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The Northern Red Sea (Shushah Island) Coral Health Inferred from Benthic Foraminifers

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Abstract: The northeastern Red Sea (Saudi Arabia) is currently being transformed to become a global hub of economic activity and tourism. This transformation requires the development of pristine coastal areas into populated and dynamic settlements. At the same time, the northern Red Sea is considered a climate refuge for corals in changing climate conditions, and efforts to preserve and protect marine biodiversity are being proposed. Accordingly, foraminifers are an efficient tool to assess and monitor their associated coral reefs' health. This study reports a modern-day health assessment of the corals of Shushah Island (Saudi Arabia) in the northeastern Red Sea as a reference for future monitoring as inferred by applying the FoRAM Index method. In general, our results revealed healthy conditions conducive to coral growth, yet some precautions and regular assessments are recommended.

Keywords: FoRAM index; water quality; coral reef health; Red Sea

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1. Introduction

Ongoing climate change projections reveal a 1.5 °C increase in global sea surface temperature [1]. This rate is 2.5 times higher in the Red Sea [2] and thus poses a danger to the unique marine ecosystem of the Red Sea [3]. In 2024, the Kingdom of Saudi Arabia submitted a proposal to UNESCO to declare their commitment and intent to protect the corals of the Red Sea and the Gulf of Aqaba for their unique biodiversity [4].

The Red Sea is an exclusive semi-enclosed basin connected to the Indian Ocean via the Gulf of Aden through the Strait of Bab el Mandab and to the Mediterranean Sea only via the anthropogenic Suez Canal. Climates of such semi-enclosed basins are highly responsive to surrounding topography, local and global climate dynamics, and anthropogenic drivers [5]. As a combined effect, high evaporation, negligible precipitation, and the absence of riverine input are reasons for the extreme salinities in the Red Sea (>40 in the northern Red Sea) [6] and variable seasonal sea surface temperatures ranging from 22 to >30 °C that are mainly controlled by monsoons [7,8]. These features are key elements of the unique and diverse biodiversity, with the high endemism of marine organisms, in the Red Sea [9]. Its distal region from the open ocean (Indian Ocean), namely the cooler northern Red Sea, is considered a coral refuge under the ongoing climate change projections [10]. In particular, in the central and southern Red Sea, not only does ocean warming slow down coral growth, thus endangering coral reef recovery [11], but it also results in coral bleaching in the southern and central Red Sea [12,13]. Bleaching occurs when the seawater temperatures exceed their average maximum for a prolonged amount of time, causing a mutualistic interaction between the corals and their algal symbionts within their tissues to break down [14]. While bleaching is already a threat in the southern and central Red Sea, the northern Red Sea is still largely resilient to thermal stress. Consequently, the northern Red Sea plays an important role as a coral reef refuge, making coral reef health assessments and monitoring of the region crucial [15–17].

Symbiont-bearing large benthic foraminifers require similar ecological factors as corals [18]. Hence, they can be used to infer whether the environmental conditions are conducive to coral reef development [19]. To this extent, foraminifers are a well-established and efficient tool for assessing and monitoring coral reef health [19]. They are bioindicators for their associated coral reefs and are practical tools for evaluating ambient water quality, as collecting foraminifers has a negligible impact on coral reefs. Their short life span, compared to the long life span of corals, facilitates the monitoring of water quality changes, which directly links them to coral decline or growth. As they are an accessible and efficient tool, several studies have focused on using foraminifers to assess coral reef health at various important coral reef locations around the world [20–26].

In this present study, we focused on the area around Shushah Island (NEOM region), which is located in the northeastern Saudi Arabian Red Sea, where a 100 ha coral restoration project is ongoing, called the KAUST Coral Reefscape Initiative (KCRI) (Figure 1). Given the risks associated with development and ecotourism added to natural stressors such as climate change and ocean acidification warrant to this previously largely untouched region [26], regular monitoring is necessary to avoid water pollution and eutrophication, and thus preserve coral health. Furthermore, being on the coral migration pathway that connects the Gulf of Aqaba to the remainder of the Red Sea, Shushah Island occupies a strategic position that needs to be kept pristine for the corals to sustain population connectivity and gene flow. This study aims to document first insights into the present-day foraminifers to infer water quality, and thus suitability to support the healthy corals of Shushah Island, and it also acts as a reference study for future water quality monitoring activities and coral migration pathway studies.

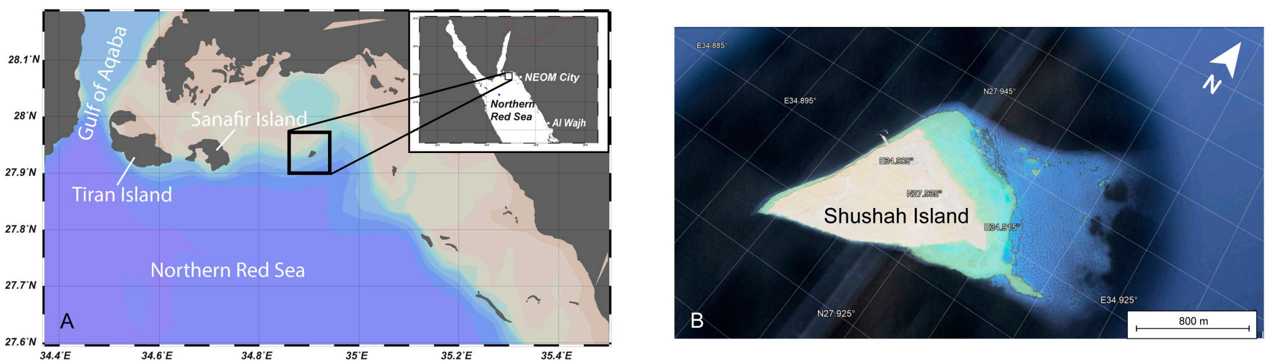

Figure 1. (**A**) Map showing the location of the study area (Shushah Island) with an inlet map of the region. Black square refers to Shushah Island. (**B**) Google Earth view of Shushah Island showing the approximate extension of the coral reef.

2. Study Area and Materials and Methods

The study area is located in the northeastern Saudi Arabian Red Sea (Figure 1A,B). A total of 11 seafloor surface sediment samples from along the eastern coast of Shushah Island where the KCRI program is being developed and from a nearby reef (samples F01 and F02) were collected during November 2022 by scuba divers who scraped the top few centimeters of the soft-bottom sediment using ziplock bags. Water depths ranged between 8 and 17 m (Table 1).

Table 1. Coordinates of locations and depths of samples used in this study.

Samples	Latitude (°N)	Longitude (°E)	Depth (m)
F01	27.95212	34.88669	9.5
F02	27.94719	34.87343	9
F03	27.94245	34.91801	12.5
F04	27.94161	34.90835	9.4
F05	27.93256	34.91718	8.3
F06	27.9357	34.91581	8.3
F07	27.935	34.92117	16.7
F08	27.939	34.91667	14
F09	27.94302	34.91983	11.3
F10	27.94182	34.91252	10
F11	27.93852	34.92245	15

Samples were washed through a standard 125 µm mesh sieve under pressurized water and then dried in a furnace at 40 °C. At least 150 benthic foraminifer individuals from 1 g of dried sample were picked using a brush under a binocular microscope [19,27]. Taxonomic identification was based on Hottinger et al.'s study (1993) [28] (Figure 2). Picked individuals were later categorized into three functional groups representing symbiont-bearing taxa (s), opportunistic/stress-tolerant taxa (o), and other smaller taxa (h) [19,21] to calculate the Foraminifera in Reef Assessment and Monitoring (FoRAM) Index (FI) by using the below equation [19,21]:

$$FI = (10 \times P_s) + (P_o) + (2 \times P_h)$$

where $P_s = N_s/T$, N_s represents the number of symbiont-bearing foraminifers and T is total fauna; $P_o = N_o/T$, where N_o represents the number of stress-tolerant/opportunistic foraminifers; and $P_h = N_h/T$, where N_h represents the number of other small taxa [19,21]. Accordingly, we present the following:

- Large benthic foraminifers (symbiont-bearing taxa) represent low-nutrient environments where algal symbiosis is advantageous [29];
- Stress-tolerant/opportunistic taxa represent oxygen-depleted waters with a terrestrial nutrient source (i.e., riverine input) and euryhaline conditions. In coral reefs, this group is only a minor component [30];
- Other smaller/heterotrophic taxa represent an environment with sufficient nutrient supply and enough oxygen [27] with a decreased light source [26].

When computed, FI varies between 1 and 10 [19]. Accordingly, we present the following:

- FI < 2 indicate ecological conditions unfavorable for calcifying organisms that host algal endosymbionts (and therefore not conducive to reef growth);
- 2 < FI < 4 indicate marginal conditions for coral growth representing environmental change and/or unsuitable for recovery;
- FI > 4 indicate favorable ecological conditions for calcifying organisms that host algal endosymbionts that support reef growth.

The results are detailed in Table 2 and displayed in Figure 3.

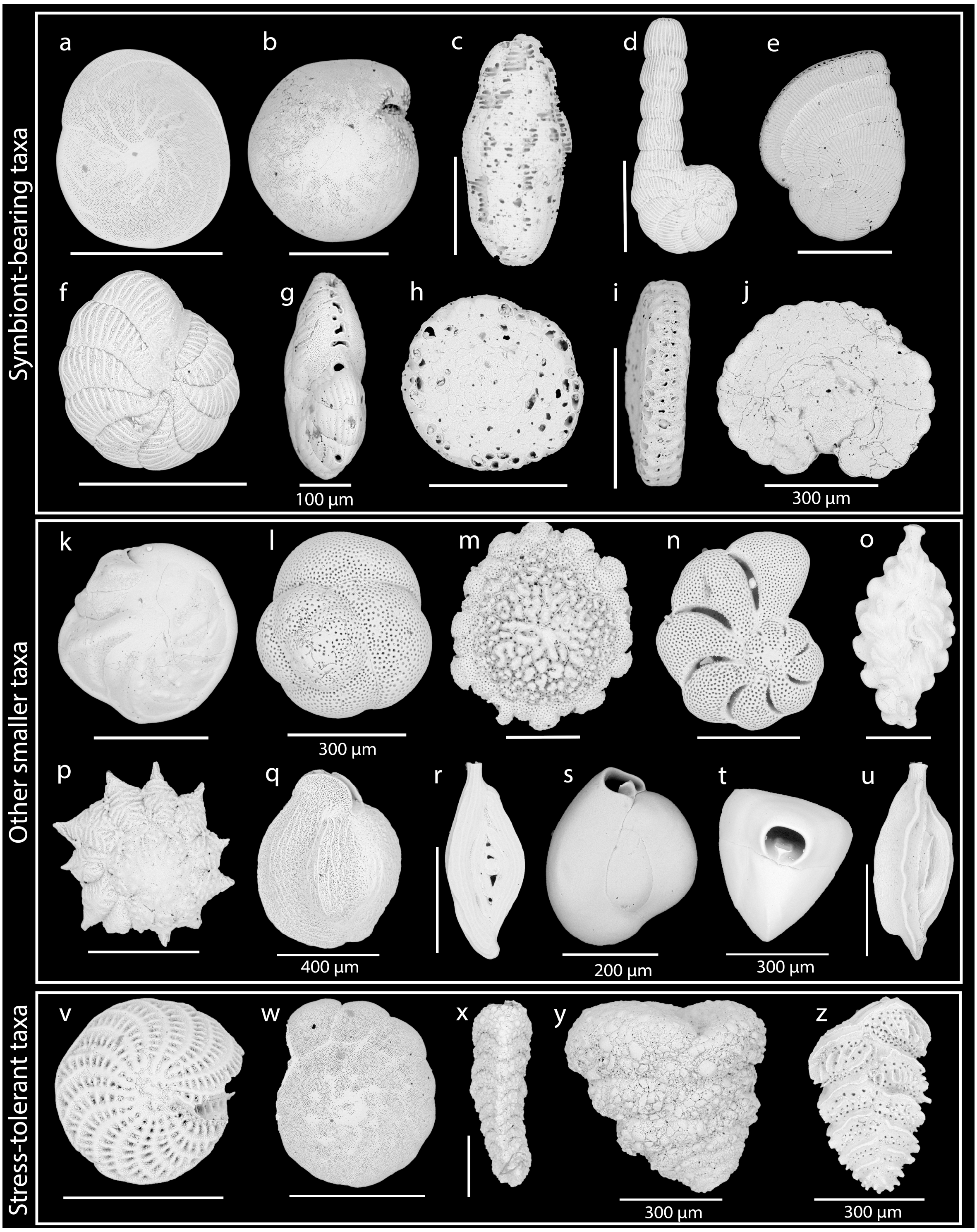

Figure 2. SEM images of selected foraminifers of Shushah Island. (**a**) *Amphistegina lessonii* (F07); (**b**) *A. lobifera* (F01); (**c**) *Borelis schlumbergeri* (F07); (**d**) *Coscinospira hemprichii* (F07); (**e**) *Peneroplis planatus* (F10); (**f**) *P. pertusus* (F05); (**g**) *P. pertusus* side view (F05); (**h**) *Sorites orbiculus* (F03); (**i**) *S. orbiculus* (F03) side view; (**j**) *Sorites* sp. (F10). (**k**) *Eponides cribroependus* (F04); (**l**) *Rosalina brady* (F04); (**m**) *Planorbulina mediterranensis* (F04); (**n**) *Epistomaroides punctatus* (F10); (**o**) *Cycloforina crenulata* (F06); (**p**) *Neorotalia calcar* (F06); (**q**) *Quinqueloculina* sp. (F01); (**r**) *Spiroloculina* sp.1 (F06); (**s**) *Triloculina tricarinata* (F08); (**t**) *T. tricarinata* aperture view (F08); (**u**) *Spiroloculina* sp.2 (F04); (**v**) *Elphidium crispum* (F06); (**w**) *Ammonia beccarii* (F07); (**x**) *Clavulina angularis* (F10); (**y**) *Textularia conica* (F10); (**z**) *Bolivina simpsoni* (F01). Scale bar is 500 µm unless otherwise stated.

Table 2. Total number of individuals belonging to each functional group, their computed values for FI calculation, and resulting FI values. s: symbiont-bearing taxa; o: opportunistic/stress-tolerant taxa; h: other smaller/heterotrophic taxa. N/A: not applicable.

Samples	#s	#o	#h	T	Ps	Po	Ph	FI
F01	66	16	105	187	0.35	0.09	0.56	4.74
F02				<150	N/A	N/A	N/A	N/A
F03	138	7	95	240	0.58	0.03	0.40	6.57
F04	82	5	145	232	0.35	0.02	0.63	4.81
F05	92	14	104	210	0.44	0.07	0.50	5.44
F06	43	26	152	221	0.19	0.12	0.69	3.44
F07	135	14	73	222	0.61	0.06	0.33	6.80
F08	128	11	94	233	0.55	0.05	0.40	6.35
F09				<150	N/A	N/A	N/A	N/A
F10	68	22	70	160	0.43	0.14	0.44	5.26
F11	70	12	68	150	0.47	0.08	0.45	5.65

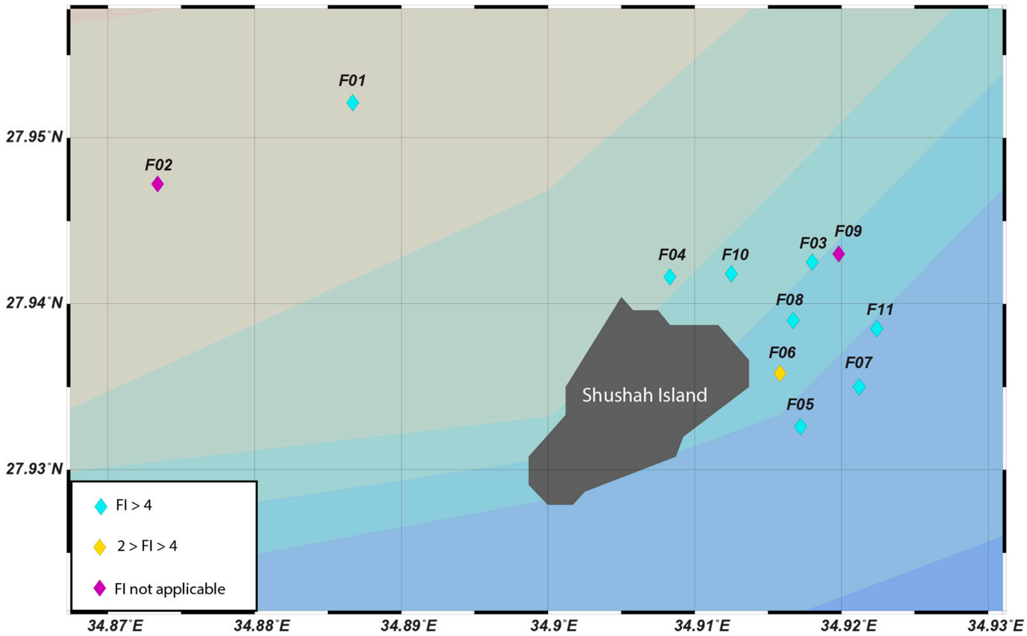

Figure 3. Map showing sampling stations and their corresponding calculated FI values. Map generated using Ocean Data View [31].

3. Results and Discussion

Out of 11 samples, 2 samples (F02 and F09) did not yield enough individuals per gram (less than 100 individuals) to apply the FI method [27], possibly indicating unfavorable conditions for calcifying organisms (Figure 3). The possibility of reworking the material was eliminated because the preservation status (i.e., post-depositional recrystallization, overgrowths, and/or damaged/broken tests were not observed) of the specimens of the samples for which the FI was calculated was good, except for sample F11. The FI was still calculated for sample F11, even though the preservation state of the specimens of this sample was moderate as the majority of the specimen tests were damaged/broken. Observed bioerosion of the foraminifers, instead, is discussed in Section 3.2 separately.

Overall, symbiont-bearing taxa were generally represented by *Amphistegina* (*A. lessonii*, *A. lobifera*), *Peneroplis* (e.g., *P. planatus* and *P. pertusus*), *Coscinospira hemprichii*, and *Sorites* (*S. orbiculus* and *S. variabilis*), with the scattered occurrence of *Borelis schlumbergeri*. Opportunistic/stress-tolerant taxa were represented mainly by *Ammonia bradyi*, *Ammonia beccarii*, *Elphidium* spp. and *Clavulina angularis*, and *Textularia conica*. Among others, heterotrophic smaller taxa included miliolids comprising *Quinqueloculina* spp., *Triloculina* spp., *Miliolinella* spp., *Adelosina* spp., and *Spiroloculina* spp.; and rotalids comprised *Planorbulina mediterranensis*, *Eponides cribrorependus*, *Epistomaroides punctatus*, *Rosalina brady*, and *Neorotalia calcar* (Figure 2). These species are in agreement with previous studies that reported coral reef health/water quality assessment along the Red Sea [32–34].

3.1. General Functional Group Assessment

Our assessment of the sampling stations are as below:

- F01: The major functional group comprises heterotrophic smaller taxa (Table 2) corresponding to >56% of the total number of specimens. This group of taxa indicates significant nutrient input in coral reef environments, resulting in higher populations compared to symbiont-bearing taxa [19,30,35].
- F02: Insufficient number of individuals per gram. Replicate analysis needed.
- F03: The major functional group comprises symbiont-bearing taxa (Table 2) corresponding to 57.5% of the total number of specimens. This group indicates nutrient-depleted waters.
- F04: The major functional group comprises heterotrophic smaller taxa (Table 2) corresponding to 62.5% of the total number of specimens pointing to increased nutrient flow to the sampling stations.
- F05: Similar to F04, the major functional group comprises heterotrophic smaller taxa (Table 2) corresponding to 49% of the total number of specimens. This group indicates nutrient input to the sampling stations.
- F06: The major functional group comprises heterotrophic smaller taxa (Table 2) corresponding to >68% of the total number of specimens.
- F07: The major functional group comprises symbiont-bearing taxa (Table 2) corresponding to >60% of the total number of specimens. This percentage is the highest number for symbiont-bearing taxa in the sample set.
- F08: The major functional group comprises symbiont-bearing taxa (Table 2) corresponding to >54% of the total number of specimens pointing to a lowered nutrient supply.
- F09: Insufficient number of individuals per gram. Replicate analysis needed.
- F10: The major functional group comprises heterotrophic smaller taxa (Table 2) corresponding to 43.7% of the total number of specimens. However, symbiont-bearing taxa represent 42.5% of the total assemblage. Hence, this station may point to an equilibrium state between the oxygen content and nutrient supply.
- F11: The major functional group comprises symbiont-bearing taxa (Table 2) corresponding to 46.6% of the total number of specimens. Similar to F11, heterotrophic smaller taxa represent 45.3% of the total assemblage and thus a similar equilibrium state between the oxygen content and nutrient supply may be considered.

3.2. First Insights into Coral Reef Health of Shushah Island

The FI values were mainly >4, ranging between 4.7 (F01) and 6.8 (F07), displaying that locations F01, F03, F04, F05, F07, F08, F10, and F11 are currently conducive for coral growth, while only one sample yielded marginal conditions indicated by an FI value of 3.4 (F06) (Table 2, Figure 3).

Stations dominated by heterotrophic taxa (F01, F04, F05, F06, and F10) did not show any patterns related to the proximity of the sampling stations to the mainland to consider the anthropogenic input as a nutrient source, given that the island was not populated at the time of the sampling (Figure 3). The northern Red Sea in general is oligotrophic [36], with monsoons being the major nutrient source for the north-central parts [37]. However, according to a culture study performed on the Red Sea corals, desert dust inputs also play an important role by providing nutrient inputs, such as iron [38], to the marine ecosystem. In addition, despite symbiont-bearing taxa favoring low-nutrient settings to maintain algal symbiosis, they still require nutrients to sustain the biological processes of their symbiont algae [38,39]. Yet, how desert dust contributes to the northern Red Sea foraminifer and coral ecology remains poorly investigated.

Stations F10 and F11 showed almost equal percentages of symbiont-bearing taxa and heterotrophic taxa. This balance may indicate a potential for turnovers between these groups under changing conditions, such as fluctuations in nutrient input and/or decreased light in the photic zone due to, e.g., turbidity [25,27]. Turbidity, which can result from the natural resuspension of sediments (e.g., tidal currents, waves, dust storms), as well as anthropogenic and terrestrial inputs, including dredging activities and runoff, may adversely affect the benthic ecosystem when present in excessive amounts. Given the plans to build a luxury ecotourism resort on Shushah Island, it is important to differentiate the impact of point-source continuous dredging, construction, and tourism activities around the coral reef from diffuse sources. A robust monitoring program would be required to elucidate whether development activities pose risks to the Shushah Island coral reefscape.

3.3. Intense Bioerosion on Foraminifers

SEM images of some of the coral reef-associated foraminifers of Shushah Island showed intense bioerosion on their surfaces (Figure 2). Bioerosion is a breakdown of a hard substrate by a living organism that can be *in vivo* or post-mortem. It is commonly manifested by traces such as microborings (e.g., Figure 2c,h,k), tubular tunnels parallel to the substrate (e.g., Figure 2m,l), or ring-shaped (e.g., Figure 2h) depending on the parasitic ichnospecies [40–42], including autotroph (algae, cyanobacteria) and heterotroph (bacteria, bryozoans, fungi, small sponges, etc.) organisms [43]. A study conducted in a lagoon close to an industrial area in southwest Sardegna, Italy, revealed that microbioerosion was more intense in porcelanaceous foraminifers (high-magnesium) compared to hyaline foraminifers (low-Mg) [40]. In the same study, it was also suggested that porcelanaceous foraminifers had a higher heavy metal concentration, such as zinc, which is an important bioelement as an inorganic nutrient. The bioerosion of foraminifers of Shushah Island coral reef does not show a specific difference between hyaline foraminifers (e.g., Figure 2k–n) and porcelanaceous foraminifers (e.g., Figure 2o,r–u). In another study conducted in Malta, Mediterranean Sea, the fungal colonization of living *Amphistegina lobifera* was reported [43]. Our data are not sufficient to identify the underlying reason of the foraminiferal bioerosion in the Shushah Island coral reef. Therefore, a more concentrated study on this matter would help understand the present-day environmental conditions in the region.

4. Concluding Remarks

We report the first assessment of foraminifer communities as a predictor of the environmental suitability to support healthy corals in Shushah Island coral reefscape, at the beginning of intensive human construction activity, as a baseline to contribute to the intent and commitment of the Kingdom of Saudi Arabia to preserve and protect coral biodiversity in the northern Red Sea as a part of its 2030 vision. Based on our FoRAM Index assessment, we conclude the following:

(1) At present day, Shushah Island water quality in general is conducive to coral growth.
(2) Stations with marginal conditions and those for which FI assessment was not possible need to be reanalyzed and monitored.
(3) Continuous monitoring and sampling, including the simultaneous acquisition of temperature/salinity/nutrient/oxygen data, is necessary to accurately assess the relationship of foraminiferal functional groups to the ambient water parameters.
(4) The underlying reasons for foraminifer bioerosion in the Red Sea should be studied carefully by collecting living samples accompanied by (bio)geochemical analysis.

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