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Benthic Foraminiferal Distribution in the Red Sea Coastal Sediments, Shalateen Area, Egypt: Environmental Biomonitoring Implications

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Abstract. The Red Sea coast is overcrowded by many international and local harbors, among of them the Shalateen harbor imposes environmental threats on marine biota. Benthic foraminiferal distribution is used here a sensitive proxy to assess the possible environmental deterioration of the Shalateen ecosystem. A total of 17 stations were sampled, and their benthic foraminiferal contents were analyzed. The findings revealed enriched benthic foraminiferal assemblages, dominated by Miliolida and Rotaliida, showing morphological deformities in their tests. Siamese twins, wrong direction of coiling, and aberrant chambers are the depicted test deformities. These test deformations are common in the miliolids rather than rotaliids. A statistical analysis enabled recognition of two distinct foraminiferal assemblages; assemblage 1 demarcates shallow (average depth 2 meters), high-energy habitats with elevated salinity and carbonate content, while assemblage 2 occupies deeper waters (average depth 7 meters) with higher organic matter and fine-grained sediments. The environmental-based foraminiferal indices (FAI, FI, FMI and AEI) showed that the stations in the vicinity of the harbor are highly impacted by harbor activities than offshore stations. These findings provide crucial baseline data for future environmental management and conservation efforts in this vulnerable ecosystem.

Keywords: Benthic foraminifera; morphological deformities; environmental impacts; Shalateen; Red Sea.

1. Introduction

Benthic foraminifera, single-celled protists renowned for their diverse shell morphologies, have emerged as invaluable environmental bioindicator in marine ecosystem assessments (Reiss and Hottinger, 1984; Murray, 2006). Their ubiquitous presence, spanning from intertidal zones to the deep ocean (Goeting *et al*., 2023; Hesemann, 2023), allows for comprehensive ecological evaluations across a wide range of habitats. These organisms are highly sensitive to variations in environmental parameters, including salinity, temperature, dissolved oxygen, water depth, substrate type and composition, nutrient availability, and anthropogenic effluents such as pollution (Frontalini and Coccioni, 2011). Their responses to variations in these factors, often manifested in shifts in species composition, abundance, distribution and even test deformities (El-Kahawy *et al*., 2018; El-Kahawy and Mabrouk, 2023), provide a unique window into the ecological health and history of marine environments, making them indispensable tools for monitoring, conservation, and informed decision-making.

The Red Sea, a semi-enclosed marginal sea characterized by high salinity, elevated temperatures, and oligotrophic (nutrient-poor) waters, presents a compelling model system for studying benthic foraminifera. Research in this region has revealed distinct patterns in the diversity and distribution of foraminiferal assemblages across various habitats, from coral reefs to coastal lagoons and mangroves (El-Kahawy *et al*., 2018). These assemblages are not only shaped by the Red Sea's unique environmental conditions but are also highly sensitive to anthropogenic pressures (Basaham *et al*., 2009).

Comprehensive baseline data on benthic foraminifera in the Shalateen area are urgently needed to understand the ecological dynamics of this important region, especially given the recognized value of these organisms as bioindicators. The aim of this study is to fill this critical knowledge gap by conducting the first detailed investigation of benthic foraminifera in the Shalateen area, by examining the influence of environmental factors, such as salinity, temperature, water depth, sediment type and nutrient availability, on the diversity and distribution of living benthic foraminifera. The main objectives of the present study are: 1) to identify the benthic foraminiferal taxa prevailed in the investigated samples, 2) to establish baseline data on the benthic foraminifera of the Shalateen area, providing a reference point for future monitoring and assessment of environmental health, 3) to elucidate the ecological preferences and tolerances of benthic foraminifers by examining their relationship with key ecological parameters, and 4) to assess the potential usage of benthic foraminifera as bioindicators of environmental stress.

2. Material and Methods

2.1. Study area DEscription

The Shalateen area (23°09'05" N, 35°36'51" E; Fig. 1), a semi-enclosed coastal region on the southern Red Sea coast of Egypt, is characterized by diverse habitats encompassing sandy beaches, tidal flats, mangroves, and a barrier reef (Nasr *et al*., 2019). The area serves as a fishing harbor, since it has shallow waters of 1.5-13m. The town of Shalateen is populated by approximately 26,868 citizen, relies heavily on fishing and maritime activities (Shaer & Elkhouly, 2016). The central metal jetty houses the main Shalateen desalination plant (El-Sorogy *et al*., 2012). Although the area is not suffering from the intensive population, the Shalateen area is experiencing escalating anthropogenic pressures (El-Sorogy *et al*., 2012). The desalination plant's brine discharge, along with potential pollution from fishing and other industries, raise concerns about the impact on the marine ecosystem, particularly the vulnerable coral reefs and their associated benthic foraminifera (Nasr *et al*., 2019).

2.2. Sediment Sampling and Processing

During the spring of 2019, a total of 17 surface sediment samples were collected along four transects extending from the shoreline to a distance of 12 meters offshore in the study area (Fig. 1; Table 1). The sampling locations encompassed the beach, tidal flat, and offshore zones up to 12 meters water depth. The investigated sediment samples were collected by SCUBA diving. Water depth was recorded at each station using a UWTEC Eco-sounder, and sample coordinates were precisely determined using a Garmin IIH GPS unit. By following the standard procedures of the ecological studies (Schönfeld *et al*., 2012), in situ measurements of physicochemical parameters, including temperature, conductivity, dissolved oxygen (DO), pH, salinity, and turbidity, were measured for each station using HANNA instruments (multiparameter water analyzer).

The upper 1-2 cm of each sediment sample was sampled and processed for subsequent analyses. The collected samples were stained with Rose Bengal dye (2 g/1000 ml of 95% ethyl alcohol) for 48 hours to differentiate living (stained) from dead (unstained) foraminiferal tests (Walton, 1952). An additional aliquot was used for grain size analysis (Folk and Ward, 1957), to determine the percentages of gravel, sand, and mud/clay fractions, following the Udden-Wentworth scale (Folk, 1974). Total carbonate content (TCC) was determined by acidification process following the method adopted by (Müller & Gastner, 1971), while the total organic matter (TOM) was quantified using the loss on ignition (LOI) method (Dean, 1974) where samples were combusted at 375°C - 450°C to determine the weight loss due to organic matter combustion.

benthic foraminiferal analysis. The taxonomic identification was done based on Loeblich and Tappan (1988), and online resources such as https://foraminifera.eu/ and the World Foraminifera Database were also consulted, with accepted species nomenclature verified using WoRMS (https://www.marinespecies.org/). Relative and absolute abundances were calculated for each species and tabulated in the Appendix 1.

The benthic foraminiferal occurrences are utilized for assessing the environmental status via diversity and environmental quality indices.

Diversity indices such as Foraminiferal Density (FD), Diversity Indices: Species richness (S), Shannon-Wiener (Shannon, 1948), and Dominance using PAST software version 4.13 (Hammer *et al*., 2001) provide insights into the overall health and biodiversity of the foraminiferal community, while environmental quality indices such as Foraminifera in Reef Assessment and Monitoring Index (FI) (Hallock *et al*., 2003), Ammonia-Elphidium Index (AEI) (Sen Gupta *et al*., 1996), Foraminiferal Abnormality Index (FAI) and Foraminiferal Monitoring Index (FMI) (Coccioni *et al*., 2005) are specifically designed to reflect the impact of environmental stressors on foraminifera.

2.3. Statistical Analysis

The statistical analysis aimed to assess the similarity and dissimilarity between samples and species within a benthic foraminiferal dataset. To evaluate the present-day environmental conditions, only living adult benthic foraminiferal individuals were selected, and dead organisms were excluded to prevent biases. Ward's method, a hierarchical clustering algorithm, was utilized to group species and samples. The dissimilarity metric chosen to quantify the differences between samples and species was squared Euclidean distance. Heatmap hierarchical cluster analysis (HCA) was performed using both Q-mode (sample-based) and R-mode (species-based) to visualize the relationships between samples and species. The dendrograms were generated using PAST software, version 4.13 (Hammer *et al*., 2001). Redundancy Analysis (RDA), a linear ordination technique, was selected to examine the ecological relationships between environmental variables and faunal associations. The data was log-transformed and standardized for proper scaling, and Monte Carlo permutation tests with 499 iterations were conducted to evaluate the significance of the RDA model.

3. Results

3.1. Water Parameters

The water depth of sampling stations ranges from 0.3 m (St.9, St.17) to 12 m (St.6), with a mean depth of 4.7 m. The salinity values across the sampling stations vary from 39.25 *PSU* to 40.49 *PSU*, with a mean value of 39.64 *PSU*, while the water conductivity values range from 61.33 mS/cm (St.10) to 63.27 mS/cm (St.9). The pH values range from 8.01 (St.3, and St.4) to 8.31 (St.17), with a mean pH of 8.13 (Table 1).

3.2. Bottom Sediments Characteristics

The sediment composition in the Shalateen area is primarily sand dominated. The gravel content is generally low (<3%) across most stations, except for St.15 (7.3%) (Fig.2A), whereas the sand fraction ranges from 79% at St.11 to ~91% at St.15 (Fig. 2B). The silt content ranges from ~6.1% (St.16) to 20.1% (St.11) (Fig. 2C). The $CaCO_3$% and TOM% show an overall fluctuation among the investigated stations (Table 1; Fig. 2). The $CaCO_3$% ranges from 14.9% (St.15) to 42.4% (St.16), with the highest values observed at St.9 and St.16 (Table 1). Overall, the TOM% are higher in the coastal stations, particularly in the vicinity of the fishing harbor and jetties. The TOM% ranges from 2.7% (St.15) to 10.6% (St.11) (Fig. 2D).

3.3 Benthic Foraminiferal Community Structure and Composition

The benthic foraminiferal analysis of the living faunal assemblage of the Shalateen sediments revealed a total of 100 benthic foraminiferal species, 43 genera and three suborders: Miliolina (66.8%), Rotaliina (31%), and Textulariina (2.2%). The dominant genera (those comprising >2% of the total foraminiferal count) and their representative taxa were selected to investigate the influence of the environmental variables on benthic foraminiferal distribution patterns (Appendix1).

Seventeen species representing the dominant genera (comprising ~60% of the total foraminiferal abundance) were selected for further analysis. These dominant species are distributed across the two suborders Miliolina and Rotaliina. The Miliolina species includ *Coscinospira hemprichii*, *Quinqueloculina carinatastriata*, *Monalysidium aciculare*, *Peneroplis* (*P. pertusus*, and *P. planatus*), *Quinqueloculina* (*Q. limbata*, and *Q. costata*), *Sorites orbiculus*, *Spiroloculina communis*, *Triloculina tricarinata*, and *Varidentella neostriata*. The remaining dominant species belonge to the order Rotaliida including *Ammonia* (*A. beccarii*, *A. tepida*, *A. bradyi*), *Neorotalia calcar*, *Elphidium advenum*, and *Nonion fabum* (Appendix 1).

The foraminiferal assemblage across the 17 stations in the Shalateen site exhibit distinct distribution patterns for the six most abundant taxa. The *V. neostriata* is the most abundant species, where the peak abundance is observed at St.2 (14.4%), followed by St.1 (12.6%), St.5 (10.4%), and St.13 (10.3%) (Fig. 3), whereas the nominate species is notably absent in the samples of southern transect (St.15- St.17). Overall, the *N. calcar* records higher abundance in the samples of the northern and southern transects than the central one (Fig. 3). This species is recorded at stations St.4, St.16, and St.15 with abundance 27.4%, 25.8%, and 14.8%, respectively. These sites are characterized by patch reef community**.** *Nonion fabum* is highly abundant in shallow to intermediate water depths, particularly at St.1 (19.1%) and St.14 (11.7%) (Fig. 3), while *M. aciculare* is highly abundant at St.7 (30.9%), followed by St.5 (16.9%) (Fig. 3)**.** *Quinqueloculina (Q.) limbata* is recorded with abundance (30.1%) at St.16, whereas it is recorded with abundances < 10 % at the other stations (Fig. 3). *Ammonia (A.) tepida* is consistently abundant, especially in shallower stations closer to the shoreline such as St.8 (21.8%) and St.13 (16.9%) (Fig. 3).

3.4. Benthic Foraminiferal Diversity Indices

The foraminiferal density fluctuated considerably across the sampling stations, ranging from 8 to 394 individuals per gram of sediment, with an average of 209 individuals/g (Fig. 4A). The highest density was observed at St.7, followed by St.1, and St.10 (Fig. 4A). In contrast, the lowest density was found in the stations nearby the Shalateen harbor, particularly at St.17, St.15, and St.16. The species richness exhibited substantial spatial variability, ranging from 7 to 63 taxon (Fig. 4A). The highest richness (63) was observed at St.7, situated in the central part of the study area, while the lowest species richness (7) was found at St.17, located near the shoreline in the southern corner near to the harbor. Stations closer to the southern shore generally displayed lower species richness compared to those in the central and northern parts of the area of study (Fig. 4A).

The dominance index, a measure of the probability that two randomly selected individuals belong to the same species, ranged from ~0.03 (St.3 and St.10) to 0.21 (St.16), with a mean value of 0.08 (Fig. 4B). The lowest values of the dominance index, indicating higher diversity, were primarily observed in the central and northern sectors of the site, whereas, the highest values, suggesting lower diversity and a greater dominance of a few species, were found near the shoreline stations, notably at St.16 (Fig. 4B). The Shannon index, a widely used measure of biodiversity, exhibited a considerable variation through the 17 stations, ranging from 1.84 to 3.75 (mean = 3.07). Notably, the highest value was observed at St.3, followed by St.10, and St.7, located in the central part of the site (Fig. 4B). Conversely, the lowest values were found at St.17, followed by St.16, both situated near the shoreline, indicating lower species richness and/or less evenness (Fig. 4B).

3.5. Benthic foraminiferal-based Environmental Indices

The foraminiferal abnormality index (FAI) is calculated to assess the percentage of foraminiferal tests exhibiting morphological abnormalities as a potential indicator of environmental stress. The percentages ranged from 0 to 16% across the stations, with an average of 3.1%. The St.12 (FAI = 16%) displayed the highest value, followed by St.6 (FAI = 7%) and St.1 (FAI = 6%) (Fig. 5A), indicating significant environmental stress impacting foraminiferal growth and development. The remaining stations displayed lower FAI values (FAI < 5%) (Fig. 5A), indicating relatively lower levels of stress. However, the presence of some abnormalities even at these stations suggests subtle environmental pressures affecting the investigated stations.

The calculated Foraminifera Index in Reef Assessment and Monitoring (FI) values for the 17 sampling stations of the Shalateen site ranged from 2.2 to 7, with an average of 4, indicating a considerable variation in environmental conditions. The calculated Reef Assessment and Monitoring Index (FI) values for the 17 sampling stations of the Shalateen site are ranged from 2.2 to 7, with an average of 4, indicating considerable variation in environmental conditions. The stations located away apart from the coastal stretch are characterized by very high FI values represented by St.4 (FI = 7), St.16 (FI = 6.5), St.15 (FI = 6.3), St.9 (FI = 4.9), St.5 (FI = 4.8), and St.14 (FI = 4.5). (Fig. 5B).On the other hand, St.17 (FI = 4.2) ,St.7 (FI = 3.5), St.2 and St.3 (FI = 3.6), St.8 (FI = 3.7) exhibited intermediate FI values, whereas, the St.12 (FI = 2.2), St.1 (FI = 2.6), St.11, and St.13 (FI = 2.7), and St.10 (FI = 3.2) have the lowest FI values, representing marginal conditions with foraminiferal assemblages dominated by opportunistic taxa and/or showing signs of stress (Fig. 5B).

The Ammonia-Elphidium Index (AEI), was calculated herein to assess the relative abundance of *Ammonia* and *Elphidium* foraminifers and infer the potential organic enrichment and oxygen conditions across the Shalateen site. The calculated values ranged from 0% to 100%, with an average of 49% (Fig. 5C). This wide range indicates a significant spatial variation in environmental conditions. Stations with AEI values > 50% predominantly located in the western, central, and southern regions, suggesting a potential organic matter enrichment and possible hypoxic conditions, especially in stations with AEI values > 80%. Conversely, stations with lower AEI values (<50%), primarily concentrated in the northern and eastern sectors, indicated relatively lower levels of organic matter enrichment and generally more oxygenated conditions (Fig. 5B).

Complementing the FAI, the foraminiferal monitoring index (FMI) was calculated to assess the percentage of deformed tests in each sample, providing further insights into environmental stress on the foraminiferal community. The FMI values ranged from 0.16% (*Q. limbata*) to 18.05% (*C. hemprichii*), with an average of 4.72% across all species. The *C. hemprichii, P. planatus, and P. pertusus* showed FMI values of 18.05%, 12.38%, and 11.44%, respectively suggesting that a significant proportion of individuals of these species showed morphological abnormalities. In contrast, the remaining foraminiferal species exhibited FMI values below 10%. The present study documented several morphological abnormalities in the benthic foraminiferal growth tests of the Shalateen stations (Fig. 6). Many benthic foraminiferal taxa rendered several types of test deformities such as *P. planatus*, *C. hemprichii*, *A. beccarii*, and *S. orbiculus* (Fig. 6).

3.6. Statistical Analyses

The statistical analyses (HCA and RDA) were employed to identify the relationships between benthic foraminiferal assemblages and environmental factors. The relationships among benthic foraminiferal species and their distribution patterns across the sampling stations are illustrated by the R-mode and Q-mode dendrograms in Figure 7. The analysis aims to assess the similarity and dissimilarity between species and stations, providing insights into their ecological relationships.

The Q-mode dendrogram on the right side of the diagram grouped the recognized species into two main clusters (A and B) based on their similarities in distribution patterns across the sampling stations. Cluster A is further divided into two subclusters, A1 and A2. Subcluster A1 is dominated by *P. planatus*, *P. pertusus*, *V. neostriata*, *Q. carinatastriata*, *C. hemprichii*, and *S. communis* (Fig. 7). This assemblage is characterized by occupying the stations of cluster X2 in the Q-mode dendrogram (Fig. 7).

While subcluster A2 is characterized by the presence of *S. orbiculus*, *N. calcar*, and *Q. limbata*, their distribution patterns show some variations. Specifically, *S. orbiculus* and *N. calcar* dominate cluster X1 (St. 4), while *N. calcar* and *Q. limbata* are more prevalent in cluster X2 (St. 16) (Fig. 7). This may reflect subtle differences in environmental conditions or microhabitat preferences within these clusters

Cluster B includes two subclusters (B1, and B2). Subcluster B1 consists of benthic foraminiferal assemblage dominated by *A. tepida*, *T. tricarinata*, and *E. advenum* (Fig. 7). This assemblage occupies stations St.7, St.8, St.11, and St.13 (Fig. 7). Subcluster B2 comprises assemblage dominated by *Q. costata*, *M. aciculare*, *A. beccarii*, *A. bradyi*, and *N. fabum* (Fig. 7). This assemblage occupies the northern transects including stations such as St.1, St.4, St.5, and St.7, however St.13 in the southern transect, is highly enriched in *A. beccarii* (Fig. 7).

Redundancy analysis (RDA) identified two distinct foraminiferal groups structured along an environmental gradient, with the first two RDA axes accounting for 47.36% of the total variation (RDA1: 38.24%, RDA2: 9.12%), that examines the relationship between foraminiferal distribution and environmental variables (Fig. 8).

Group 1, located on the right side of the ordination chart, is characterized by occurrence of benthic foraminiferal assemblage comprises *C. hemprichii*, *P. pertusus*, *P. planatus*, *Q. limbata*, and *N. calcar*. They show a strong positive correlation with sand percentage, carbonate content, pH and salinity, suggesting a preference for shallower, well-oxygenated environments with higher salinity levels. This group characterizes St.4, St.6, St.9, St.10, St.12, St.15, St.16 and St.17. Group 2 is located on the left side of the plot, including, *A. tepida*, *Q. costata*, *A. beccarii*, *T. tricarinata*, *S. communis*, *A. bradyi*, *Q. carinatastriata*, *M. aciculare*, *N. fabum*, and *V. neostriata*. These species exhibit a negative correlation with sand percentage and carbonate content, indicating a preference for deeper environments (average depth 7 meters) with finer-grained sediments, higher total organic matter (TOM), and lower salinity. Groups 2 includes St.1, St.2, St.3, St.5, St.7, St.8, St.11, St.13, and St.14.

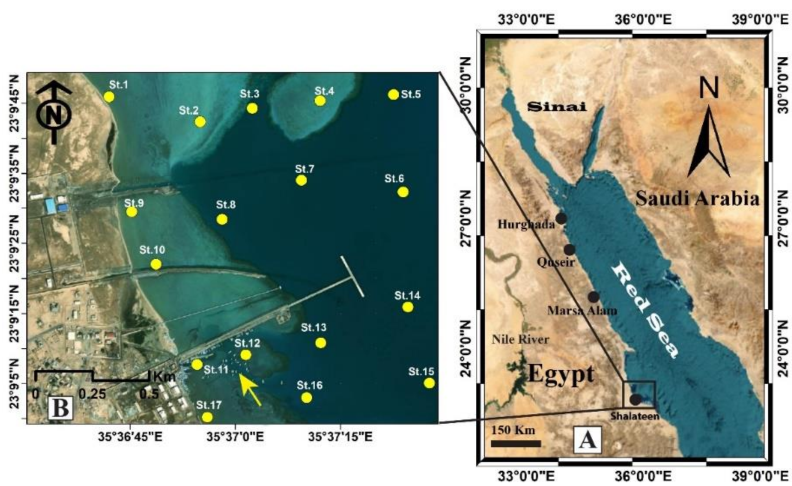

Fig. 1: A) Location map for the Shalateen City on the Red Sea coast, B) Google earth map showing the sampled stations from the Shalateen site. The yellow arrow refers to the harbor.

Table 1. The results of the measured ecological variables, grain size%, carbonate%, and TOM%.

Station	Gravel %	Sand %	Silt %	Water depth (m)	Salanity ‰	Conductivity S/m	pH	$CaCO_3$%	TOM%
St. 1	1.46	84.62	13.92	0.5	39.29	61.39	8.12	16.70	5.33
St. 2	2.42	88.36	9.23	3.0	39.49	61.70	8.10	24.60	5.04
St. 3	2.98	86.24	10.78	7.0	39.48	61.69	8.01	24.70	4.59
St. 4	1.89	85.08	13.04	3.0	39.45	61.64	8.01	19.70	4.43
St. 5	1.20	86.50	12.30	9.0	39.42	61.59	8.00	15.50	4.09
St. 6	1.10	86.10	12.80	12.0	39.45	61.64	8.13	19.90	4.08
St. 7	1.88	87.14	10.97	10.0	39.38	61.53	8.12	19.20	4.31
St. 8	2.00	90.61	7.40	6.0	39.47	61.67	8.10	30.20	5.61
St. 9	1.20	85.90	12.90	0.3	40.49	63.27	8.17	41.50	6.94
St. 10	0.92	86.98	12.10	3.0	39.25	61.33	8.00	25.10	3.51
St. 11	0.90	79.00	20.10	1.0	39.64	61.94	8.00	20.60	10.58
St. 12	1.31	81.30	17.38	2.0	39.69	62.02	8.03	19.80	8.80
St. 13	2.72	86.74	10.54	6.0	39.70	62.03	8.05	19.40	4.83
St. 14	2.34	85.66	12.00	8.0	39.64	61.94	8.06	27.70	4.36
St. 15	7.29	90.94	1.78	6.0	40.43	63.17	8.20	14.90	2.70
St. 16	3.84	90.10	6.07	3.0	39.95	62.42	8.22	42.40	3.01
St. 17	1.34	88.62	10.04	0.3	39.97	62.45	8.31	29.70	5.25

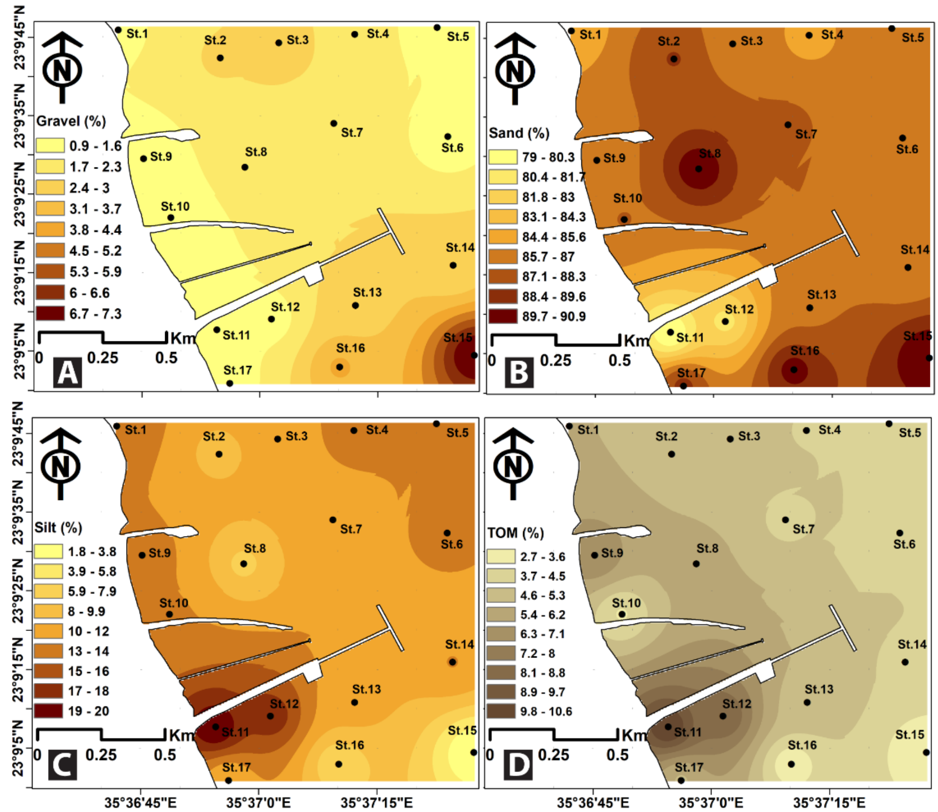

Fig. 2. Spatial distribution of grain size; gravel % (A), sand % (B), silt % (C), and organic matter content % (D) in the nearshore and offshore sediments in the Shalateen area.

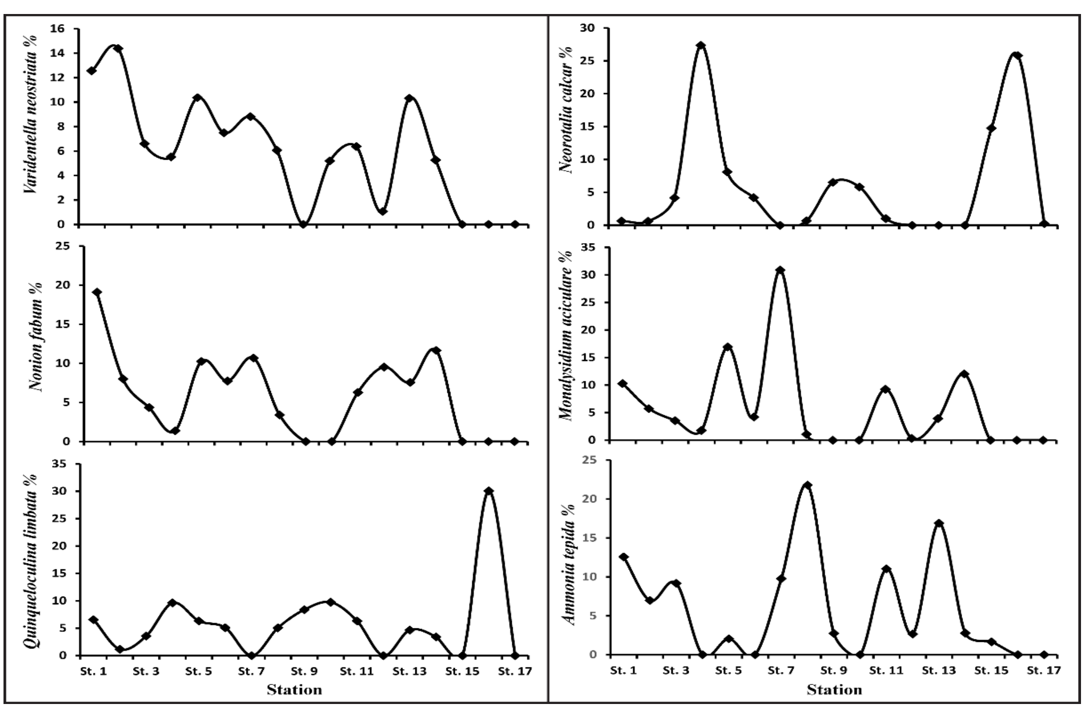

Fig. 3. The abundance (%) of the six most common benthic foraminiferal taxa in the bottom sediments of sampling stations in the Shalateen area.

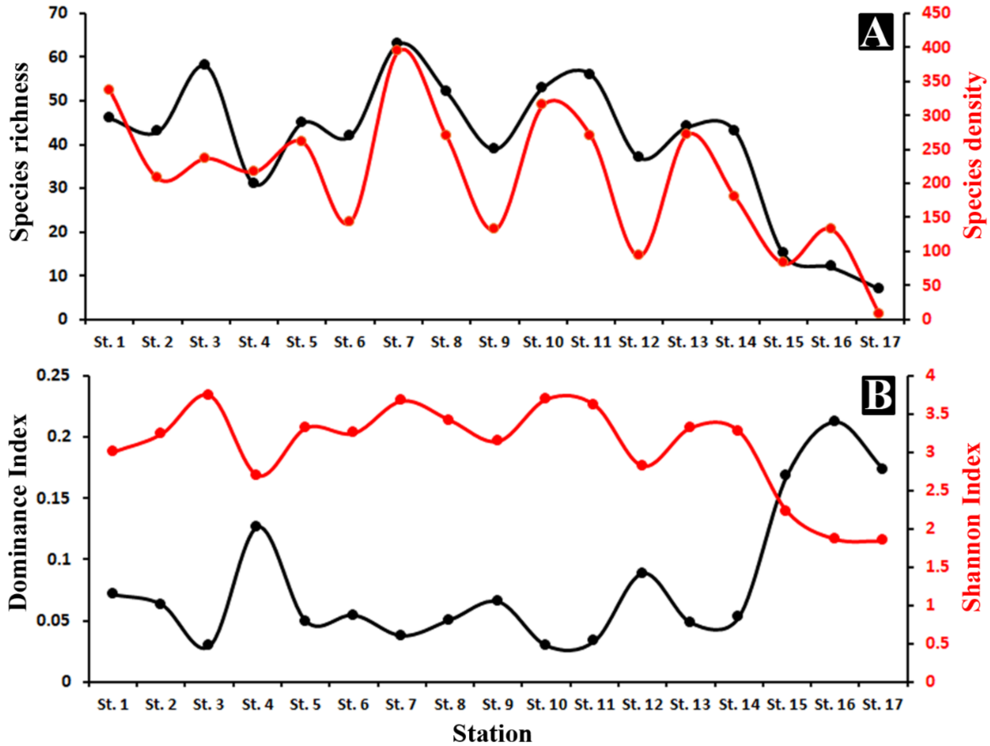

Fig. 4. The benthic foraminiferal diversity indices across the investigated stations in the Shalateen site, A) Species richness (black color) and species density (red color), B) Dominance (black color) and Shannon (red color) indices.

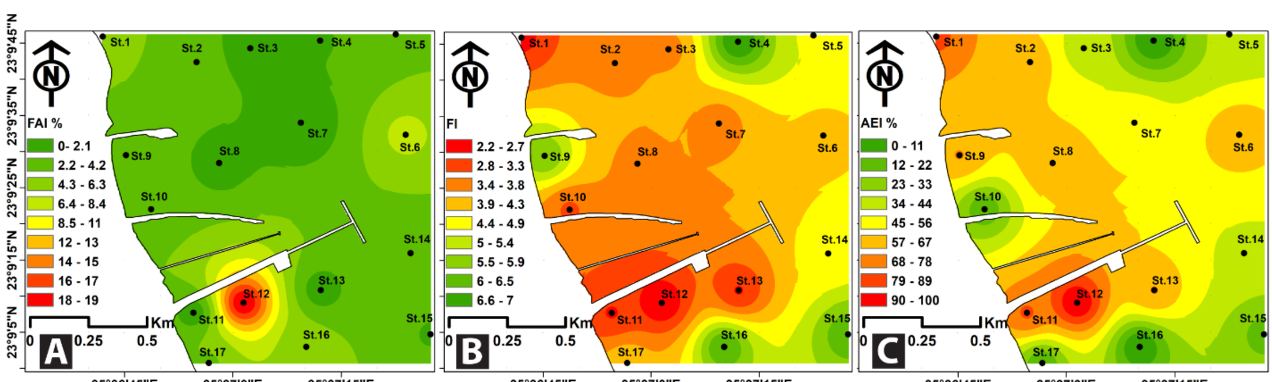

Fig. 5. The spatial distribution of benthic foraminiferal environmental indices for the Shalateen stations; A) Foraminiferal abnormality index B) Foraminifera index in reef assessment and monitoring, and C) Ammonia-Elphidium index.

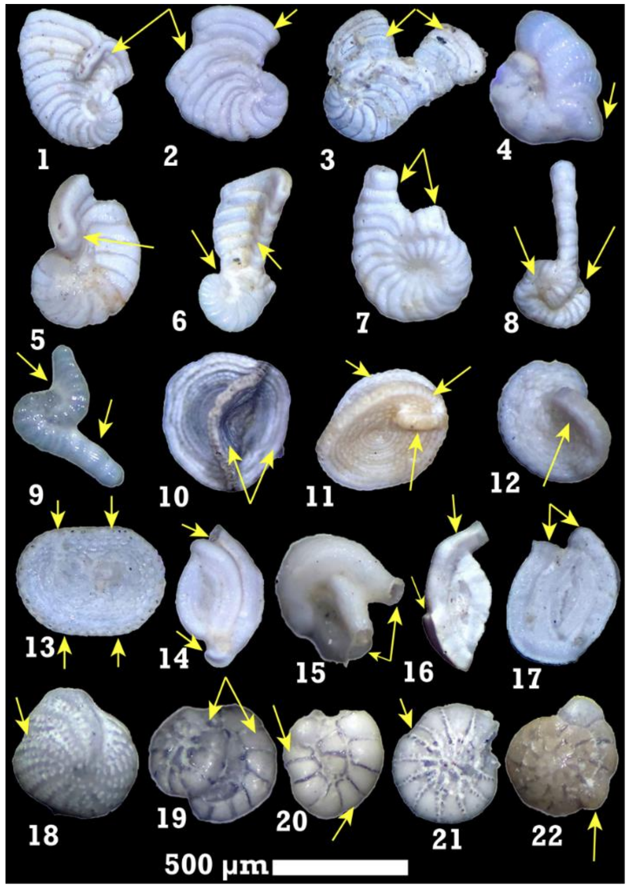

Fig. 6. Digital photomicrographs showing benthic foraminiferal test abnormalities in the bottom sediments of the Shalateen site.

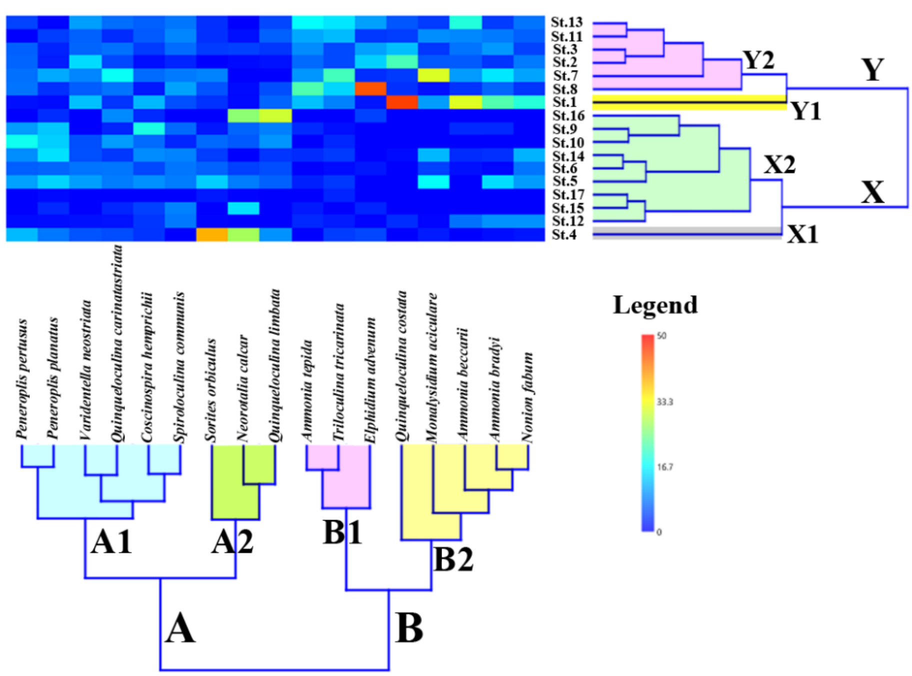

Fig. 7. Q- and R-modes cluster dendrograms adjusted with heatmap and squared Euclidean algorithms of Ward's method.

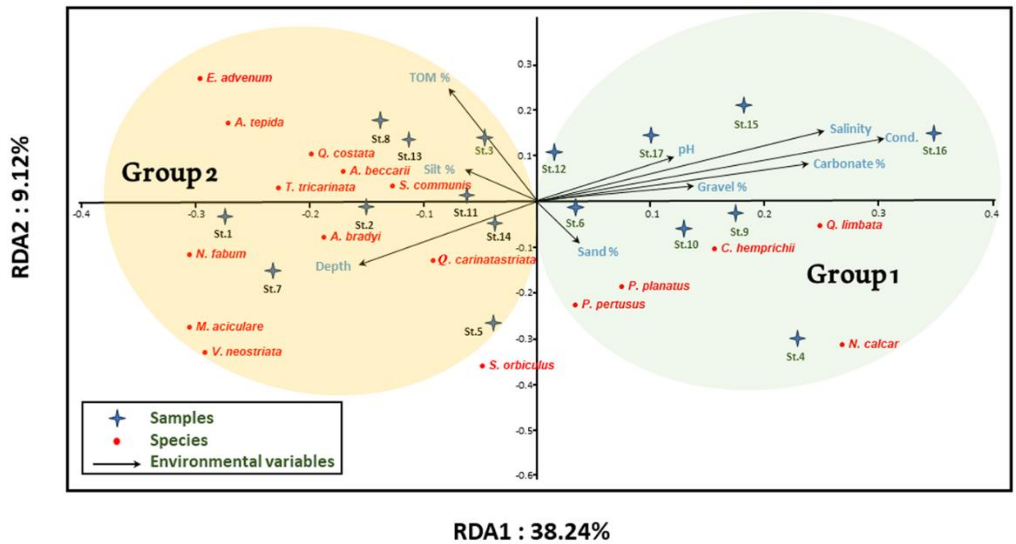

Fig. 8. Triplot RDA ordination for the environmental variable, abundant species, and their sampling stations.

4. Discussion

4.1. Benthic Foraminiferal Distribution and their Environmental Drivers

The foraminiferal assemblages in the Shalateen site exhibit distinct spatial patterns closely linked to environmental parameters and anthropogenic stress. The site hosts a diverse foraminiferal fauna, with 100 benthic species identified, dominated by Miliolida (66.8%), Rotaliida (31%) and Textularida (2.2%). the distribution of benthic foraminifera in the Shalateen site was primarily influenced by salinity, conductivity, pH, water depth, TOM, sediment composition, $CaCO_3$, and proximity to the shoreline and the human activities in the harbor. In the Shalateen site, specific taxa are associated with distinct combinations of environmental drivers, highlighting the complex interplay of factors that govern foraminiferal distribution. The investigated site exhibited two distinct groups (1 and 2) structured along with environmental parameters and benthic foraminiferal distribution patterns.

Group 1 is thriving in shallow water depths (nearshore stations) and controlled via environmental drivers such as coarse-grained substrate (gravel and sand), elevated salinity and pH. It is dominated by *C. hemprichii*, *P. pertusus*, *P. planatus*, *Q. limbata*, and *N. calcar*. These taxa favour well-oxygenated, hypersaline, coarse-grained substrates with high carbonate content, in association with healthy reef environments (Hottinger *et al*.,1993; Murray, 2006). The *C. hemprichii*, an algal symbiont known to flourish in hypersaline settings (Abu-Zied *et al*., 2011), dominates the hypersaline shallow water stations (St.9 and St.15). Furthermore, *C. hemprichii* and *Peneroplis* spp. are also influenced by substrate type and phytal content (Haunold *et al*., 1997). The abundance of *Quinqueloculina* spp. in this group also aligns with their tolerance for hypersaline environments (Fajemila *et al*., 2022). *N. calcar*, an epiphytic foraminifera, thrives in shallow reefal high-energy environments occupied by green algae (Abu-Zied *et al*., 2011). This species is well-adapted to high-energy, well-oxygenated conditions, and its distribution is primarily influenced by host availability rather than water depth

(Hohenegger, 1994). Its association with *Sorites orbiculus* and the abundance of *Peneroplis planatus*, and *Quinqueloculina limbata* suggest a healthy, well-oxygenated marine ecosystem (Al-Dubai *et al*., 2017). In contrast, *Q. carinatastriata* was found in high abundances at St.10 and associated with silty substrate, and relatively low salinity level, that is consistent with the observations reported by Langer *et al*. (2013). The dominance of stress-tolerant taxa in this biotope suggests that these taxa are well-adapted to the dynamic and potentially challenging conditions of the shallow, high-energy environments in the Shalateen site.

On the other hand, group 2 characterizes relatively deep-water within the shoreface zone ow salinity northern stations with fine-grained (silty) substrate and high TOM content. The group comprises an assemblage dominated by *A. beccarii*, *A. tepida*, *A. bradyi*, *Q. carinatastriata*, *M. aciculare*, *N. fabum*, *P. calcariformata*, *Q. costata*, *S. communis*, *T. tricarinata*, *S. orbiculus*, and *V. neostriata*. This assemblage favours brackish water with high organic matter content (El-Menhawey *et al*., 2021). *A. beccarii*, the dominant taxon in this group, tolerates a wide range of salinities, from brackish to hypersaline conditions (13-92‰), and is often associated with moderate organic matter content in muddy to sandy substrates (Debenay *et al*., 1998; Mendes *et al*., 2004; Murray, 2006). Similarly, *A. tepida*, an euryhaline and opportunistic, taxon flourishes in organic-rich muddy substrate (Abu-Zied *et al*., 2011). Furthermore, *A. bradyi* is associated with other *Ammonia* spp. and its abundance suggests a tolerance for lower salinities and fine-grained substrate. *Q. costata*, typically found in shallow waters, adapts to deep waters and thrives in both sandy and muddy substrates. Its high abundance at St.1 (45.9%) could be due to its tolerance to varying salinities and its ability to utilize organic matter as a food source (El-Menhawey *et al*., 2021). The dominance of foraminiferal species *A. beccarii*, *A. tepida*, and *Q. costata* closer to the desalination plant and harbor stations is attributed often to their opportunistic nature and tolerance to varying environmental conditions (Yanko *et al*., 1998), particularly the anthropogenic inputs and natural stress (Debenay *et al*., 2000; Yanko *et al*., 1994b). Their abundance and dominance in the stations close to the harbor (ships; see Fig. 1B) and coastal constructions, could also indicate a stressed environment due to the relatively low diversity and high dominance values of these opportunistic taxa. The abundance of *Q. carinatastriata* aligns with its reported tolerance for a wide range of salinities (Sgarella and Zei, 1993). *M. aciculare* survive the intertidal zone to depths of several meters, slightly hypersaline warm waters, typically in tropical to subtropical regions (Abu-Zied *et al*., 2013). It favours attaching to various substrates, including seagrasses and algae, and is often found in vegetated coastal lagoons and estuaries (Al-Dubai *et al*., 2017). *N. fabum*, and *P. calcariformata*, known for their tolerance to a wide range of salinities, prefer muddy substrates rich in organic matter and are commonly found in deeper waters (Murray, 1991). Their prevalence in most Group 2 stations, coupled with their decreasing abundance towards the eastern stations, suggests a preference for the environmental conditions characterizing the western portion of the study area, where higher silt content and organic matter levels are more prevalent .The high relative abundance of *P. calcariformata* at St.8, which is dominated by sand, could be attributed to the presence of a nearby patch reef, potentially providing suitable substrate and food sources. This observation is consistent with the findings of Hohenegger (2004) who reported the preference of this species for hard substrates and its association with algae in reefal environments. *S. communis* is an euryhaline taxon, preferring relatively deep, organic-rich muddy substrates. *T. tricarinata* thrives lagoon and offshore environments with normal marine salinity, typically favouring fine-grained substrates (Debenay *et al*., 2001; Murray, 2006). However, reporting of this species with high abundance at St.7 suggests its tolerance in a relatively low salinity deep water. Furthermore, the *T. tricarinata* is a pollution-sensitive species that has been reported from sites impacted by industrial and domestic/agricultural effluents (Vidović *et al*., 2014), Therefore, its occurrence near St.11 and St.13 (harbor stations) indicates possible anthropogenic effect. *V. neostriata* occupies intertidal zone and prefers fine-grained stable substrate (Al-Dubai *et al*., 2022). These conditions facilitate its growth and ecological success in marine ecosystems, as evidenced by its dominant presence at St.2.

4.2. Environmental Indices Assessment

The nearshore and harbor stations (St.9, St.10, St.12, St.16, and St.17), exhibit varying foraminiferal diversity indices. High salinity at St.9 and St.10 was responsible for high miliolids deformities and AEI (Yanko *et al*., 1994a). In addition, environmental deterioration related to enriched TOM resulted in high and low FI values at St.9 and St.10, respectively(Lo Giudice Cappelli *et al*., 2019) and influence the growth of coral reef community (Hallock *et al*., 2003). The St.12, St.16, and St.17, located near the harbor, show contrasting diversity patterns. The reduced diversity at St.16 and St.17, and to a little extent St.12 reflects the effect of pollution from the harbor activities (Dijkstra *et al*., 2017).

Additionally, the dominance of stress-tolerant species at these stations further suggests environmental stress (Al-Zubieri *et al*., 2020).The significantly low foraminiferal density and elevated FAI observed, particularly at St.12 (19%), raise concerns about anthropogenic impacts from the harbor activities (boats, and yachts), and sewage outfalls (Alve, 1991; Yanko *et al*.,1998). Aside, the shallow water depth and high salinity most probably contribute to unfavorable conditions, and the sensitivity of species like *Peneroplis* spp. and *C. hemprichii* to stress is reflected in their elevated FMI values (Hallock *et al*., 1995). The FI values offered further insights, where the St.16 (6.5), with a low AEI (0), suggest well-oxygenated, oligotrophic conditions favoring reef growth (Hallock *et al*., 2003). In contrast, the FI values at St.12 (2.2) and St.17 (4.2), coupled with high AEI values, indicate hypoxia potentially due to organic enrichment (sewage sludge), and ship activities, suggesting unsuitable conditions for reef growth and recovery (Hallock *et al*., 2003). The St.4, St.6, and St.15 occupied the offshore part, and located away from the pollution sources. These stations show high diversity indices and low dominance index, coupled with low values of FAI and AEI, and high FI values, indicating a healthy benthic ecosystem suitable for coral reef growth (Hallock *et al*., 2003). Additionally, the reduced impact of wave energy and currents with depth could favor the settlement and growth of larger, symbiont-bearing foraminifera, contributing to a higher FI value (Hohenegger *et al*., 2000).

Group 2, is characterized by proximity to potential anthropogenic source. It exhibits a range of ecological conditions as reflected in the diversity and environmental indices. The nearshore biotope, St.1, St.2, St.3, and St.8, a dynamic nature of this coastal environment. The moderate diversity indices, coupled with low to moderate FAI, FI, and AEI reflect environmental stresses likely associated with salinity fluctuations, increased sedimentation, and potential pollution in this dynamic coastal environment that hinder the corals reefs growth (Hallock *et al*., 2003; Jayaraju *et al*., 2011). Notably, St.1, closest to the shoreline, shows the highest FAI (6%), potentially due to environmental threats. Interestingly, a decreasing trend in FAI is observed with increasing depth: St.1 (FAI=6%), St. 2 (FAI=3%), St. 3 (FAI=1%), St. 8 (FAI=1%), suggesting a link between water depth and stress levels.

The near-harbor biotope, represented by St.11 and St.13, exhibits moderate diversity indices signifying a rich and evenly distributed foraminiferal community (Coccioni *et al*., 2009). This high diversity may be attributed to the influx of species from both nearshore and offshore environments due to well-circulated water and the elevated levels of total organic matter (TOM) providing ample food resources (Lo Giudice Cappelli., 2019). However, the presence of deformed tests with high FMI values for the dominant taxa; *Ammonia* spp.,and *S. orbiculus* along with high AEI, and low FI values suggests that this area is suffering from the harbor environmental stress (Coccioni *et al*., 2009), that influence on the coral community.

The deeper water and patch reef biotope stations (St.5, St.7, St.8, and St.14) in group 2, exhibits high benthic foraminiferal diversity, indicating a rich and balanced community, likely due to reduced environmental stress and increased habitat heterogeneity (Goeting *et al*., 2023).The absence of deformed tests (FAI = 0) and lower AEI values further support the presence of favorable conditions in this biotope. The dominance of specific species reflects microhabitat preferences and tolerances for varying depths and sediment types. *M. aciculare* dominates at St.5, potentially due to the nearby patch reef offering suitable substrate and food sources (Frontalini and Coccioni, 2008). Although the low FAI values in stations (St.7, and St.8) located at the desalination plant outlet, their elevated FI values, and AEI% indicate moderate level of environmental disturbance (Hallock, 1981; Hohenegger, 2004). In contrast, St.14 occupies the offshore part, where high diversity indices without deformed tests, suggesting stable conditions. This suggests that the deeper waters in the central transect may provide more stable and favorable conditions for foraminiferal growth and reproduction, potentially due to reduced environmental stress.

5. Conclusion

This study illuminates the intricate relationship between benthic foraminiferal assemblages and environmental parameters in the Shalateen area, highlighting their sensitivity to both natural and anthropogenic stress. The identification of two distinct assemblages, one thriving in shallower, high-energy environments and the other in deeper, organically enriched areas, underscores the influence of salinity, water depth, sediment composition, and proximity to human activities on foraminiferal distribution. The presence of stress-tolerant species and morphological abnormalities near the harbor, however, raises concerns about the potential impact of human activities on the site's ecological health. This research promotes the value of benthic foraminifera as sensitive bioindicators for monitoring environmental change in coastal ecosystems. The findings provide a crucial baseline for future studies, highlighting the need for long-term monitoring and comprehensive assessment programs to evaluate the ongoing impact of anthropogenic pressures on the Shalateen site's biodiversity and ecological health. Understanding and mitigating these impacts is paramount for ensuring the sustainable management of this vital ecosystem and safeguarding the livelihoods of local communities depending on its resources.

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Conflicts of Interest

The authors declare that there is no competing of interests.

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توزيع الفورامينيفرا القاعية في الرواسب الساحلية للبحر الأحمر، منطقة شلاتين، مصر: الآثار المترتبة على الرصد البيئي

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المستخلص. يكتظ ساحل البحر الأحمر بالعديد من الموانئ الدولية والمحلية، ومن بينها ميناء شلاتين الذي يفرض تهديدات بيئية على الكائنات البحرية. يستخدم توزيع الفورامينيفرا القاعية هنا كوكيل حساس لتقييم التدهور البيئي المحتمل للنظام البيئي في شلاتين. تم أخذ عينات من إجمالي ١٧ محطة، وتم تحليل محتويات الفورامينيفرا القاعية الخاصة بها. كشفت النتائج عن تجمعات الفورامينيفرا القاعية الغنية، التي تهيمن عليها الميليوليدا والروتاليدا، والتي أظهرت تشوهات مورفولوجية في اختباراتها. التوائم السيامية، والاتجاه الخاطئ للالتفاف، والحجرات الشاذة هي التشوهات الموضحة في الاختبار. هذه التشوهات الاختبارية شائعة في الميليوليدات وليس الروتاليدات. مكن التحليل الإحصائي من التعرف على مجموعتين متميزتين من الفورامينيفرا؛ المجموعة ١ تحدد الموائل الضحلة (متوسط العمق ٢ متر) عالية الطاقة مع ارتفاع الملوحة ومحتوى الكربونات، بينما المجموعة ٢ تحتل مياه أعمق (متوسط العمق ٧ أمتار) مع مادة عضوية أعلى ورواسب دقيقة الحبيبات. أظهرت مؤشرات الفورامينيفرا القائمة على البيئة (FAI وFI وFMI وAEI) أن المحطات القريبة من الميناء تتأثر بشدة بأنشطة الميناء مقارنة بالمحطات البحرية. توفر هذه النتائج بيانات أساسية حاسمة لإدارة البيئة في المستقبل وجهود الحفاظ عليها في هذا النظام البيئي الهش.

الكلمات المفتاحية: الفورامينيفيرا القاعية، التشوهات المورفولوجية، التأثيرات البيئية، شلاتين، البحر الأحمر.