focus hinders a comprehensive understanding of the ecological consequences of coastal armouring, impeding effective coastal management strategies.

Furthermore, the ecological importance of macrobenthos is significant, especially in light of coastal development's impact on the coastal ecosystem (Chowdhury et al., 2024). However, there is a paucity of research investigating the impacts of breakwater installation on the benthic community. Hence, this study provides valuable insights into the repercussions of different breakwater systems on local marine ecosystems, highlighting the complex interactions between soft-bottom characteristics, food availability, and hydrodynamic stress. While previous global reports highlighted the potential impact of such structures on marine organisms, this research adds novelty by providing empirical data on the actual effects.

This study hypothesised that various coastal structures in Kuala Nerus may have distinct effects on sediment characteristics, seabed condition and hydrodynamics, which may, in turn, modify the food sources' distribution and composition, ultimately impacting the macrobenthos composition, abundance and trophic structure (Holzhauer et al., 2020). The primary objective of this study is to investigate the spatial impact of different breakwater systems in Kuala Nerus on the benthic community over one monsoonal cycle, supported by comprehensive environmental data of sediment (grain size, organic matter and heavy metals) and water physical parameters acquired through multiple field surveys.

MATERIALS AND METHODS

Samplings have been conducted at five main stations with 12 substations (average depth 7 m) in the Kuala Nerus coastal area, specifically from the Sultan Mahmud Airport runway (5°23′25.7″ N, 103°06′59.9″ E) to Batu Rakit (as a reference station) (5°27′09.0″ N, 103°02′58.4″ E), covering different breakwater systems such as groyne (St. 1), semi-enclosed jetty-type breakwater (St. 2), and parallel breakwaters—without (St. 3) and with tombolo (St. 4), in the first four stations (Table 1; Figure 1). Sampling over one monsoonal cycle was conducted as follows: in March 2021 and 2022, representing the post-northeast monsoon (NEM) season; in July 2021, denoted the southwest monsoon (SWM) season;

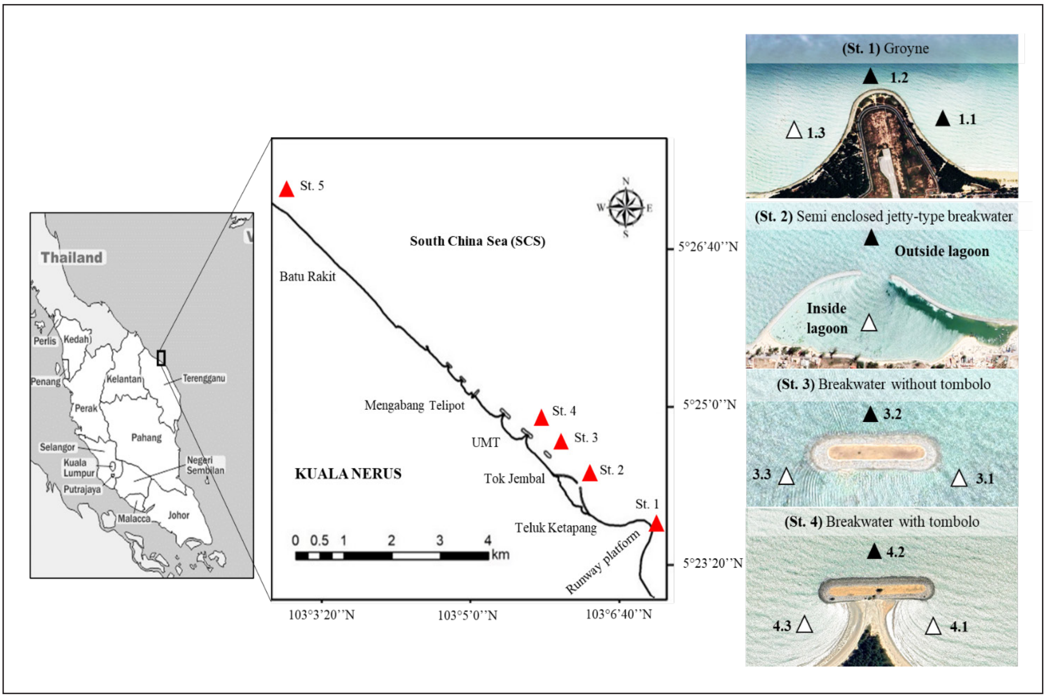

Figure 1. Map of the study sites along the Kuala Nerus coastal area. Map of Peninsular Malaysia showing the location of Kuala Nerus, Terengganu (left), and five main stations near the different breakwater systems along the Kuala Nerus coastal area (right). Station 1: groyne; Station 2: semi-enclosed jetty-type breakwater; Station 3: parallel breakwater without tombolo; Station 4: parallel breakwater with tombolo; and Station 5: Reference station in Batu Rakit (free from breakwater). ▲: exposed substations. Δ: sheltered substations

Table 1
Geographical location and category of 12 substations from five main stations of different breakwater systems in Kuala Nerus, Terengganu

	Stations (St.)	Locations	Substations	Latitude (N)	Longitude (N)	Category
1	Groyne	Teluk Ketapang	1.1	5°23'25.7"	103°06'59.9"	Exposed
			1.2	5°23'47.5"	103°07'04.3"	Exposed
			1.3	5°23'58.0"	103°06'26.6"	Sheltered
2	Semi-enclosed jetty-type breakwater	Tok Jembal	Outside lagoon	5°24'08.2"	103°06'06.6"	Exposed
			Inside lagoon	5°24'12.6"	103°06'15.5"	Sheltered
3	Parallel breakwater without tombolo	Tok Jembal	3.1	5°24'21.6"	103°05'56.7"	Sheltered
			3.2	5°24'32.4"	103°05'54.2"	Exposed
			3.3	5°24'32.0"	103°05'45.7"	Sheltered
4	Parallel breakwater with tombolo	Tok Jembal	4.1	5°24'38.2"	103°05'39.4"	Sheltered
			4.2	5°24'45.9"	103°05'40.3"	Exposed
			4.3	5°24'42.9"	103°05'33.4"	Sheltered
5	Reference station	Batu Rakit	5	5°27'09.0"	103°02'58.4"	Exposed

in October 2021, representing the post-SWM season; and in December 2021 indicating the NEM, subjected to suitable tides, sea conditions, and weather. Sampling locations were based on the water current flow and longshore drift, likely influencing the sediment types and macrobenthos distribution. The substations were categorised as either sheltered (the inner, left, and right sides of breakwater systems) or exposed (directly facing the sea). Coordinates of all sampling locations were marked using the Global Positioning System (GPS).

Macrobenthos Collection

A total of 36 sediment samples were collected (triplicates at each substation) using a Ponar grab with a 0.023 m^2 surface area operated from a boat (Discovery IV of Universiti Malaysia Terengganu). Samples were prepared for environmental and biological analyses. Approximately 150 g of sediment samples were allocated for grain size determination, total organic matter (TOM) measurement, and heavy metal analysis. Simultaneously, biological analyses comprising macrobenthos from the remaining samples were retrieved via the decantation method using a 0.5 mm mesh size sieve, preserved in 80% ethanol, and stored in labelled containers for further identification (Ibrahim et al., 2023).

The ethanol-preserved sediment samples containing macrobenthos were roughly sorted under a stereoscopic microscope to remove shell fragments, grain particles, and macro-marine debris. Subsequently, the clean macrobenthos samples were finely sorted for species classification, identification, and quantification using references such as Abele and Kim (1986), Day (1967), Gibson and Knight-Jones (2017), and Valentich-Scott (2003).

Grain Size, TOM, and Heavy Metals

In grain size analysis, approximately 100 g of sediments were oven-dried at 70°C for 72 hours and then dry-sieved using an Octagon mechanical shaker with 4, 2, 1, 0.5, 0.25, 0.15, and 0.63-mm layer sizes. The sediments retained on each layer were weighed, and the data were computed in Microsoft Excel for further analysis (Bachok et al., 2009).

The TOM content in sediments was determined using a loss-on-ignition method, ashed at 550°C for eight hours in a muffle furnace (Carbolite Gero, UK) (Bensharada et al., 2022). Heavy metal detection encompassing lithium (Li), chromium (Cr), lead (Pb), copper (Cu), zinc (Zn), iron (Fe), and cadmium (Cd) was performed using the Teflon bomb digestion method (Ong et al., 2016), and measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS Perkin Elmer ELAN 6100) (Method EPA 6020A; EPA, 2007).

Water Physical and Hydrodynamic Parameters

Triplicates water physical parameters' readings (salinity, pH, dissolved oxygen [DO], and temperature) were recorded using a Quanta Multiparameter Probe (OTT Messtechnik

GmbH & Co. KG) at seawater surface (~ 1 m depth). Bathymetry data from the Kuala Terengganu River mouth estuary until Batu Rakit was obtained from a study by Ariffin et al. (2020). The estimation of the wave and current patterns of Kuala Nerus was performed using MIKE 21 Spectral Wave and Flow Model FM. Wave and current data validation was conducted by field sampling using an Acoustic Doppler Current Profiler (ADCP) in July 2021. Tidal readings were computed using harmonic constants at the Kuala Terengganu tidal station, provided by the Royal Malaysian Navy. The model used secondary wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) as a time series input.

Data Analysis

Macrobenthos density (ind./m^2), relative abundance (%), Margalef species richness (d), Shannon diversity index (H′), and Pielou's evenness index (J′) were determined at each substation using Paleontological Statistics Software Package (PAST). Mann–Whitney and Kruskal–Wallis tests were used for non-normally distributed data ($p < 0.05$). Subsequently, species composition and abundance were grouped using the Bray–Curtis similarity coefficient (Bray & Curtis, 1957) displayed in the dendrogram plot. The relationship between the biological indices and environmental factors of the sediment characteristics (organic matter, heavy metal, gravel, sand, silt, and clay) and physical parameters (current speed, significant wave height, depth, wind speed, temperature, DO, salinity, and pH), were analysed using Spearmen's correlation and Multiple Linear Regression (MLR) analysis by utilising Statistical Package for the Social Sciences (IBM SPSS Statistics version 21). The MLR models were constructed using a stepwise approach, where variables were added or removed based on their significance levels ($p < 0.05$). Model fit was assessed using the coefficient of determination (R^2) and Kruskal–Wallis. Assumptions of MLR, including linearity, independence of residuals, homoscedasticity, and normality of residuals, were checked and met. The relationship between macroinvertebrate assemblages and environmental variables was further analysed using principal component analysis (PCA), computed in statistical software, PAST version 2.14.

RESULTS

Species Composition and Abundance of Macrobenthos

A total of 27,137 macrobenthos individuals belonging to 7 phyla, 16 classes, 92 families, 124 genera, and approximately 144 species were recorded in the present study. The commonly shared phyla among all stations were Mollusca, Annelida, Arthropoda, and Echinodermata. The commonly shared classes at the lower taxonomic level included Gastropoda, Bivalvia, Scaphopoda, Polychaeta, Ostracoda, Malacostraca, and Echinoidea. Phylum Mollusca recorded the highest composition (90.68%), followed by Annelida (6.19%) and Arthropoda (2.26%). In detail, Gastropoda had the highest abundance (4971.01–41608.70 ind./m^2),

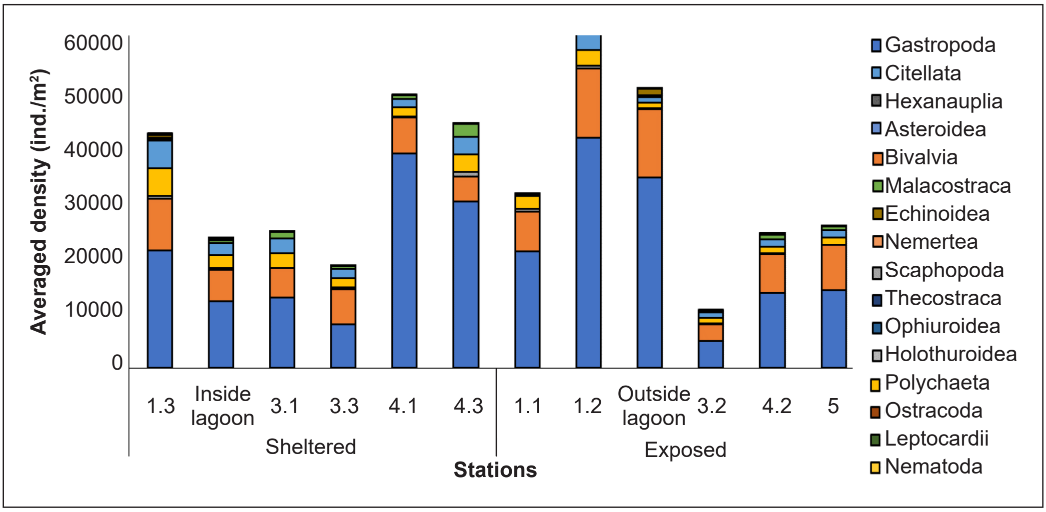

Figure 2. Average density (ind./m^2) of macrobenthos (class taxa) throughout the sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu

followed by Bivalvia (2927.54–12391.20 ind./m^2) and Polychaeta (1000.00–4956.52 ind./m^2) (Figure 2).

The highest average macrobenthos density was documented in station 1 of the groyne structure (8448.79 ± 2813.733 ind./m^2), whereas the lowest was in station 3 of parallel breakwater without tombolo (3213.53 ± 1276.324 ind./m^2) (Figure 3). The macrobenthos density in the reference station (St. 5) documented half of the first station (groyne) (4872.46 ind./m^2). The macrobenthos density in the sheltered stations is higher (201956.52 ± 12982.672 ind./m^2) than in the exposed stations (177340.58 ± 20267.560 ind./m^2). A significant macrobenthos density was detected among the five main stations of different breakwater systems and between sheltered and exposed sites ($p < 0.05$).

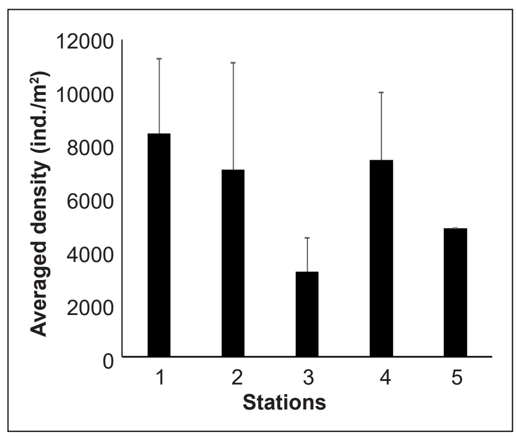

Figure 3. Average density (ind./m^2) of macrobenthos in five main stations of coastal man-made structure areas in Kuala Nerus, Terengganu

Species diversity (H′) ranged from 2.014 to 2.878, with the sheltered stations recording a lower species diversity (H'= 2.014–2.622) (Figure 4). Macrobenthos in both sheltered and exposed stations were interpreted as having low to moderate species diversity (H'= 2.014–2.878). The evenness index (J′) ranged from 0.410 to 0.802, with the sheltered stations recording lower values (0.410–0.729). The Margalef richness index varied from 4.185 to 6.028, showing relatively stable values across the sheltered stations, in contrast to the more variable values observed at the exposed stations. No significant differences in macrobenthos diversity, evenness, and richness were detected between the sheltered and exposed stations ($p > 0.05$).

Spatially, two prominent groups were recorded at a 48% similarity level, separating exposed station 3.2 from the others (Figure 5). At approximately 63%, another two main groups were documented, splitting Clusters A and B. In Cluster A, the exposed and sheltered sides of station 1 of the large groyne (substations 1.1 and 1.3) were grouped. The cluster was further divided into two main groups: 1) station 3.3 (80% similarity level) and 2) stations 4.2 and 5 (96% similarity level), and the stations of the inside lagoon and station 3.1 (93% similarity level). In Cluster B, at an 81% similarity level, two main branches formed, with sheltered station 4.3 standing alone and separated from another branch.

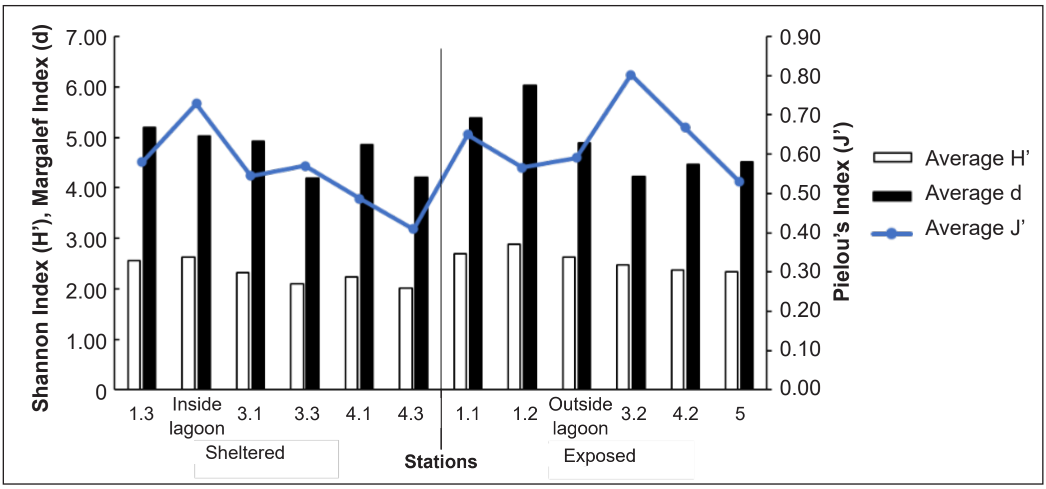

Figure 4. Species diversity (H′), richness (d), and evenness (J′) of macrobenthos across sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu

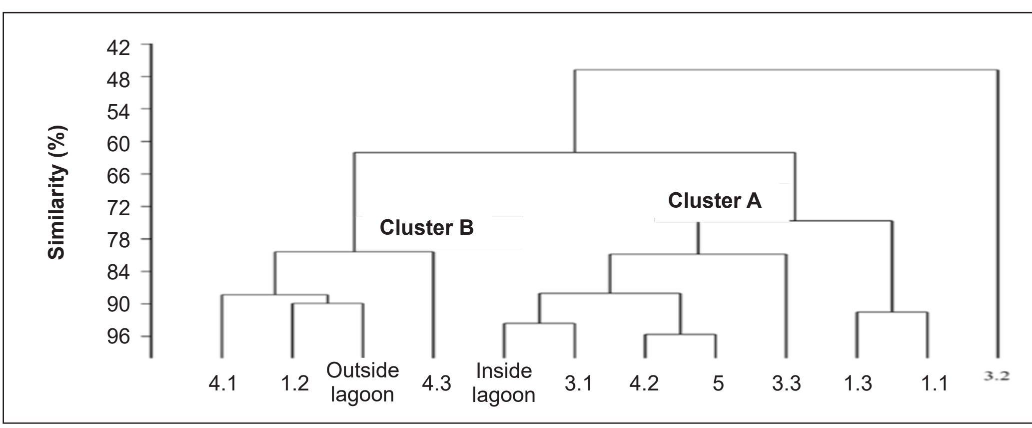

Figure 5. Bray-Curtis similarity based on hierarchical clustering of substations shown using a dendrogram plot showing the macrobenthos assemblage pattern in different breakwater systems in Kuala Nerus

Environmental Aspects of Different Breakwater Systems

Various sand sizes have mostly made up the soft bottom of the Kuala Nerus coastal area (Figure 6). In detail, the sheltered stations are dominated by very fine sand (30.680%–77.322%) and the exposed stations are governed by coarse sand (up to 44.34%). Overall, TOM content ranges from 0.88% to 2.97% (Figure 7), with the sheltered stations being relatively stable compared to the exposed stations. No significant difference exists in TOM percentages between the sheltered and exposed stations ($p > 0.05$). The heavy metal concentrations of lithium (Li), chromium (Cr), iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) in the surface sediments of the Kuala Nerus coastal area are within the allowed value for the Upper Continental Crust (UCC) (Table 2). Hence, the area is considered uncontaminated and unpolluted.

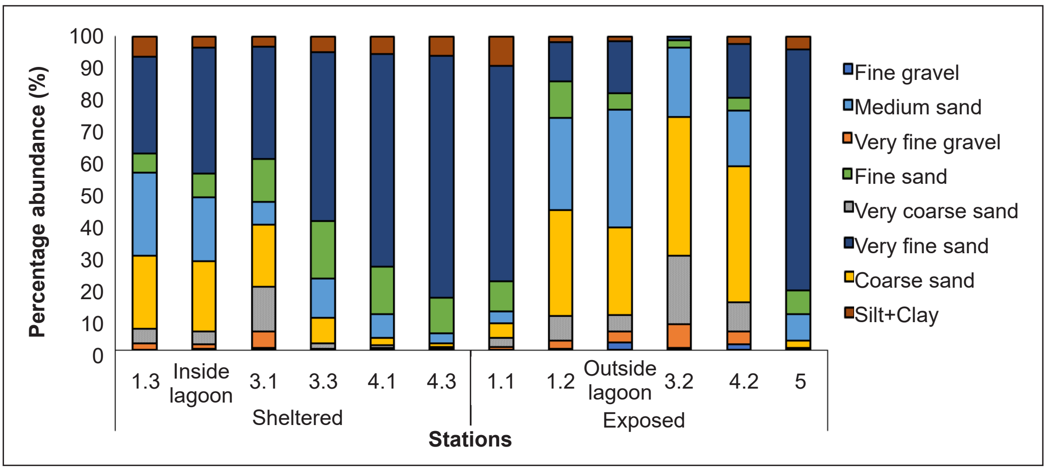

Figure 6. Sediment characteristics at sheltered and exposed stations in coastal man-made structure areas in Kuala Nerus, Terengganu

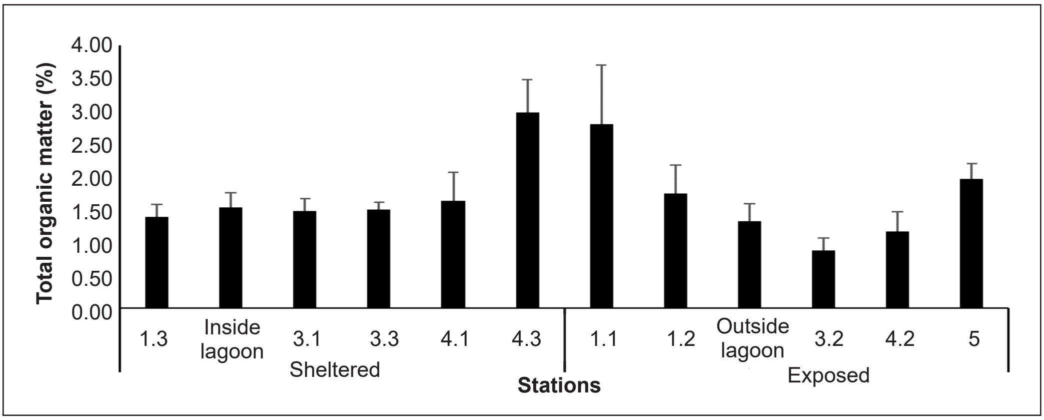

Figure 7. Percentage value of total organic matter content (%) across sheltered and exposed stations in different breakwater systems in Kuala Nerus, Terengganu

The current speed showed a decreasing pattern across the sheltered stations and an increasing trend across the exposed stations, ranging from 0.0292 to 0.0421 m/s and 0.0507 to 0.0812 m/s, respectively (Figure 8). A consistently low significant wave height

Table 2
Heavy metal concentrations in the sheltered and exposed sites of the different breakwater systems in Kuala Nerus. UCC = upper continental crust

	Average of heavy metals (ppm)												
	Sheltered						Exposed						
	1.3	Inside lagoon	3.1	3.3	4.1	4.3	1.1	1.2	Outside lagoon	3.2	4.2	5	UCC
Li	3.82	3.11	4.18	4.18	4.18	6.09	4.77	3.68	2.85	2.75	4.16	4.45	22
Cr	4.97	3.51	1.29	11.11	6.11	8.38	3.15	2.16	8.41	6.79	3.76	8.05	35
Fe (%)	4.86	3.67	3.60	6.44	10.87	13.55	8.47	4.51	3.95	4.69	6.39	12.62	308.9
Cu	0.67	0.30	0.82	2.14	0.18	0.26	0.98	0.17	0.40	0.89	1.12	0.29	14.3
Zn	4.12	4.09	6.02	6.66	6.25	6.63	6.96	5.01	3.17	2.80	5.97	6.01	52
Cd	0.02	0.02	0.05	0.06	0.04	0.02	0.03	0.03	0.01	0.00	0.03	0.02	0.1
Pb	0.96	0.85	1.05	1.27	1.29	1.94	1.41	0.91	0.59	0.43	1.17	1.34	16
As	0.61	0.80	0.82	0.90	0.90	1.32	1.21	0.89	0.57	0.55	0.90	0.83	2
Hg	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.06

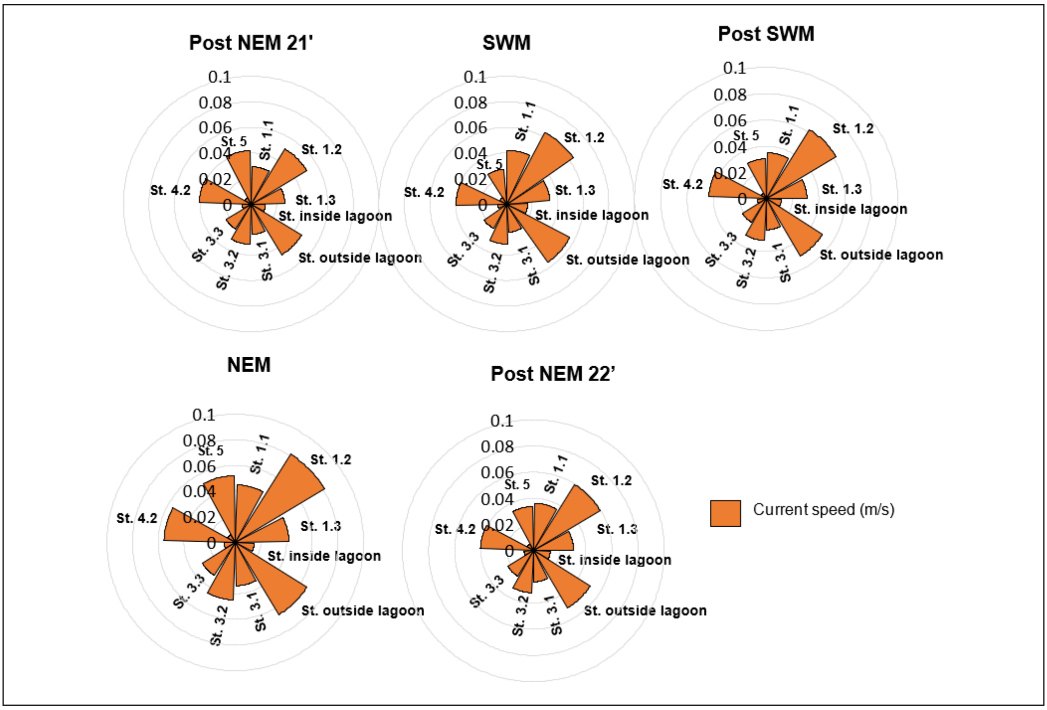

Figure 8. Temporal current speed (m/s) in the Kuala Nerus coastal area throughout the Asian monsoon system

(H_s) was recorded in the sheltered station (Figure 9). The bathymetry of the Kuala Nerus coastal area varied from 2.5 ± 0.5 to 8 ± 0.5 m, with a control station of 10 ± 1 m in depth (Figure 10). The deepest station was located at the front side of the large groyne (station 1.2), whereas the shallowest station was on the left side of the parallel breakwater without tombolo (station 3.3).

The average water parameters showed consistent readings (Figure 11). The temperature and salinity range from 29.23°C to 29.73°C and 31.44 to 32.02 ppt, respectively (Figure 11A), while the DO and pH range from 2.22 to 2.61 mg/L and 8.26 to 8.42, respectively (Figure 11B). Overall, no significant difference was detected in water physical parameters across the sheltered and exposed stations ($p > 0.05$).

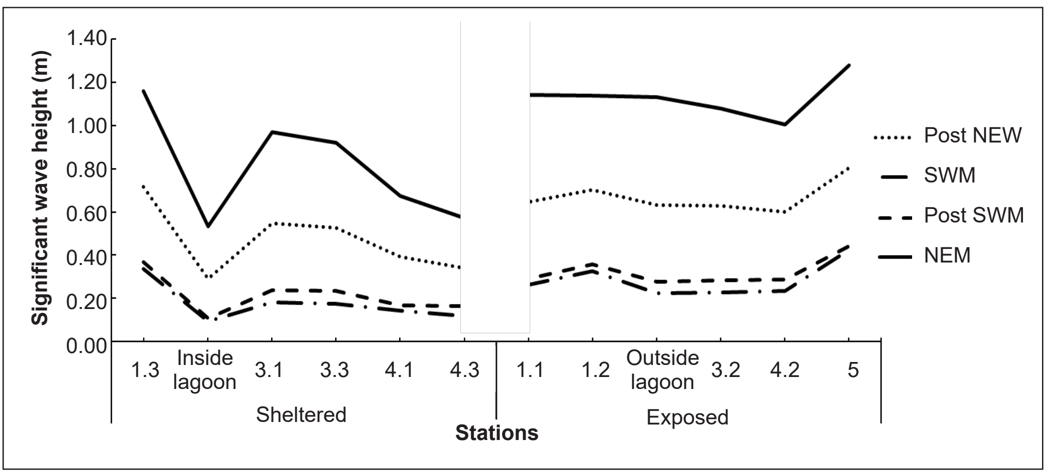

Figure 9. Seasonal significant wave height (Hs) at sheltered and exposed substations in different breakwater systems in Kuala Nerus, Terengganu

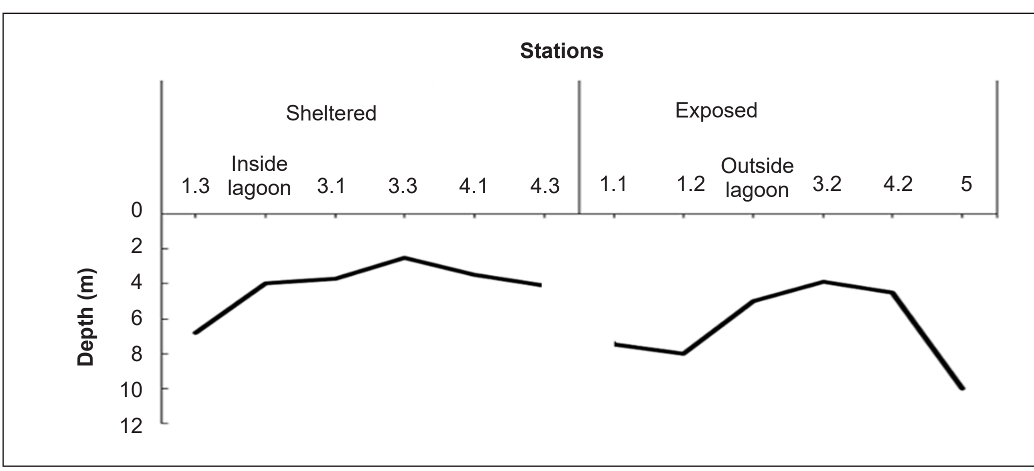

Figure 10. Bathymetry of the Kuala Nerus coastal area in sheltered and exposed substations in different breakwater systems

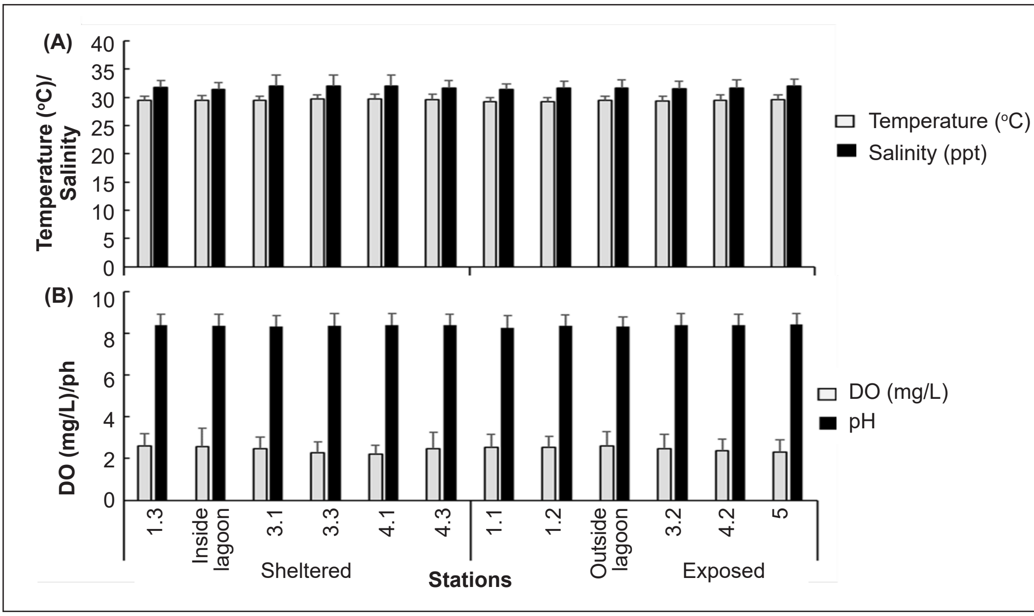

Figure 11. Average water physical parameters throughout sheltered and exposed stations in different breakwater systems in Kuala Nerus: (A) Temperature (°C) and salinity (ppt); and (B) Dissolved oxygen (DO) (mg/L) and pH

Relationship between Macrobenthos Assemblages and Environmental Parameters

PCA accounted for 43.75% of the sample variation in the first two axes (Figure 12). PC1 showed TOM, silt + clay, all heavy metal types, temperature, salinity and pH as the most significant factors with a positive correlation. In contrast, gravel, DO, current speed, and wave height revealed a negative correlation on factorial axis 1 (35.86% of the total variance). In PC2, current speed, wave height, depth, TOM, silt + clay, AS, Li, Fe, Pb and Zn were the most significant factors and positively correlated. In contrast, Cd, Cr, temperature, salinity, sand, pH, Cu, gravel, and DO negatively correlate on factorial axis 2 (7.85% of the sample's variation). The macrobenthos density strongly correlated positively with wave height, depth, TOM, and silt + clay, revealing a negative correlation with DO, gravel, Cu, pH, sand, salinity, and temperature. The macrobenthos diversity has a strong positive correlation with current speed, DO, gravel, wave height and depth and negatively correlates with pH, sand, salinity, temperature and heavy metals of Cr and Cd. The macrobenthos evenness has a strong positive correlation with gravel and DO and a strong negative correlation with TOM, silt and heavy metals of As, Li, Fe, Pb and Zn. The macrobenthos richness has a strong positive correlation with current speed, wave height, and depth, and it revealed a strong negative correlation with the pH, sand, salinity, temperature, and heavy metals of Cr and Cd.

Table 3 shows the spatial correlation between the environmental parameters and macrobenthos assemblages. Macrobenthos density had a significant positive correlation

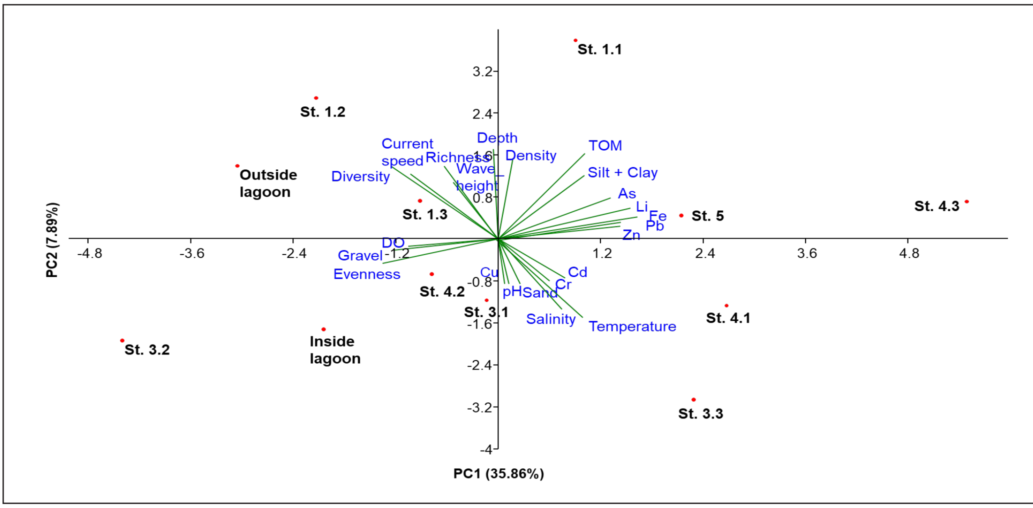

Figure 12. Principal component analysis (PCA) ordination showing sampled stations clustering based on a Euclidean distance matrix considering environmental parameters and four biotic assemblages (diversity, evenness, density, and richness)

Table 3

Spearmen's correlation (r) between each environmental parameter and macrobenthos assemblages in different breakwater systems in Kuala Nerus, Terengganu

Parameters	Density (ind./m^2)	Diversity (H′)	Evenness (J′)	Richness (S)
TOM (%)	**.417******	0.072	**−.467****	**.315***
Sand (%)	0.211	0.242	−0.030	0.204
Gravel (%)	0.185	0.192	0.088	0.205
Silt + clay (%)	−0.052	−0.126	−0.208	−0.094
Li (ppm)	0.090	−0.026	**−.380****	0.148
Cr (ppm)	0.180	0.030	−0.203	0.134
Pb (ppm)	0.159	0.007	**−.384****	0.207
Cu (ppm)	−0.085	0.070	0.033	0.096
Zn (ppm)	0.044	0.062	**−.255***	0.186
Fe (%)	0.107	−0.196	**−.270***	−0.032
Cd (ppm)	0.022	0.026	−0.230	0.198
As (ppm)	0.201	0.024	**−.467****	**.257***
Current speed (m/s)	0.039	0.170	0.213	−0.014
Wave height (m)	−0.199	−0.179	0.158	**−.298***
Depth (m)	**.262***	0.132	−0.059	0.079
Wind speed (m/s)	**−.388****	**−.319***	**.299***	**−.502****
Temperature (°C)	**.286***	0.140	−0.232	**.275***
DO (mg/L)	−0.250	−0.028	**.278***	−0.173
Salinity (ppt)	0.028	**.307***	0.003	**.342****
pH	0.021	−0.238	−0.062	−0.245

Note. **Correlation is significant at the 0.01 level (two-tailed); *Correlation is significant at the 0.05 level (two-tailed) with TOM (%), depth (m), temperature (°C), and wind speed (m/s) ($p < 0.05$). Macrobenthos diversity had a significant positive correlation with salinity (ppt) and a negative correlation with wind speed. Macrobenthos evenness showed significant positive correlations with the wind speed (m/s) and dissolved oxygen (DO) and a significant negative correlation with TOM (%) and heavy metals of Li, Pb, Zn, Fe, and As. Macrobenthos richness had a significant positive correlation with TOM (%), salinity, As, and temperature and a significant negative correlation with wind speed (m/s) and wave height (m).

Multiple Linear Regression (MLR) analysis revealed TOM (%) as the most significant predictor for macrobenthos density (Figure 13). Salinity, wind speed, and current speed were the significant predictors of macrobenthos diversity. TOM (%) and arsenic (As) were significant predictors for macrobenthos evenness, with As being the most important

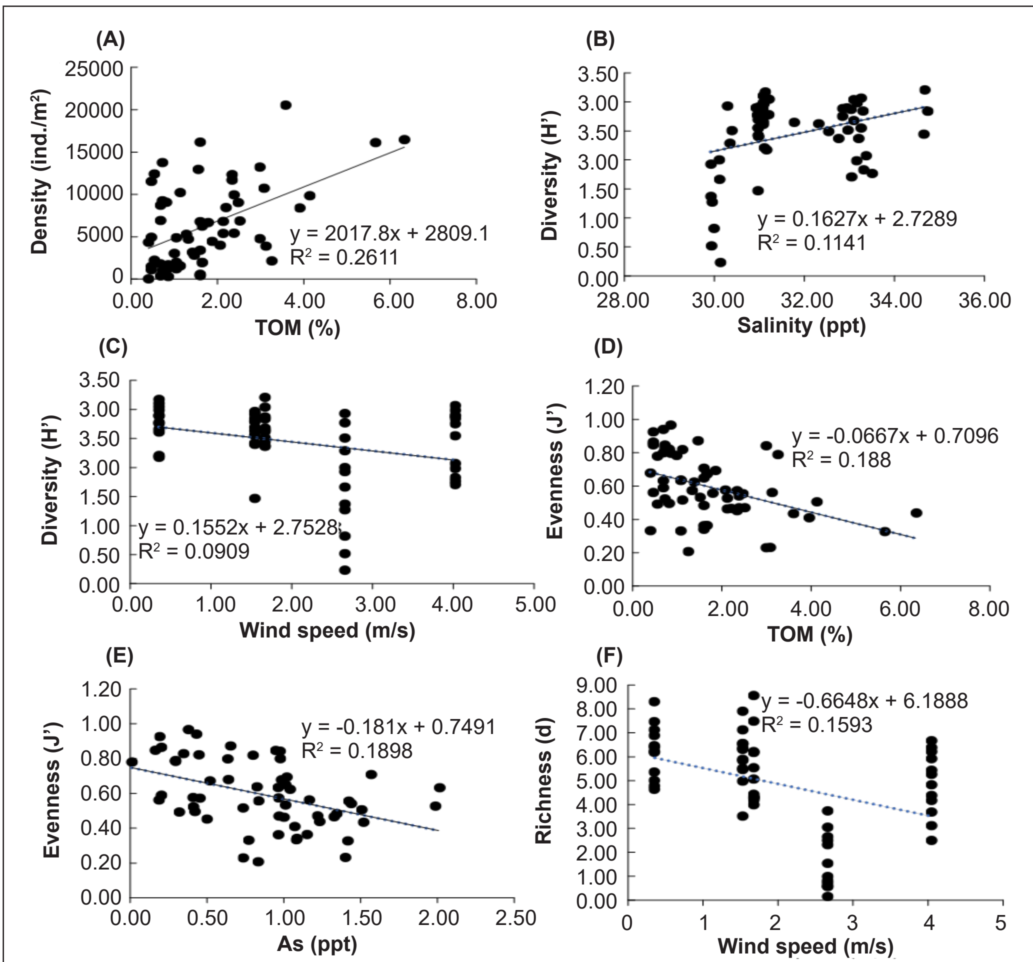

Figure 13. Multiple Linear Regression (MLR) analysis between macrobenthos assemblages (density (ind./m^2), diversity (H'), evenness (J') and richness (s)) and environmental parameters (sediments, heavy metals and water physical parameters) with significant correlations ($p < 0.05$)

contributor influencing evenness. Wind speed, salinity, TOM, wave height, and silt + clay were selected as significant predictors for macrobenthos richness, with wind speed as the most influential factor. In summary, the MLR analysis revealed specific environmental parameters that significantly influenced each type of macrobenthos assemblage.

DISCUSSION

Breakwater systems have been widely acknowledged as artificial reefs, influencing macrobenthos assemblages by changing the hydrodynamics, sediment characteristics, food sources, and food web interactions (Holzhauer et al., 2020). In this study, station 1 of the groyne structure harbours the highest macrobenthos population, consistent with studies by Walker et al. (2008) in Southern Queensland (Australia) and Keller and Pomory (2008) in Santa Rosa Island Beach (USA). The groyne exhibited great macrofaunal abundance and biodiversity by restricting water circulation, producing lower energy conditions, creating a muddy pool and facilitating the thriving of a diverse macrobenthic community in the region (Becchi et al., 2014).

The macrobenthos composition in the sheltered stations in the present study can be related to findings in Bertasi et al. (2007) and Munari et al. (2011) in the Lido di Dante (Northern Adriatic Sea) and Punta Marina (Italy), respectively. The low-crested breakwaters from both studies have created sheltered areas for establishing brackish-water species and served as lagoonal species' channels along the coast. In addition, the species diversity and density in the sheltered beaches are typically higher than the exposed beaches (Kaullysing et al., 2017), with the macroinvertebrates' distribution in sandy beaches generally patchy due to the biological aggregations, localised food concentrations and tidal as well as seasonal migrations (Ellers, 2021).

In relation to Mollusca as the dominant taxa found in the present study, the different breakwater systems prove to be able to host diverse assemblages of molluscs, with the structure, slope and age of breakwaters possibly affecting the mollusc species (Orand & Fisher, 2021). Molluscs, considered early colonisers of substrates, have become the most abundant organisms in the coastal zone. They are attributed to their strong adaptation and survival skills, making them more tolerant to biological and chemical changes (Underwood & Chapman, 2013). In addition, their resilience to physical stressors in wave-exposed areas is potentially attributed to their intrinsic characteristics, such as reproduction and stress resistance, as well as extrinsic factors, like habitat availability and species interactions (Airoldi & Bulleri, 2011; Fortunato, 2015).

In contrast to the present study, Moreira et al. (2006, 2007) and Rivera-Ingraham et al. (2011) reported the unsustainable of molluscs (limpet and chiton) on artificial substrates due to the substrate complexity, which lack of microhabitats (crevices and rock pools). The microhabitats created by the coastal structures possibly contribute to a higher number of taxa (Kefi et al., 2015; Strain et al., 2018), leading to enhanced recruitment and survival of sessile and mobile macrofauna (Atilla et al., 2005).

In the Kuala Nerus coastal area, the complex and uneven bathymetry notably impacts the area's dynamic processes, particularly water flow, exchange, and particle transport pathways across passages, as Daryabor et al. (2016) highlighted. The deepest locations at the front and right sides of Station 1 are attributed to the strong hydrodynamic effect of waves and currents from the southward areas, which cause continuous scouring, leading to active sediment transport and erosion (Ariffin et al., 2020). The presence of shallow sheltered and deeper exposed areas in station 2 of the semi-enclosed jetty-type breakwater is attributed to the slow current speed inside the lagoon compared to the exceptionally high current speed outside the lagoon, which then flows northward and parallel to the shorelines (Ariffin et al., 2020). The strong current that washed away the sediments has led to the unsuccessful creation of a sand tombolo at the original location but successfully forming it at the next parallel breakwater station (e.g., station 4) with a weaker current speed.

The low significant wave height (H_s) across the sheltered stations of Kuala Nerus might be attributed to the dissipation, reflection, transmission, and diffraction of wave energy through wave breaking induced by the structures (Galani et al., 2019; Sierra & Casas-Prat, 2014). The presence of different breakwater systems in the Kuala Nerus coastal area has resulted in changes in current speeds and the creation of both sheltered and exposed areas, potentially leading to shifting in community equilibrium and affecting the macrobenthos assemblages and distributions (Stender et al., 2021). The interaction between ocean waves and currents around the breakwater structures has affected wave properties. It has reduced the current strength in the area, creating favourable environmental conditions and promoting species survival (Munari et al., 2011). Similarly, Zanuttigh et al. (2005) reported that breakwaters and groynes increased water residence time during extreme events and caused current flow reduction in sheltered stations. Conversely, in the absence of breakwater structures, currents are stronger in shallow water, leading to severe serial erosion, hence washing away the organisms from the area (Jeans et al., 2012).

The domination of coarser and medium sands in exposed stations (excluding the reference station) might be attributed to several combined factors of stronger wave propagation, fast water current flow and low water level, which hinder the deposition of fine particles and allow settlement of coarser and medium-sized particles (Bertasi et al., 2009). Conceptually, the heaviest particles settle first along the coast, whereas the finest ones are carried further, thus contributing to muddy bottoms (López, 2017). In exposed stations, strong currents have transported the sediments by picking up and moving fine particles to other stable hydrodynamic areas (e.g., sheltered areas) while leaving coarser grains suspended in the stronger current area. The fine sands in the sheltered areas are presumed to create frictional surfaces that demand significant energy for macrobenthos penetration and movement. The substantial energy has caused the organisms to stay below the interface, potentially contributing to higher macrobenthos density in sheltered stations (Wiesebron et al., 2021).

In the reference station in Batu Rakit (St. 5), the macrobenthos composition is potentially shaped by organic matter content and sediment grain size. The sufficient organic matter not only supports the food web diversity of macrobenthic organisms (Sczcepanek et al., 2021) but also helps in creating microhabitats for various macrobenthic organisms (e.g., some polychaetes species construct tubes using organic matter, providing shelter and protection from predators) (Merz, 2015; Vinn, 2021). The stable organic matter content, particularly in the sheltered stations of Kuala Nerus, is presumed to be contributed by the rigid sediment structures, which effectively entrapped the drifting organic materials. This finding is supported by Carugati et al. (2018), who reported the highest TOM at sheltered stations due to a reduced hydrodynamic export to the open sea. The exposed stations dominated by coarser and medium sands recorded lower TOM, likely due to the high sands' porosity and permeability, which slightly inhibit the passage of high organic matter in the area.

The lower heavy metal concentrations in the surface sediments in the Kuala Nerus breakwater area were deemed to have a minimal impact on the coastal ecosystem. The movement of pollutants in this area is affected by the combination of currents and waves near the coastal structures, as supported by Tao and Han (2002). Prevailing currents potentially transport heavy metals and originate from various sources, such as sewage and industrial effluents, brine discharge, agricultural activities, and coastal development (Yunus et al., 2020). In this study, the heavy metals in the sediments might derived from natural processes as no significant enrichment sources (e.g., anthropogenic activities) were found. As a result, all sampling stations in the Kuala Nerus coastal areas were classified as having a good ecological status, indicating an unpolluted environment with uncontaminated sediments.

In addition, as the Kuala Nerus coastal area is mainly composed of sandy substrates, heavy metals did not absorb well onto the sandy particles, as compared to clay, fine, and very fine silt particles, with a larger surface area-to-volume ratio, which provided broader and more active sites for heavy metal absorption (Yao et al., 2015; Yunus et al., 2020). These smaller particles can better form large aggregates of metals bound together by electrochemical forces and organic matter (Raji et al., 2023). As a result, the breakwater areas in Kuala Nerus, dominated by sandy substrates, showed lower concentrations of heavy metals, in line with the findings by Yunus et al. (2020).

The present study found a positive correlation between macrobenthos density and sediment characteristics, indicating that sediment characteristics influence the community and distribution of macrobenthos, as Qiu et al. (2018) suggested. Specifically, sheltered stations, dominated by very fine sand and a higher TOM content, exhibited a higher macrobenthos density. The fine sand macrobenthos communities are suggested to receive sufficient nutrients from microphytobenthos' primary production, leading to enhanced growth and blooming, contributing to the higher density of organisms, as Hope et al. (2020) supported.

This study documented a higher macrobenthos density with the increase in depth and salinity, consistent with Costas (2016) and Huang et al. (2021), who highlighted salinity as one of the most influential factors in shaping benthic communities. The macrobenthos density is higher in marine environments due to higher salinity than in brackish and freshwater areas (Alipoor et al., 2011). The optimal salinity positively affects the benthic organisms' reproductive system (Vizakat et al., 1991). The broad temporal salinity variation can increase taxa numbers and lower species abundance (Alongi, 1989; Dittmann, 2002). Less-tolerated marine organisms may encounter challenges with their osmotic regulation, leading to reduced species richness and diversity (Stender et al., 2021).

The present study revealed a significant positive correlation between macrobenthos density and depth, in concordance with Kim et al. (2023). Water temperature and salinity, influenced by water depth, also play a crucial role in shaping the macrobenthos community. Shallow areas near breakwater systems may experience disturbance from waves and currents, altering sediment distribution and composition, thereby impacting organism assemblages (Munari et al., 2011). Masucci et al. (2020) highlighted that a control station with irregular depth profiles provides more microhabitats, supporting a diverse array of micro and macro-marine organisms. By contrast, sheltered stations with consistent depth profiles may experience higher levels of ultraviolet (UV) radiation, thus inhibiting the macrobenthos recruits' settlement (Masucci et al., 2020; Turner et al., 2018).

The strong relationship between water physical parameters and macrobenthos assemblages suggests that hydrodynamic activities influence distributional patterns and functional structure of macrobenthos, leading to a shift in community equilibrium, favouring opportunistic species and reducing overall diversity (Foulquier et al., 2020; Stender et al., 2021). The hydrodynamic conditions, particularly wave action, affect the soft bottom communities by smothering immobile organisms and inducing migration in mobile organisms (Foulquier et al., 2020).

In the present study, the macrobenthos assemblages were influenced by soft-bottom characteristics and food availability, both of which were governed by the area's hydrodynamic condition. The different breakwater systems, including groyne, semi-enclosed jetty-type breakwater and parallel breakwaters without and with tombolo, effectively governed the hydrodynamic condition in the study area.

CONCLUSION

This study emphasised the effect of different breakwater systems on the distribution and composition of macrobenthos in the Kuala Nerus coastal area. Station 1 of groyne structures harboured the highest macrobenthos population, with the sheltered stations exhibiting higher macrobenthos composition than the exposed stations.

The study revealed the morphological dynamism of the investigated stations, with bottom sediment and nearshore hydrodynamic circulation being major driving factors. The hydrodynamic condition significantly influenced the sediment characteristics, particularly the various sand sizes, leading to changes in organic matter and heavy metal contents. Coarser and medium sands dominate the exposed stations, while the sheltered stations are dominated by very fine sand. Low heavy metal concentrations in the surface sediments indicate an unpolluted environment of the Kuala Nerus coastal areas.

The relationship between macrobenthos and environmental factors demonstrated the importance of sediment characteristics and food availability (organic matter content) in the soft-bottom habitat governed by the hydrodynamic factors. The different breakwater systems in Kuala Nerus have altered sediment dynamics and nearshore hydrodynamics, affecting wave energy, water currents, and sediment transport, ultimately impacting the macrobenthic population and assemblages.

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