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Benthic Foraminiferal Distribution and their Environmental Significance of Selected Red Sea Coastal Ecosystems, Saudi Arabia

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Abstract. The present study uses benthic foraminiferal abundance and diversity indices in the coastal bottom sediments of the Farasan Island, Southern Cornich of Jeddah (SCJ) and Rabigh areas, Saudi Arabia to identify the ecological controls on their distribution. A total of 20 recent sediment samples were collected from the studied sites. Grain size analysis, $CaCO_3$ content and organic matter were determined. Multivariate analyses were applied to test and represent the diversity indices and distribution of benthic foraminiferal assemblage. Two main benthic foraminiferal assemblages; A and B have been distinguished. The assemblage-A includes a high abundance of *T. trigonula* (33%), *S. communis* (30%), *Q. bosciana* (21%), *E. striatopunctatum* (18%) with low diversity indices in the Rabigh coastal sediments indicating high ecological stress. The Farasan ecosystem is dominated by sub-assemblage-B1 *P. planatus* (55%), *S. orbiculus* (27%), *N. calcar* (15%), *Q. limbata* (14%), which totally ranges between 60%-82%, indicating a highly oxic marine environment and normal ecology stress. Sub-assemblage-B2 such as *P. planatus* (39%),*C. hemprichii* (26%), *V. neostriata* (15%),*Q. costata* (10%) dominate the Southern Corniche of Jeddah (SCJ) with relatively high diversity indices, indicating moderate stress ecology or unstable environmental conditions.The cluster and the canonical correspondence analyses (CCA) indicated that the distribution and diversity pattern of benthic foraminifera are controlled by the enrichment of organic matters, $CaCO_3$ contents, and sediments grain size characteristics. The concept of differentiation between these ecosystems is probably related to several factors, such as seasonal flash floods carrying a considerable amount of dissolved nutrients and mangrove communities on the Rabigh coast. In contrast, it is negligible on the south Jeddah coast and absence on Farasan Island.

Keywords: Benthic foraminifera, Farasan island, Jeddah coast, Rabigh, Red Sea coastal ecosystems.

1. Introduction

Coastal ecosystems are influenced by the continental, marine and anthropogenic controls (Helal and Abd El-Wahab, 2010; El-Kahawy *et al*., 2018, 2021; Alongi, 2020; Mannaa *et al*., 2021). They are storehouses for seafood resources and provide many edible materials for fish and aquatic organisms (Watanabe *et al*., 2018). A series of natural processes affect these ecosystems, such as freshwater input, and sediments input, waves, and tidal currents (Salisbury *et al*., 2008; Davidson-Arnott *et al*., 2019). These processes control primary productivity, altering the structure of the trophic webs for aquatic organisms such as benthic foraminifera (Murray, 2006; Chierici and Fransson, 2009). Benthic foraminifera is abundant in the bottom sediments of coastal ecosystems and have a short reproductive cycle (Murray, 2006 & 2014). Thus, they are highly sensitive to environmental changes and can be used as an ecological indicator (Koukousioura *et al*., 2011; El-Kahawy *et al*., 2018). The study of benthic foraminifera distribution helps to understand and solve many environmental issues in coastal ecosystems (Frontalini and Coccioni, 2011; Bouchet *et al*., 2012, 2018, 2020; Koukousioura *et al*., 2012; Moreno *et al*., 2014; Dimiza *et al*., 2016; Al-Dubai *et al*., 2017; Charrieau *et al*., 2017; Sreenivasulu *et al*., 2019). They can be dependable indicators for monitoring the disturbance in coastal ecosystems in response to anthropogenic impacts.

Recently, Saudi Arabia has undertaken numerous development projects, which could be sources for various pollution types such as oil spills and wastewater discharge. Previously, many studies have been carried out on the Saudi Red Sea to investigate the relationship between environmental conditions and benthic foraminifera (Abu-Zied *et al*., 2013; Youssef, 2015; Abu-Zied and Hariri, 2016; Al-Dubai *et al*., 2017; Youssef *et al*., 2021). Abu-Zied *et al*. (2013) stated that increasing values of Loss of ignition (LOI) and concentrations of heavy metals play a critical role in the diversity of benthic foraminifera. Youssef (2015) mentioned that human activities led to distort some foraminiferal tests in the Red Sea coast. Al-Dubai *et al*. (2017) found a positive correlation between intertidal-subtidal foraminiferal assemblages, water salinity and temperature. The increase in the abundance of epiphytic foraminifera rather than opportunistic foraminifera indicates a normal environmental condition (Youssef *et al*., 2021). However, the effect of anthropogenic activities on foraminiferal distribution is a hot topic for future debate and still needs more attention.

This research studies the abundance and distribution of epiphytal benthic foraminiferal assemblages on the Saudi Red Sea coast including Farasan coast, the Southern Corniche of Jeddah (SCJ) and Rabigh coast. Moreover, our study aims to clarify the effects of the human activities on the benthic foraminiferal ditrebution in the three sites.

2. Materials and Methods

2.1 Area of Study and Sampling

The area of study includes the Saudi Red Sea coastin the Farasan Island (FAR), Sothern Cornich of Jeddah (SCJ), and the coast of Alkharar (KHR) in Rabigh area (Fig. 1). A total of 20 recent sediments were collected from these areas during the period between December and February 2020. The collected samples were 7, 7, and 6 samples from FAR, SCJ, and KHR, respectively. The coordinates of each sample were recorded by GPS (Garmin II) (Table 1). The collected surficial sediments samples from Rabigh were recovered by a Veen grab sampler of the upper 1-2 cm. In contrast, a scoop was used to collect the surficial samples from SCJ and FAR coasts. The collected samples were placed in clean and labeled polyethylene bags, stored in a freezing icebox, and then brought to the laboratory. In the lab, the samples were dried at room temperature. Each sample was then homogenized and divided into four parts for textural, $CaCO_3$, loss on ignition (LOI) at 550^0C, and microfossils analysis.

2.2 Grain Size Analysis

About 35 grams of each dried sample was soaked in distilled water overnight to disintegrate coherent particles. In the next day, a wet-sieving technique was applied to separate the sizefractions throughout sieves 2 mm and 63 µm. The retained fractions in the sieves were dried and weighed. The weight percentage of gravel (>2 mm), sand (<2 mm - >63 µm) and mud (<63µm) were calculated.

2.3 $CaCO_3$ Content

About a gram of the dry sample was ground and treated with 1 mol HCl in a 20 ml bottle inside the calcimeter following the method of Şenlikci *et al.* (2015). The calcimeter method utilizes the pressure of the released CO_2 from the sediments in reaction with HCl as PSI. The PSI reading of the sample was recorded and compared with the calibration curve of pure $CaCO_3$ to calculate the percentage of $CaCO_3$.

2.4 Loss on Ignition (LOI)

To determine organic matter content, approximately 2 g of dry sample was ground and oven-burnt at 550°C for 4 hours following the method of (Heiri *et al*., 2001). After that, the burnt sample was taken and weighed again. In the end, the LOI values were calculated as the difference in weight between the first and last weighing of the sample.

2.5 Benthic Foraminifera

A total of 5 grams of the sand fraction (0.063–2 mm) of each sample was splitted via a micro-splitter, followed the procedure of Murray (2006). The shells were examined under a stereomicroscope at a magnification of ~40x, and around 200 benthic foraminiferatests were picked using aWindsor Newton sable hairbrush (“00”). Benthic foraminifers were classified into three major orders based on wall composition (Hyaline, porcelaneous, and agglutinated) (Fig. 2). The counted tests were then presented as the total number of tests per gram of dry bulk sediment (hereafter called faunal density) and the total benthic foraminiferal assemblage percentages. The individual foraminifer species were taxonomically identified according to the classification of Loeblich and Tappan, (1987), Hottinger *et al*. (1993), Abu-Zied and Hariri (2016), and Al-Dubai *et al*. (2017).

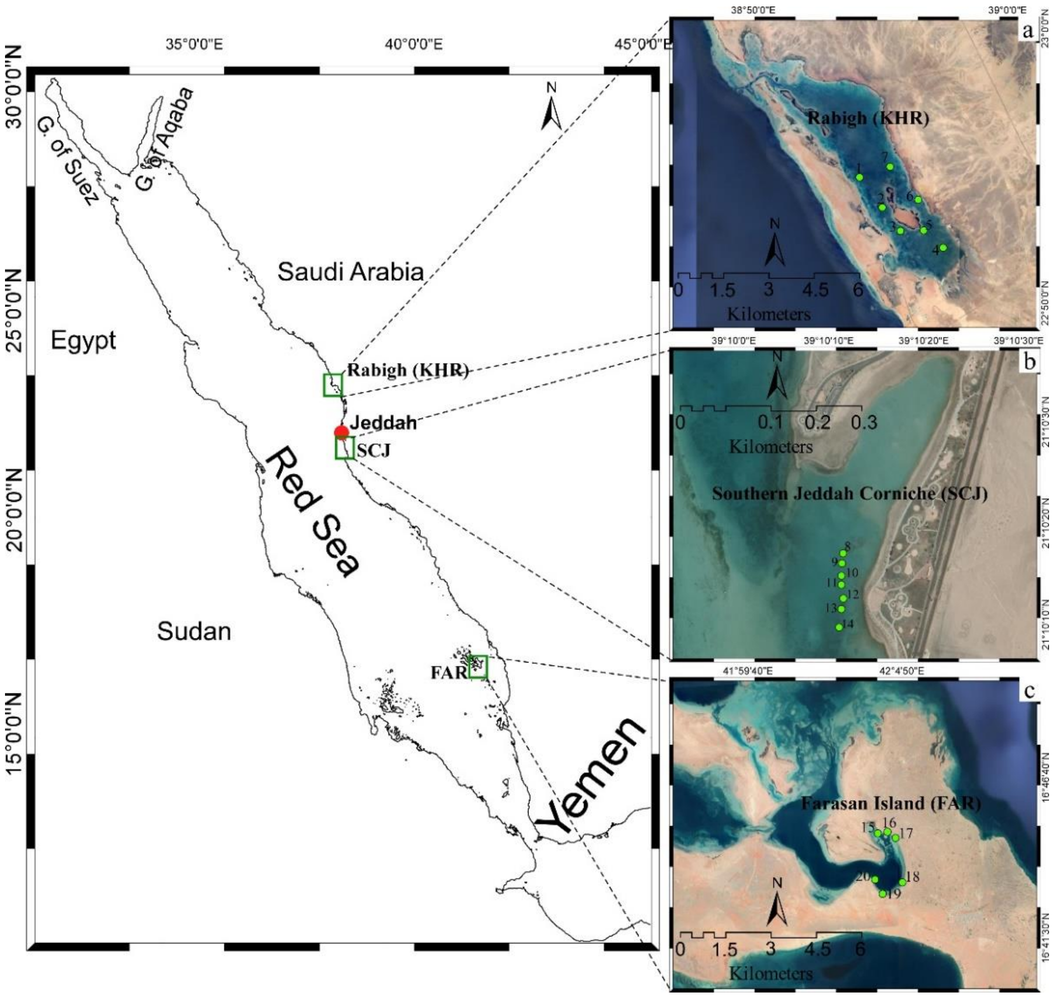

Fig. 1 Location map and landsat images showing the studied sites: a) Rabigh (KHR), b) the Southern Corniche of Jeddah (SCJ), and c) Farasan Island (FAR).

Fig. 2. An example of the identified benthic foraminifera a) *Coscinospira hemprichii* (miliolina), b) *Varidentella neostriata* (milliolin), c) *Clavulina multicamerata* (Agglutinated).

2.6 Statistical Analysis

Statistical analyzes were carried out on benthic foraminifera species recovered from 20 sediment samples collected from three different areas on the Red Sea, namely Farasan Island (FAR), Sothern Cornich of Jeddah (SCJ), and the coast of Alkharar (KHR). Simple diversity (S, total number of specimens in each sample), faunal density (number of tests per gram of dry weight sediment. Shannon-wiener diversity index (H`) was calculated using the equation: H`=-sum (Pi (in Pi)), where Pi is the proportion of the specimens in the dry sample. Equitability (evenness index) (E) was used to describe how individuals were divided between species. They were achieved using Primer v. 5.0 (Clarke and Warwick, 1994). Hierarchical Q- and R-mode cluster analyses were conducted on 7% of benthic foraminifera assemblage using (Past software) based on Burt-court correlation (r>0.90). Canonical correspondence analysis (CCA) was performed using Past software (Hammer *et al*., 2001). The aim of the CCA is to explore the relationship between environmental variables such as LOI, $CaCO_3$, mud, sand, gravel, foraminiferal indices, and benthic foraminifera distribution.

3. Results

The results of the grain size analysis (Fig. 3) show that Rabigh is dominated by mud fraction, whereas sand fraction dominates both SCJ and Farasan. The sediments of the Farasan area yielded relatively higher content of gravel than to the other two areas.

The $CaCO_3$ content in the three areas ranges from 10 to 90% (with an average of 55 %) (Fig. 4a). It fluctuates from 10 to70% and 40-80%, with averages of 41 and 54 %in Rabigh sediments and the SCJ, respectively. The Farasan coastal sediments show the highest $CaCO_3$ content that varies between 60 and 90% with an average of 70%. In contrast, the $LOI_{550°C}$ (organic matter) results show opposite trends (Fig. 4b), where the highest content are recorded from the Rabigh coastal sediments (6.5-13.1%; average of 10.1%). On the other hand, the lowest $LOI_{550°C}$are observed from the SJC coast, with variations 1.9-3.8% and a mean of 2.9%.

3.1 Benthic Foraminiferal Distribution

Eighty-two benthic foraminifera species (Table 1) belonging to three orders (Rotaliids, Miliolids, and Agglutinateds were recorded from the coastal sediments of Farasan, Rabigh and SCJ. The distribution of these orders among the sites is presented in Figure 5a-c, and the census data of species were calculated as the relative abundance of faunal density and diversity indices. About 7% of the total species were statistically analyzed to represent the benthic foraminiferal assemblages variations among the lagoonal ecosystems.

As shown in Fig. 5a-c, the sediments samples of Rabigh coast are dominated by miliolids, which show an abundance range from 36% to 74% and an abundanceof rotaliids with a range of 29-59%. However, it is notable that the highest abundance of miliolids occurs in Rabigh, and the highest abundance of rotaliids occurs in the sediments of SCJ coast. In comparison, the sediments of the Farasan coast show an inverse relationship between Rotaliids and Miliolids. The abundance of rotaliids fluctuates between 60 and 82%, while the abundance of miliolids ranges from 10 to 37.5%. In contrast, the abundance of agglutinateds is generally low attaining 10, 1.5, and 9% in the sediments of Rabigh, the SCJ, and Farasan coast, respectively.

The density of the three coastal ecosystems show the different specimens per gram density (Fig. 6a). The surface sediments of the southern Corniche of the Jeddah display a high density that reaches around 1178 specimen/g. The surface samples of the Farasan lagoonal coast represent moderate density, ranging from 187 to 374 specimen/g. However, the density of benthic foraminifera in Rabigh coast is less than 200 specimen/g.

The diversity of benthic foraminifera (simple diversity) ranges from 13 to 39, with an average of 25 among the three coastal lagoonal ecosystems. The highest diversity is recorded in the southern Corniche of Jeddah, while the lowest is recorded in Rabigh lagoon coast. Within each coast shows minor fluctuations (Fig. 6b). The foram diversity indices are shownin Fig. 6 c-f. The Equitability evenness index (E & J) and Shannon-Wiener diversity index (H'(loge)) show approximately similar trends among the three coastal ecosystems (Fig. 6 c and d). The evenness index straddles close to 0.7 and 0.9, while the H index ranges between 1.5 and 3. The lowest values of these indicesare observed in the samples of the Farasan Island. On the other hand, Fisher (α) and Margalef (d) indices clearly differentiate the three coastal ecosystems. They showed the highest values in the southern Corniche of the Jeddah, whereas the lowest wason the Rabigh lagoon coast.

3.2 Benthic Foraminifera Assemblages

Heirarchical cluster analysis differentiates the identified benthic foraminiferal species into two major assemblages (A and B). The assemblage-B includes two sub-assemblage-B1 and sub-assemblage-B2 (Fig. 7). Assemblage-A dominates most samples of the KHR ecosystem and is rarely recorded in the other ecosystems. However, assemblage-B occurs in most samples of the FAR and the SCJ ecosystems.

The most common species in the KHR were *Triloculina trigonula* (33%), *Spiroloculina communis* (30%), *Quinqueloculina bosciana* (21%), *Elphidium striatopunctatum* (18%), *Quinqueloculina laevigata* (14%), *Quinqueloculina mosharrafai* (12%), *Sigmoilopsis schlumbergeri* (11%), *Quinqueloculina tropicalis* (9%), *Quinqueloculina patagonica* (8%), *Triloculina serrulata* (8%), *Triloculina bermudezi* (7%), and *Spiroloculina rugosa* (7%). The FAR ecosystem is characterized by a slightly high relative abundance of *Peneroplis planatus* (55%), *Sorites orbiculus* (27%), *Neorotalia calcar* (15%), *Quinqueloculina limbata* (14%), and *Clavulina angularis* (8%). In contrast, the common species in the SCJ ecosystem is *Peneroplis planatus* (39%), *Coscinospira hemprichii* (26%), *V. neostriata* (15%), *Quinqueloculina costata* (10%), and *Quinqueloculina seminula* (8%). *P. planatus* species occur mostly in both of the FAR and SCJ ecosystems with high frequency among the samples. They approximately disappeared along the coasts. On the contrary, they are rare or absent in the KHR ecosystems.

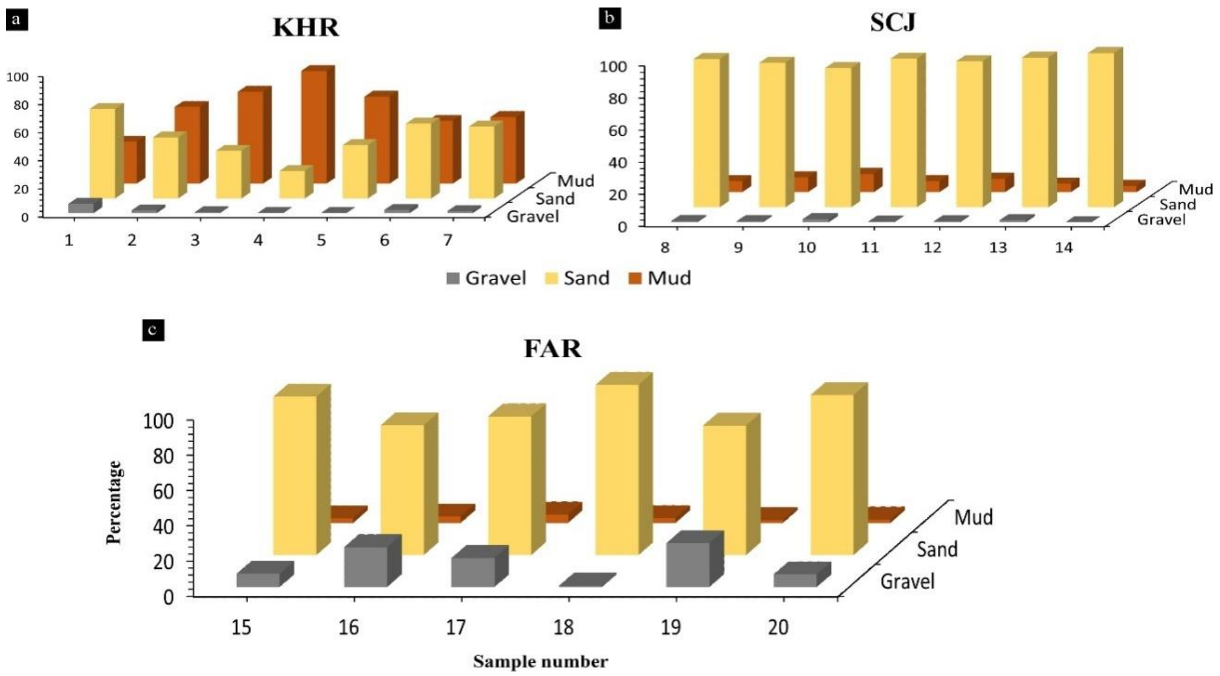

Fig. 3. The weight percentages of gravel, sand and mud in the sedmints of; a) Rabigh (KAR), b) the Southern Corniche of Jeddah (SCJ), c) Farasan Island (FAR).

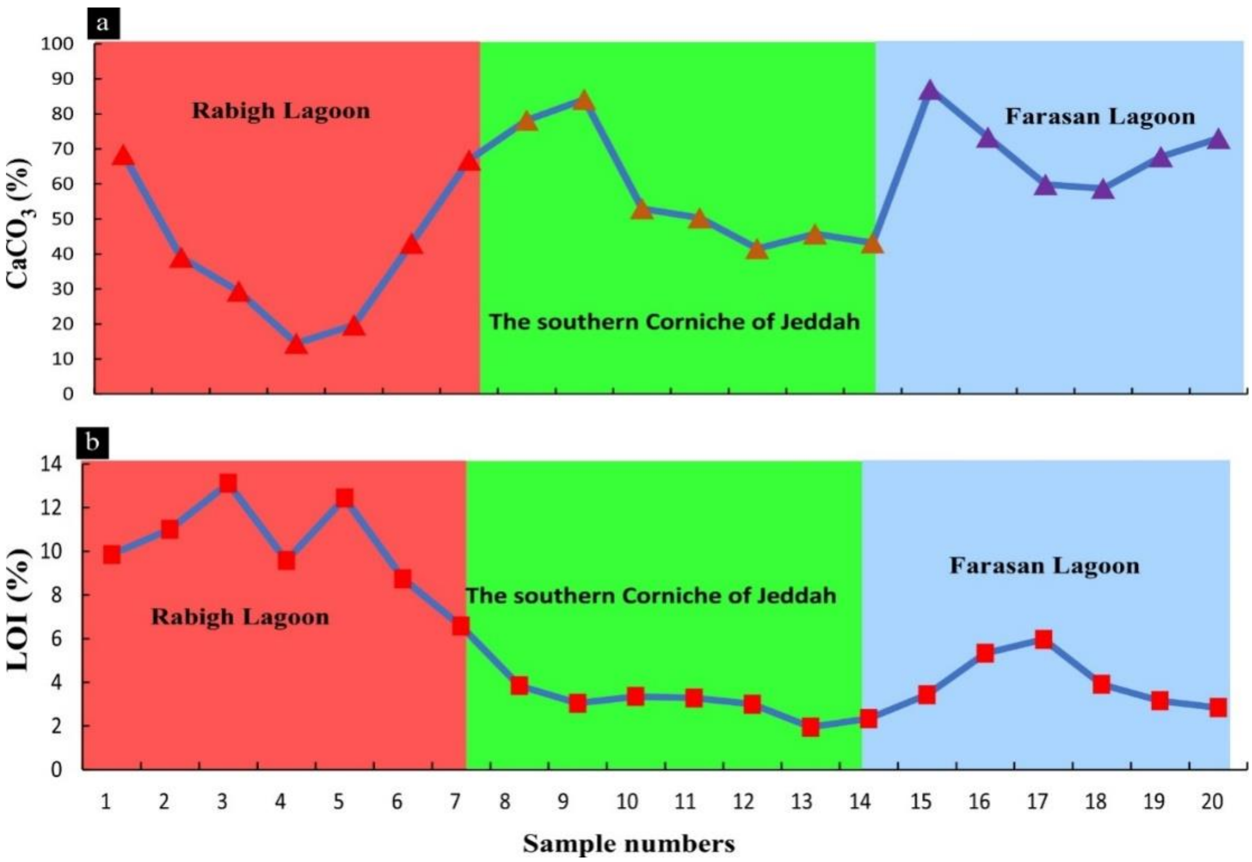

Fig. 4. A comparing chart among the three coastal lagoonal ecosystems; a) the percentages of $CaCO_3$, b) the percentage of organic matter.

Table 1. The identified benthic foraminifera species among the investigated ecosystems.

Sample no./species	Rabigh (KHR)							Southern Corniche Of Jeddah (SCJ)							Farasan Island (FAR)					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Adelosinabicornis		3				3	4													
Adelosina longirostra		4					3	1												
Adelosina elegans		1																		
Affinetrinaquadrilateral is				2			1	2	1	1			1	1	1		1	1		1
Agglutinellacompressa									1		1			1						
Agglutinellarobusta										1	1			3						
Ammonia convexa	1	1		2				4	5	8	4	2	4	4	1				1	
Ammonia tepida						1			2		2		1							
Bolivinastriatula													1							
Challengerellabradyi	1			1		3	2													1
Cibicidesmabahethi									1											
Clavulinaangularis															8	9	19	1	2	14
Clavulinamulticamerata										1					4	3	5		1	7
Coscinospirahemprichii						2		25	38	15	4	7	6	22	2				9	3
Cycloforinacarinatastria ta					2		1	2	3	1	5	3	10	3	2			3		2
Cycloforinaquinquecarinata								3	1		2	1								9
Cycloforinasulcata									3	1	1	1	2							
C. tabellaeformis																		1		2
Edentostominamilletti						1	1													1
Elphidiumadvenum						1		2	3	3	1	5	3						1	
Elphidiumcraticulatum	2						1		1	2	1			1						
Elphidiumcrispum											1		1	3						
E. Discoidalismultiloculum	3	5				4	1													
Elphidiumjenseni													1							
Elphidiummacellum													1							
Elphidiumstriatopuncta tum	15	4		1	2	2	23	1	4		3		1							
Elphidiumwillimsoni											1	2	3	1						1
Haynesina depressulus							1		1	1										
Lachlanellacorrugata			1											1						
Lachlanellasubpolygona		1							1	1	1			1	3			8	3	4
Masslinagualtieriana									1		1			1						1
Miliolinellalabiosa				2												3	2			
Monalysiumacicularis							1	2	2	4	3	11	4	9		1				
Neorotalia calcar										2		3	3	2	2	35	12	6		2
Nonionfabum	1					1														
Parrellinamilletti										3			1			1				
Parrinabradyi										1					1	5	1	3	1	1

Peneroplisplanatus	20	22	1	2		25	14	47		51	60	69	56	64	102	118	128		79	82
Peneroplis pertusus						7														
Pseudomassilinareticulata						4	1	2		5	2	4	1	4					3	
Pseudomassilina australis		2				2		1				1	3							
Pseudotriloculinaelongata											2		1							
P. granulocostata					1			2					1							1
P. subgranulata	1									1										
Pseudotriloculinaoblonga								1	1	1				1	1				2	
P. chrysostoma														1						
Quinqueloculinabicarinata	8			1		5	1		4	7	4	2	6	4			1			
Quinqueloculinaboscianа	1		6	6	3			1		9	5	4	2	1						
Quinqueloculinacostata	1		1			2		10	7	18	14	6	3	2	1			6	2	
Quinqueloculinaeburnea			1	6	1		1			1	3		3				3	1		1
Quinqueloculinalaevigata	1		1	6	5			1	4		2	3	4		2	1	1	5	2	1
Q. lamarckiana	1		1		1	1		9	9	5	5	10	6		12			2	3	4
Quinqueloculinalimbata				1	3			2	20	4		1	3	8		14	8	13	1	8
Q. mosharrafai	9			4		15	4				1	2								
Quinqueloculinapatagonica			1	8	3				2	1	1	2		1			1	6		1
Quinqueloculinapoeyana									2		1		2	2	4			1		
Quinqueloculinaseminula	1			2			7	5	4	3	7	7	14	5	5	5	1	11	3	3
Quinqueloculinapolygona								1	1	1	1			1		2	3			
Quinqueloculinatropicalis				1	3			1	3	2										
Rosalina Bradyi																				1
Sigmoilopsisschlumbergeri	16	4				7	2					1		2						
Sigmoihauerinabrady											1			1						
Siphonapertapittensis							1		2	1		2	1							
Soritesorbiculus	5	2	1	1	1	2	7		3	1		2		2	59	25	47	24	9	
Spiroloculinaantillarum	1					1	1		1	1	1				1			2		
Spiroloculinacommunis	13	31	2	11	5	13	34		2	2	2		2	4	2	1		9		
Spiroloculinaconvexa							1											1	2	
Spiroloculinacorrugata																1				
Spiroloculinacostigera	2	2																1		
Spiroloculinarugosa			2				2													
Spiroloculina sulcate						1			1	1		1	1					1		
Triloculinabermudezi	4		2				1	2												
Triloculinafichteliana								3			1	1		2	2	1	1	1	4	
Triloculinaschreiberiana								2	1		1			2						
Triloculinaserrulata	10	3	1	6		7	10	2	2		1	1	1						1	

Triloculinatricarinata						2							1							
Triloculinatrigonula	22	14	7	31	6	10		2	1		1	3	1	5						3
Trochamminainflata				1																
Varidentellaneostriata	4	4				2	3	12	8	14	6	27	25	17		3		10	27	18
Vertebralinastriata									1	1										
Simple Diversity (S)	24	16	14	20	13	26	27	28	37	36	38	29	37	34	20	17	16	23	20	27
Dead density/gram	143	103	45	95	58	198	129	947	941	1120	986	1178	1152	1165	344	365	374	187	250	280
Evenness index (E & J)	0.8	0.8	0.9	0.8	0.9	0.9	0.8	0.8	0.8	0.77	0.7	0.72	0.76	0.733	0.6	0.6	0.5	0.9	0.6	0.7
(H'(loge))	2.6	2.2	2.3	2.4	2.4	2.8	2.5	2.5	2.9	2.75	2.7	2.44	2.73	2.585	1.7	1.7	1.5	2.7	1.8	2.2

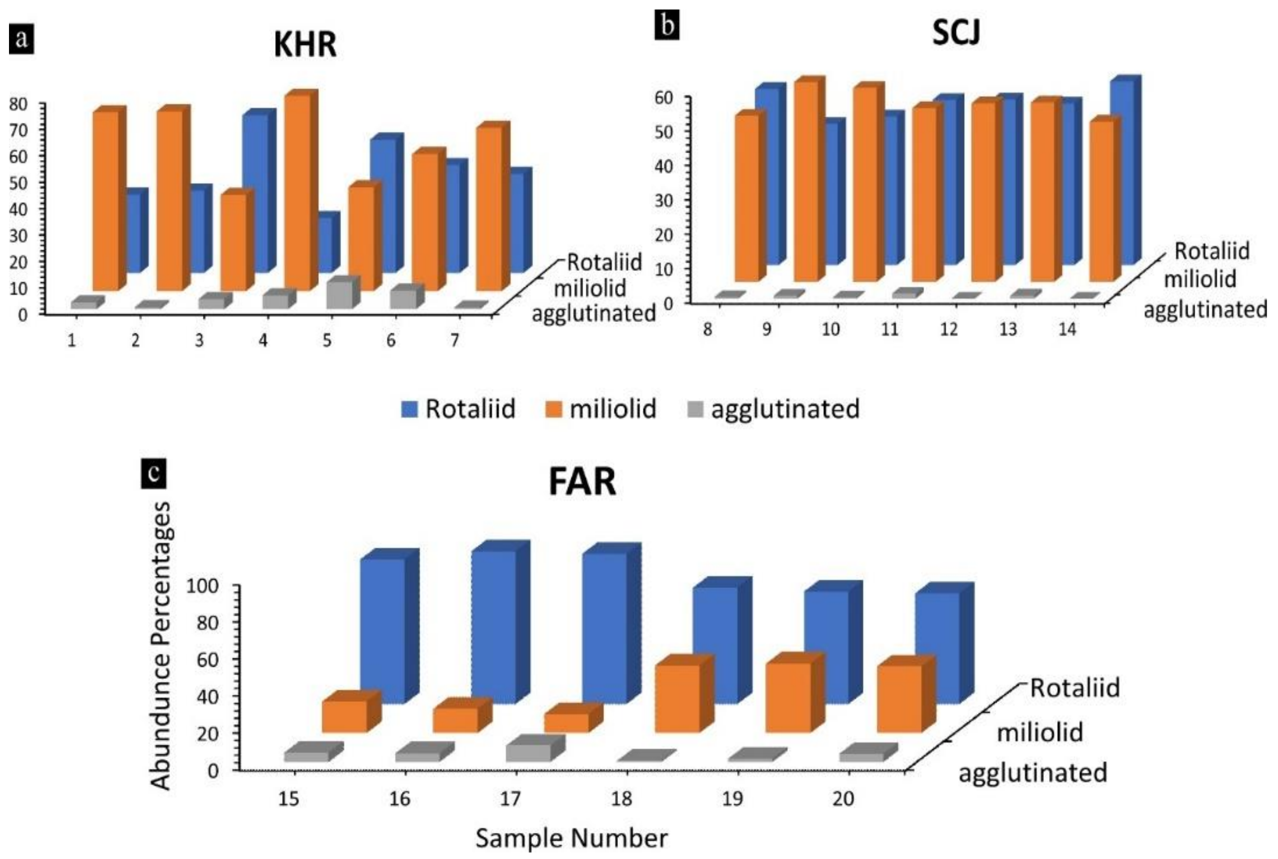

Fig. 5. The abundance of benthic foraminifera among the investigated sits; a) Rabigh lagoonal coast (KAR), b) Southern Corniche of Jeddah coast (SCJ), and c) Farasan island coast (FAR).

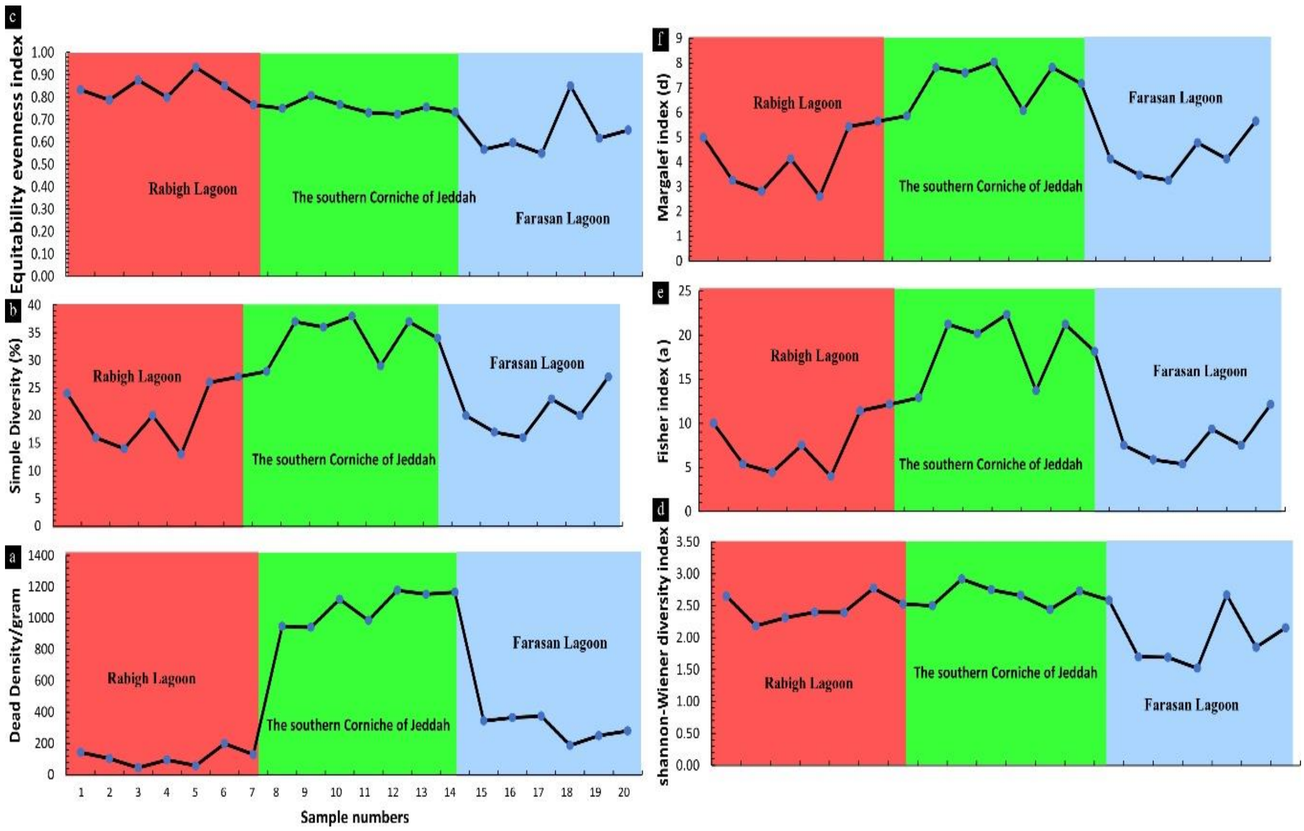

Fig. 6. Diversity of benthic foraminifera and foram indices in the investigated sites; a) Simple diversity, b) density/gram, c) Equitability evenness index (E & J), d) Shannon-Wiener diversity index (H'(loge)), e) Fisher index (α), and f) Margalef index (d).

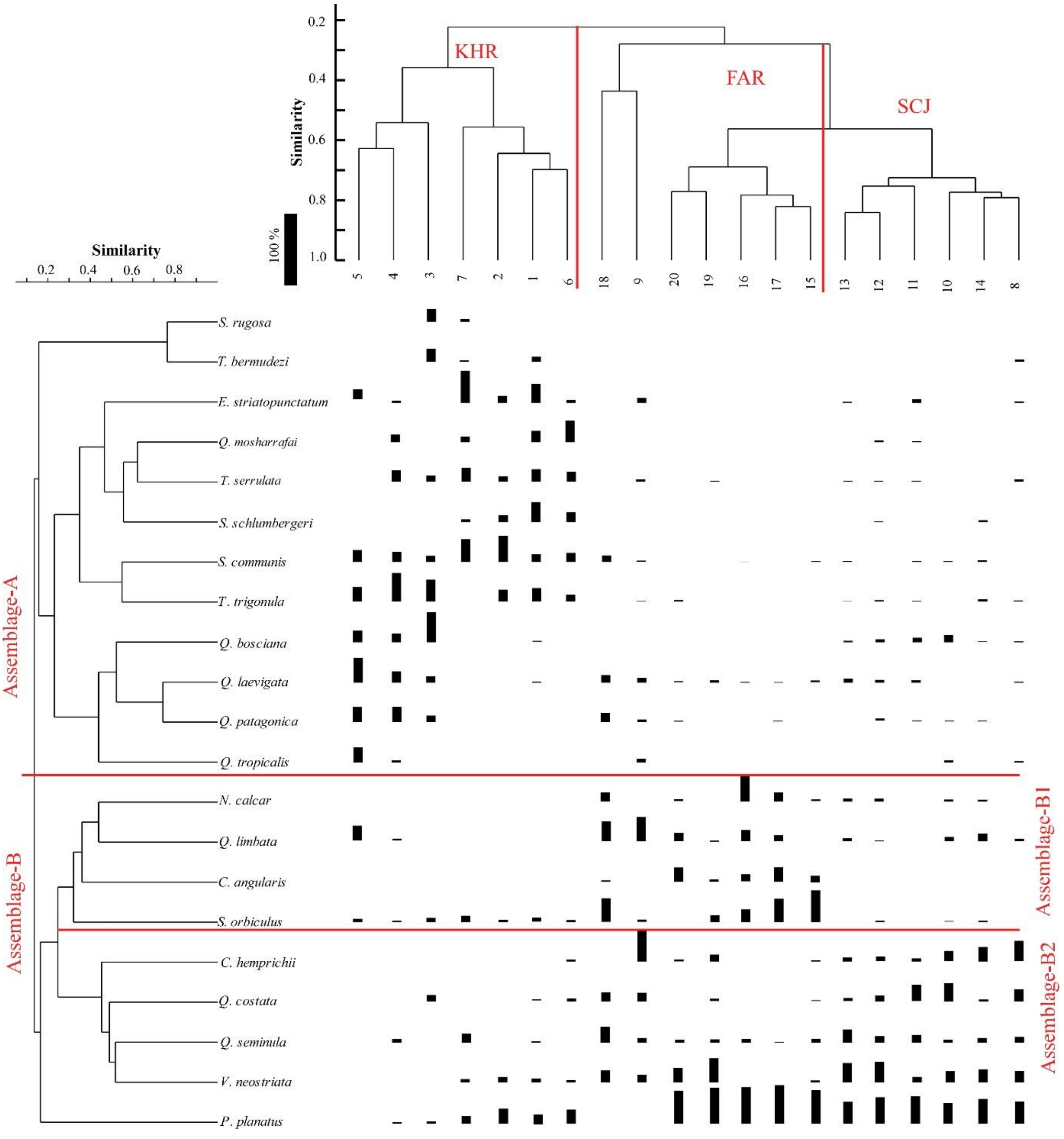

Fig. 7. Hierarchical (Q & R- modes) cluster analyses for 7% of benthic foraminiferal species and the investigated samples based on Bray-Curtis correlation (r>0.90).

4. Discussion

Benthic foraminifera abundance coupled with grain size analysis, organic matter, and $CaCO_3$ of the surface sediments of the three Red Sea coastal ecosystems enabled clarifying the controlling factors on benthic foraminiferal distribution.

The sediment samples of the KHR ecosystem are characterized by a relatively high organic matter, relatively low $CaCO_3$ contents, high mud content, and low density and diversity of benthic foraminifera, indicating the dilution effect of terrestrial input in the Rabigh area ecosystem (Bantan *et al*., 2019; Ghandour and Haredy, 2019). Terrestrial inputperiodically lead to algal efflorescences and the rapid consumption of oxygen, resulting in depletion of oxygen in the surficial sediments or strata that benthic foraminifers are lived (Bouchet *et al.*, 2018). This suggestion is also confirmed by the decreasing values of the Fisher and Margalef diversity indices. According to Q and R-modes (Fig. 7), the KHR ecosystem is dominated by *T. trigonula* and *S. communis* assemblage, with abundances more than 30 %. These fungal species could be able to live an opportunistic life strategy (Jorissen, 1987; Abu-Zied *et al*., 2013). Abu-Zied *et al*. (2016) stated that such assemblage might adapt with organic rich substrate .Youssef *et al.*, (2021) mentioned that the epiphytic foraminifers occur in the substrate-type enriched in seagrasses and macroalgae. On the other hand, the CCA (Fig. 8) showed a positive correlation between the KHR samples and organic matter and mud fractions as well as benthic foraminiferal assemblage A, which is considered to be relatively tolerant to environmental stress. Al-Dubai *et al*., (2017) found apositive relationship between similar assemblage with pH, organic matter, and mud substrate. Many other authors also have stated that this assemblage can survive under brackish to hypersaline conditions (Almogi-Labin *et al*., 1992; Geslin *et al*., 2000; Abu-Zied *et al*., 2011; Abu-Zied and Hariri, 2016).

Additionally, visual observation of benthic foraminiferal tests reveals substantial black foraminifera (Fig. 9). These black/dark imprints are probably attributed to high organic matter or iron (Fe) concentration (Abou Ouf, 1992; Abou Ouf and El-Shater, 1993). This evidence confirms that miliolids species could be living within this reducing benthic condition. Also, mangrove communities that widely occupythe KHR ecosystem play a significant role in lowering the pH due to high primary productivity that consumes excessive dissolved oxygen to optimize the biogeochemical cycle (Charrieau *et al*., 2017). This could eventually reduce the pH and consequently dissolve the high-magnesium calcite of the benthic foraminifera tests (Abu-Zied *et al.*, 2013; Al-Dubai *et al*., 2017).

In the SCJ ecosystem, the sand content in the sediments samples correlates positively with the density and diversity indices of benthic foraminifers (Fig. 8). The Fisher and Margalef diversity indices display high values more than 6, and the benthic foraminiferal assemblage-B is the most abundant in this ecosystem (Fig. 7). All these evidence indicate a moderately stressed ecosystem. The high density and highly diverse benthic foraminifers live under stable and well-oxygenated bottom water and suitable pH (Bouchet *et al*., 2012; Charrieau *et al*., 2017). The slightly abundant of *P. planatus* (39%) and *C. hemprichii* (26%) revealed a sandy substrates with seagrasses and algae. Haunold *et al*., (1997) mentioned that the occurrence of *C. hemprichii* and *P. planatus*favor substrates enriched in autochthonous sediment with abundant seagrass. The abundance of the same two species positively correlated with the vegetated substrate type in the shallowed restricted lagoonal system in western parts of the Arabian Gulf (Amao *et al*., 2019).

Thebottom sediments of the FAR ecosystem have high $CaCO_3$ and organic matter content. They are highly enriched in rotaliids species and the R and Q-modes have clustered it in assemblage-B1 (Fig. 7). In addition, the CCA shows a positive correlation between the sediment samples especially gravel fraction, $CaCO_3$, and assemblage-B1 that dominated the FAR ecosystem but negatively correlateswith sand fractions (Fig. 8). The benthic foraminiferal tests are well preserved without any imprints or stains by dark/grey color, as in the case in Rabigh lagoon and the SCJ. These characteristics could be suggesting a well-oxygenated well-conditioned normal marine ecosystem. The abundant *P. planatus* (55%), *S. orbiculus* (27%), *N. calcar* (15%) and *Q. limbata* (14%) confirm the above suggestion. These species favour warm waters, macro-algae, and mangrove vegetation (Al-Dubai *et al.*, 2017). Troelstra *et al*., (1996) stated that a relative abundance of the *P. planatus* at the coral reefs in the outer shelf in Spermonde Archipelago. The dominance of these two species has also been documented in the coral reef environment and marine seagrass occurrence (Gupta and Gupta, 1999; Uthicke and Nobes, 2008; Murray, 2014). Abu-Zied *et al*. (2011) and Al-Dubai *et al*. (2017) found a positive relationship between large species such as *Sorites orbiculus*, *Peneroplis planatus* and seagrass. These two species are known for their capability of symbiotic relationship with marine algae (Gupta and Gupta, 1999). Therefore, the positive relationship between seagrass and large rotaliids is mainly due to hosting significant marine algae in a symbiotic relationship. In addition, the diversity indices revealed that this ecosystem has normal ecology.

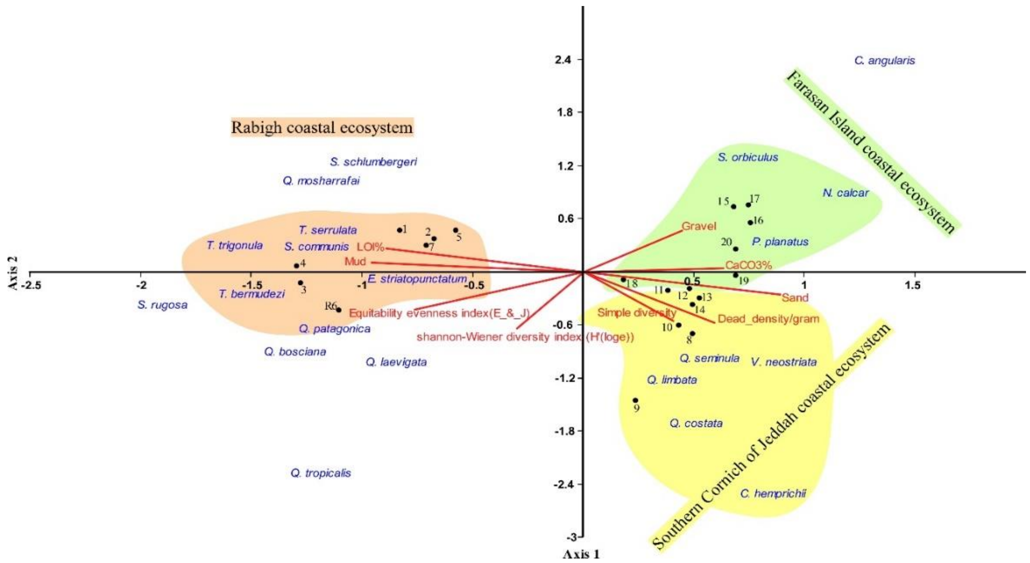

Fig. 8. Canonical correspondence analysis (CCA) represents the correlation between foraminiferal occurrence, diversity indices, grain size, CaCo3, and organic matter (%) among the three coastal ecosystems.

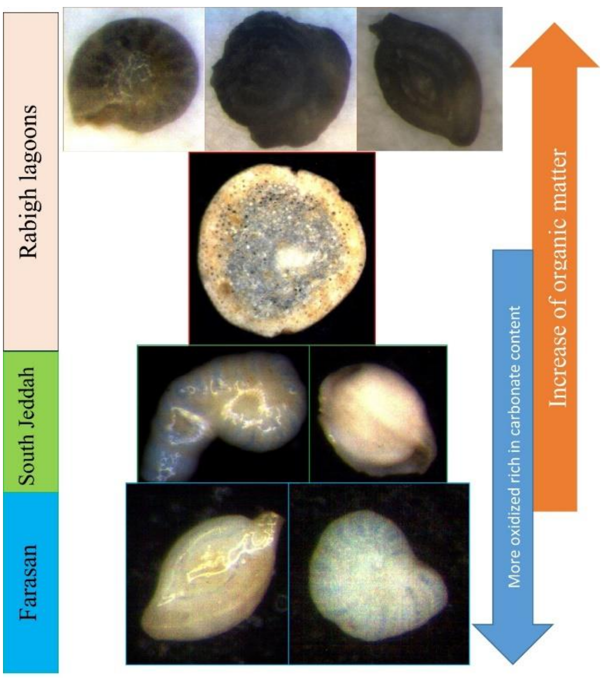

Fig. 9. Accumulation of organic matter embedded in the benthic foraminiferal tests of Rabigh, SJC, and Farasan (magnification of 40x).

5. Conclusion

Three lagoonal coastal systems on the south and the central Red Sea coast have been compared based on benthic foraminifera, organic matter, and carbonate content. The results suggest the following conclusions:

- Benthic foraminifers are sensitive to significant trophic changes in the Red Sea lagoons.
- The Rabigh coastal ecosystem is characterized by high organic matter, low carbonate ($CaCO_3$), and low density and diversity of benthic foraminifera occurrence. It is dominated by molilids species such as *T. trigonula* (33%), *S. communis* (30%), *Q. bosciana* (21%), *E. striatopunctatum* (18%). This assemblageis positively correlated with high organic matter and substantial dark/grey imprints or stains of what is assumed to be high concertation of iron. The source of the high organic matter is probably related to 1) seasonal floods during the spring season carrying a huge amount of dissolved nutrients and 2) Presence of mangrove communities surrounding the lagoon.
- The consistent low diversity indices of benthic foraminifera in the KHR ecosystem indicate that the ecosystem is ecologically moderate to high stress.
- The Southern Corniche of Jeddah (SCJ) is characterized by normal carbonate content, low organic matter, and moderate foraminifera preservation with uniform miliolid-rotaliid ratio such as *P. planatus* (39%), *C. hemprichii* (26%), *V. neostriata* (15%), *Q. costata* (10%). The consistent relatively high diversity indices of benthic foraminifera in the SCJ ecosystem suggest that the ecosystem is moderatelyecological stress or unstable environmental conditions.
- The Farasan ecosystem is considered a normal, highly oxic marine environment demonstrated by the dominated occurrence of nearshore-rotaliids, especially *P. planatus* (55%), *S. orbiculus* (27%), *N. calcar* (15%), *Q. limbata* (14%) and the high amount of carbonate at the expense of organic matter in addition to as well as high species abundance. The moderate diversity indices suggest normal ecology stress.

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توزيع المثقبات القاعية وأهميتها البيئية للنظم البيئية الساحلية المختارة على البحر الأحمر، المملكة العربية السعودية

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المستخلص. تستخدم الدراسة الحالية مؤشرات وفرة المثقبات القاعية والتنوع في رواسب القاع الساحلي لجزيرة فرسان، والكورنيش الجنوبي لجدة (SCJ)، ومنطقة رابغ بالمملكة العربية السعودية، للتعرف على العوامل البيئية المسيطرة على توزيعها. تم جمع ٢٠ عينة حديثة من الرواسب من المواقع المدروسة. وتم تحديد حجم الحبيبات، ومحتوى كربونات الكالسيوم والمادة العضوية. كما تم تطبيق تحليلات متعددة المتغيرات لاختبار وعرض مؤشرات التنوع وتوزيع تجمعات المثقبات القاعية. مجموعتان من المثقبات القاعية تم تمييزهما A وB. يحتوي التجمع– A على وفرة عالية من *T. trigonula* (٣٣٪)، و(٣٠٪) *S. communis*، و(٢١٪) *Q. bosciana* و(١٨٪) *E. striatopunctatum* ضغوط بيئية عالية. ويهيمن التجمع الفرعي– *P. Planatus* B1 على النظام البيئي لفرسان (٥٥٪)، (٢٧٪) *S. orbiculus*، (١٥٪) *N. calcar*، *Q. limbata* (١٤٪)، والتي تتراوح إجمالاً بين ٦٠٪ – ٨٢٪ ، مما يشير إلى بيئة بحرية شديدة التأكسد وإجهاد بيئي طبيعي. التجميع الفرعي B2 مثل (٣٩٪) *P. planatus*، (٢٦٪) *C. hemprichii*، (١٥٪) *V. neostriata*، (١٠٪) *Q. costata*. تهيمن على الكورنيش الجنوبي لمدينة جدة (SCJ) بمؤشرات تنوع عالية نسبيًا، مما يشير إلى بيئة إجهاد معتدلة أو ظروف بيئية غير مستقرة، وأشارت المجموعة والتحليلات المتعارف عليها (CCA) إلى أنه يتم التحكم في نمط التوزيع والتنوع للمثقبات القاعية. عن طريق إثراء المواد العضوية ومحتويات كربونات الكالسيوم وخصائص حجم حبيبات الرواسب. ربما يرتبط مفهوم التمايز بين هذه النظم البيئية بعدة عوامل، مثل الفيضانات الموسمية السريعة التي تحمل كمية كبيرة من المغذيات الذائبة ومجتمعات المنجروف على ساحل رابغ. في المقابل، لا يكاد يذكر على الساحل الجنوبي لمدينة جدة ويغيب تمامًا في جزيرة فرسان.

الكلمات المفتاحية: المنخربات القاعية، جزيرة فرسان، ساحل جدة، رابغ، النظم البيئية الساحلية للبحر الأحمر.