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Spatial Distribution and Diversity of Benthic Macrofauna in Coastal Waters of the Jabal Ali Marine Sanctuary (JAMS), Dubai

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Abstract: The present study aimed to characterize the benthic macroinvertebrate community of the Jabal Ali Marine Sanctuary (JAMS), the sole marine protected area in the Emirate of Dubai, during the summer and winter seasons of 2017. Limited research on the biological quality of the JAMS prompted this investigation, which involved 10 sampling stations to assess macroinvertebrate diversity and community composition in relation to abiotic factors such as sediment granulometry, trace metals, salinity, and temperature. Collected sediment samples were analyzed for macroinfauna, and their abundance was measured, revealing an average abundance of 2150 ind/m^2 in summer and 2132 ind/m^2 in winter without a significant difference between both seasons. Univariate indices, including the Margalef diversity index and Pielou evenness index, indicate a range of diversity values across sampling sites. Community composition was assessed through SIMPROF and Bray–Curtis similarity clustering, further elucidating the relationship between community structures and environmental gradients. The dominant macroinvertebrate species varied across seasons and stations, providing insights into seasonal variations in community dynamics. These findings contribute to the understanding of benthic community structures and biodiversity in the JAMS and serve as a baseline for future monitoring and management efforts aimed at preserving the ecological integrity of this important marine sanctuary.

Keywords: invertebrates; species richness; marine biodiversity; United Arab Emirates; marine protected area

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1. Introduction

The coastline of the Emirate of Dubai was increased, by coastline modification through construction and artificial island creation, from 70 km to 1500 km long in the past 25 years and is one of the most noticeable coastlines in the Arabian Peninsula. The coastline, arguably, with natural (high temperature and high water salinity) and anthropogenic (megaprojects) stressors, results in a functional and structural modification of ecosystems [1–4]. The main physical impacts of various activities are related to the removal of sedimentary material, alteration of bottom topography, and re-deposition of

sediment [5–9], which changes the physicochemical characteristics of the sediment, especially its grain size composition and organic contents [10], and may subsequently change the benthic community composition [5,11,12]. Benthic organisms are usually considered bioindicators of disturbances occurring in the water column [13–15]. Furthermore, benthic macroinvertebrates of soft-bottom habitats are excellent indicators of the general state of the environment and determine the presence or absence of some sensitive organisms, which may control natural and anthropic disturbances [16–18]. Soft-bottom, benthic communities are key components in coastal and marine ecosystems [19]. These bring considerable changes in sediments' physical and chemical composition, through perturbation, especially in the water–sediment interface [20,21]. In that regard, accurately characterizing coastal benthic habitats and the living communities' diversity and density is a significant diagnostic process for effective management, particularly in protected areas [22,23].

Previous studies of macrobenthos in the coastal waters of Dubai have been limited in scope and frequency. The first comprehensive survey of benthic communities in the region documented 87 species across the Dubai coastline, establishing an initial baseline for biodiversity assessment [24]. Subsequently, a targeted study in the nascent Jabal Ali Marine Sanctuary identified 56 benthic species, noting the dominance of polychaeta and bivalves in the assemblage [25]. The Dubai Municipality conducted regular but limited monitoring between 2008 and 2015, primarily focusing on water quality parameters with minimal benthic sampling, resulting in a data gap for comprehensive community structure analysis [26]. Most recently, the northern portion of the JAMS in a broader Arabian Gulf assessment reported declining species richness compared to earlier studies, potentially attributable to increased coastal development and thermal stress [27]. These previous investigations, while valuable, utilized varying methodologies and sampling intensities, limiting direct temporal comparisons and highlighting the need for standardized, long-term monitoring of this ecologically important protected area to establish clear biodiversity trends and inform management decisions.

Sediment analysis plays a crucial role in detecting the impacts of anthropogenic activities on the sea floor and current patterns. Various materials transferred from land can accumulate in coastal and marine environments, sinking within sediments. Naturally occurring chemicals, such as hydrocarbons, nutrients, and trace metals, may become mobilized through both natural and human-induced processes, leading to their accumulation in sediments. While water quality measurements provide an overview of current pollutant inputs, numerous factors can lead to contamination during sampling and analysis, and these contaminants may occasionally leak out [28]. Moreover, water samples offer only short-term insights, as liquids continuously move, making it difficult to characterize specific geographical locations accurately. Contamination can occur within certain time intervals, and inadequate spatial and temporal resolution in sampling strategies may result in missed contamination episodes.

In contrast, living organisms, particularly bioindicators, integrate water quality over time and offer a more representative assessment than chemical analyses. Benthic macroinvertebrates are ideal indicators for evaluating marine quality and monitoring changes over time. The monitoring advantages of infauna communities include their relatively long and stable lifespans, the rate at which they respond to stress, and the presence of many species that accumulate pollutants over time [29,30]. Furthermore, benthic infauna in marine sediments plays a vital role in ecosystem processes, including nutrient cycling, pollutant metabolism, dispersion and burial, and secondary production [30,31].

The Jabal Ali Marine Sanctuary (JAMS) is the only marine protected area in Dubai (UAE). The sustainable use of its coastal waters requires a good knowledge of its state. However, research on the biological quality of the JAMS is very limited [23]; therefore,

the present study aims to provide the first benthic macroinvertebrate characterization of the soft bottom of the JAMS in summer and winter 2017, comparing summer and winter communities, and associate diversity indices with abiotic (sediment granulometry, trace metals, salinity temperature) variables as well as habitat classes.

2. Materials and Methods

2.1. Study Area

This study covered an area that is located along a 14 km coastal area. The habitat types studied include construction submerged with corals, dredged channels, dense coral framework, bivalves on sand, mixed seagrass assemblage, dense brown algal assemblage, sparse massive corals, and hardground with a sparse *Porites* and faviid community (Figure 1).

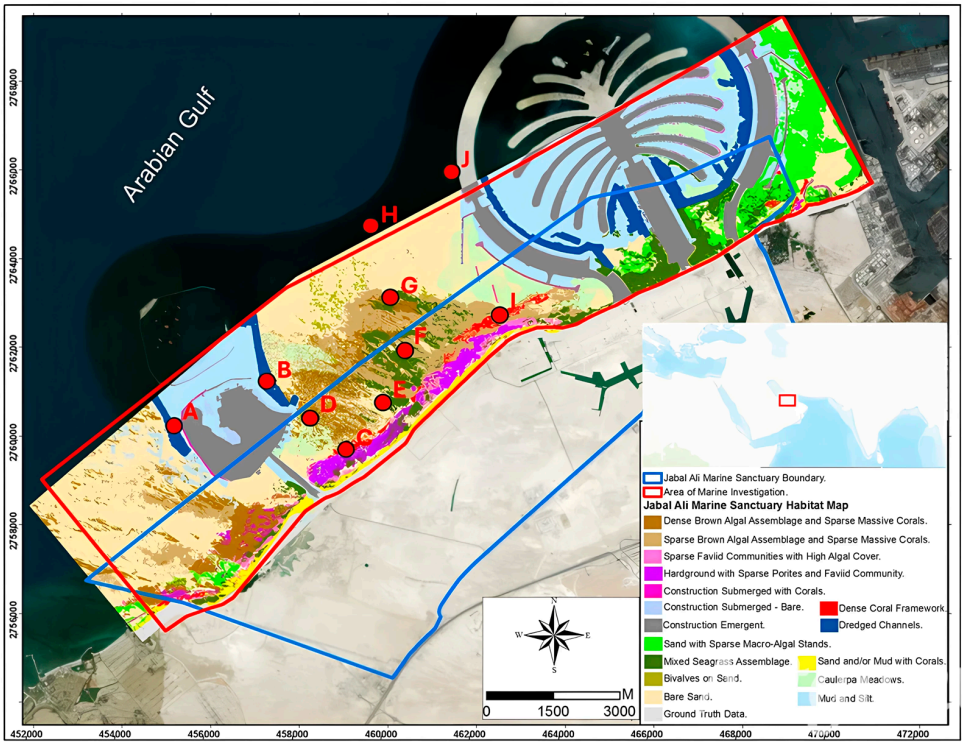


Figure 1. Location of sampling stations (red dot with corresponding letter ID) and habitat map [24].

2.2. Sample Analysis

Temperature and salinity measurements were taken at each sampling station during both seasons using a calibrated YSI ProDSS multiparameter water quality meter (YSI Inc., Yellow Springs, OH, USA). The instrument was calibrated before each sampling day using manufacturer-provided standards. At each station, measurements were taken approximately 30 cm above the sea floor to characterize the near-bottom water conditions experienced by the benthic fauna. Three readings were recorded at each station with a 5 min interval between readings to account for short-term fluctuations, and the average values were calculated. The accuracy of the instrument was ±0.2 °C for temperature and ±0.1 ppt for salinity measurements. Calibration verification was performed daily using a secondary standard to ensure measurement accuracy throughout the study period.

The sediment samples were collected from ten (10) sampling stations in the June 2017 (summer) and December 2017 (winter) fieldwork campaign using a stainless steel Van Veen Grab Sampler, with a 10 cm × 10 cm opening (0.01 m^2) and 10 cm depth. Immediately after collection, the samples were sieved through a 0.5 mm mesh screen and preserved in 10% buffered formalin with added rose Bengal dye. Sediment texture analysis was performed

using a standardized wet sieving method [32]. Approximately 100 g of each sample was processed through a series of sieves (2 mm, 1 mm, 0.25 mm, 0.125 mm, and 0.063 mm) to separate gravel (>2 mm), sand (0.063–2 mm), and silt/clay fractions (<0.063 mm). The weight of each fraction was determined using an analytical balance (±0.01 g precision), and the percentage composition was calculated relative to the total sample weight. At each station, three replicate samples were collected for macrofauna analysis, resulting in a total of 60 samples (10 stations × 3 replicates × 2 seasons), following the standard QA/QC procedures. For the determination of trace elements, the sample digestion procedure followed EPA Method 3050B (acid digestion for sediments, sludges, and soils) by using an Agilent 7700× Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (Thermo Fisher Scientific—Waltham, MA, USA) equipped with a collision/reaction cell to minimize polyatomic and isobaric interferences [33–35]. In the present study, the assessment of the collected sediment samples was performed according to the Dutch Target and Intervention Values (issued by the Ministry of Housing, Spatial Planning and the Environment) [36]. For mercury determination, a separate aliquot of each sample was analyzed using Cold Vapor Atomic Fluorescence Spectrometry (CV-AFS) [37]. The infauna analysis was performed by cleaning animals from the remaining sediment under a dissecting microscope. All animals were identified with the lowest reliable taxonomic rank using taxonomic monographs and textbooks [38,39]. Patterns of infauna community composition were compared among sites for numerically common taxa (those comprising at least 1% or 3% of the total fauna collected at that site), for higher taxonomic groupings. The comparison of higher taxonomic groups (polychaetes, amphipods, bivalves, oligochaetes) allows the observation of overall patterns of the community distribution in relation to the bottom sediment grain sizes and other features.

The number of macrobenthic animals present in the sample was calculated using the following formula:

$$\frac{Ind}{m^2} = \frac{Number\ of\ animals\ in\ the\ sample \times 10,000}{Area\ sampled\ (cm^2)}$$

All statistical analyses were performed using PRIMER v7 (Plymouth Routines in Multivariate Ecological Research) with the PERMANOVA+ add-on package. Prior to analysis, abundance data were transformed into fourth roots to reduce the influence of highly abundant species while maintaining the relative importance of rarer taxa. Bray–Curtis and SIMPROF similarity matrices were constructed to compare community composition between stations and seasons. SIMPER (similarity percentages) analysis was used to identify species contributing most to observed differences between seasons. The relationship between environmental variables and community structure was analyzed using distance-based linear models (DistLMs) with forward selection and AICc criterion. Spearman rank correlation was used to assess relationships between diversity indices and environmental parameters. Furthermore, the samples were subjected to standard QA/QC procedures to ensure that the sediment data used in this study were reliable and accurate and adequately represented the environmental conditions at the Jabal Ali Marine Sanctuary.

2.3. Univariate Indices

To assess and understand species diversity and its evenness within ecological communities, several univariate indices were employed, i.e., (1) Margalef index (d), (2) Shannon–Wiener diversity index (H′), and (3) Pielou evenness index (J). These indices provide quantitative measures that help in characterizing the richness and distribution of species in each area.

In addition to these univariate indices, more complex multivariate analyses were utilized to further differentiate and analyze ecological communities across various conditions, specifically, between summer and winter, and among different geographic locations.

The combination of Bray–Curtis similarity measures and SIMPROF testing provides a robust, objective approach for identifying natural groupings in complex ecological community data, making it particularly useful for marine benthic studies where understanding spatial patterns in community structure is essential.

These indices and analytical methods provide a comprehensive framework for ecological analysis, providing insights into species diversity and evenness and the dynamics of community composition across different environmental conditions.

3. Results

3.1. Environmental Parameters

Temperature and salinity measurements showed significant seasonal variations across the study area (Table 1). Summer temperatures ranged from 32.1 °C to 35.8 °C (mean: 34.2 ± 1.1 °C), while winter temperatures were substantially lower, ranging from 22.4 °C to 24.7 °C (mean: 23.5 ± 0.7 °C), a seasonal difference of approximately 10.7 °C.

Table 1. Temperature and salinity measurements at sampling stations during summer and winter seasons in Jabal Ali Marine Sanctuary.

Station	Summer		Winter	
	Temperature (°C)	**Salinity (ppt)**	**Temperature (°C)**	**Salinity (ppt)**
A	35.8 ± 0.3	43.5 ± 0.2	24.7 ± 0.2	42.6 ± 0.1
B	35.3 ± 0.4	42.8 ± 0.3	24.2 ± 0.3	42.1 ± 0.2
C	34.7 ± 0.2	42.4 ± 0.2	23.8 ± 0.2	41.7 ± 0.2
D	34.1 ± 0.3	41.9 ± 0.2	23.4 ± 0.1	41.2 ± 0.1
E	33.8 ± 0.4	41.5 ± 0.3	23.2 ± 0.2	40.9 ± 0.2
F	33.5 ± 0.3	41.2 ± 0.2	23.1 ± 0.3	40.5 ± 0.2
G	33.2 ± 0.2	40.8 ± 0.3	23.0 ± 0.2	40.3 ± 0.3
H	32.8 ± 0.5	40.5 ± 0.4	22.8 ± 0.4	40.1 ± 0.2
I	32.5 ± 0.3	40.3 ± 0.3	22.6 ± 0.3	40.0 ± 0.3
J	32.1 ± 0.4	40.2 ± 0.2	22.4 ± 0.2	39.8 ± 0.2
Mean	34.2 ± 1.1	41.8 ± 1.2	23.5 ± 0.7	41.1 ± 0.9

Salinity was consistently high throughout the study period, with summer values ranging from 40.2 to 43.5 ppt (mean: 41.8 ± 1.2 ppt) and winter values from 39.8 to 42.6 ppt (mean: 41.1 ± 0.9 ppt). The highest temperatures and salinities were recorded at stations A and B, which are located in shallower waters closer to shore with reduced water circulation.

A significant spatial gradient was observed in both parameters, with temperatures decreasing by approximately 3.7 °C and salinity decreasing by 3.3 ppt from the shoreline (station A) to the outer sampling locations (station J) during summer. This gradient was less pronounced during winter (2.3 °C and 2.8 ppt, respectively), indicating more homogeneous conditions throughout the study area during cooler months.

3.2. Sediment Characterization

The sediment texture analysis of ten sampling locations revealed distinctive patterns in the distribution of sand, gravel, and silt components. Based on these compositional characteristics, most locations can be classified as either “Sand” or “Gravelly Sand”, while locations B and J align more closely with a “Silty Sand” classification (Figure 2).

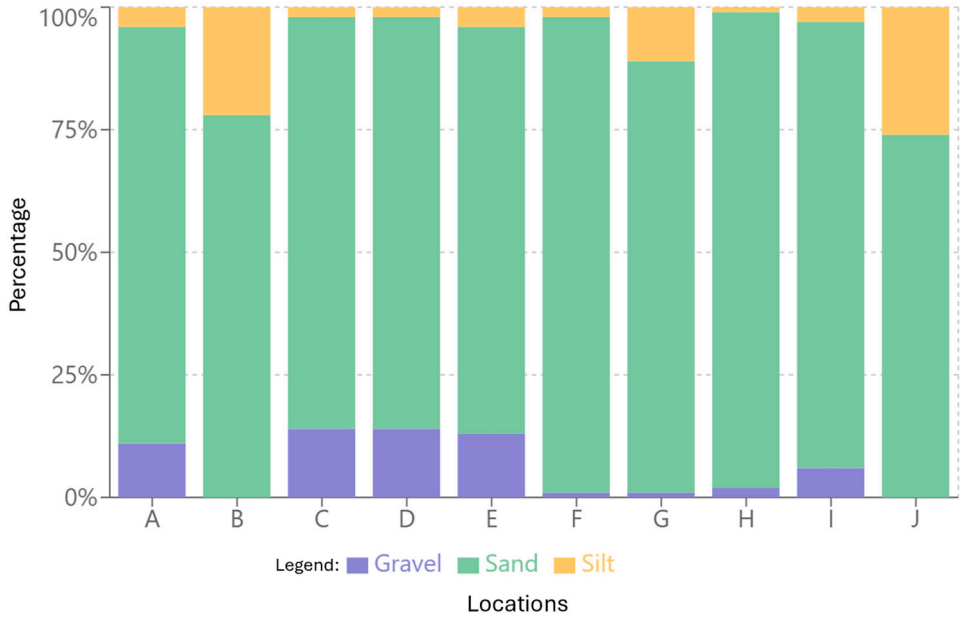


Figure 2. Sediment texture analysis.

The majority of sampling sites contained sand content exceeding 80%, where locations F and H exhibited the highest sand content at 97%, and location J showed the lowest at 74%. Gravel content displayed considerable variation throughout the sampling area, ranging from complete absence in locations B and J to a maximum of 14% in locations C and D. Silt, while generally present in smaller proportions, showed notable variation, with values ranging from as low as 1% in location H to as high as 26% in location J. None of the sampling locations exhibited dominant gravel or silt textures.

Furthermore, several locations demonstrated remarkable compositional similarities. Locations C and D displayed identical compositions, each containing 14% gravel, 84% sand, and 2% silt (Figure 2).

The data also suggest some spatial clustering of similar compositions, particularly evident in locations C, D, and E, which display similar distributional patterns.

3.3. Sediment Quality Assessment

There are no established ecological standards for sediment quality in Dubai, particularly in marine protected areas.

The intervention value is the concentration "when the functional properties of soil for humans, plants, and animals are seriously impaired or threatened". The levels have been derived from comprehensive risk-based eco-toxicological and human toxicological studies and are considered representative of current industry best practices. Furthermore, and for indication purposes only, the trace elements were compared with the QCC standards (ADS 19/2017—potentially endorsed by ESMA/EAD).

The levels of trace elements such as arsenic (average < 0.05 mg/Kg), boron (average 10.20 mg/kg), cadmium (average 0.62 mg/kg), chromium (average 33.92 mg/kg), copper (average 0.67 mg/kg), lead (average < 0.05 mg/kg), manganese (average 76.23 mg/kg), nickel (average 76.81 mg/kg), zinc (average 16.08 mg/kg), aluminum (average 1357.06 mg/kg), tin (average < 0.05 mg/kg), mercury (average 0.01 mg/kg), vanadium (average 10.16 mg/kg), selenium (average < 0.05 mg/kg), barium (average 21.54 mg/kg), cobalt (average < 0.05 mg/kg), and iron (average 3155.29 mg/kg) were generally low and in compliance with DCLS (Deleterious, Contaminated, or Leachable Substances) Standards (Table 1).

Elevated levels of nickel were observed at stations C, E, and G, where concentrations exceeded both Dutch Target Values and ADS 19/2017 standards. Nickel is commonly

utilized as an indicator of crude oil. Thus, the elevated levels can be attributed to pollution from oil tankers and other ships. Tugboats and barges frequently use the investigated area during breakwater rock transportation, from the nearby Waterfront Island 1.

The sediment analysis results further indicate that the concentration of trace elements (Cu, Cr, Pb, Ni, Cd, and Zn) is generally low (Table 2). When compared with the ADS 19/2017 standards for marine protected areas, exceedances in cadmium (at stations B, D, and I) and chromium (at stations C, E, G, and H) can also be highlighted. However, these standards are still under review by ESMA and EAD.

Table 2. Sediment quality assessment against Dutch Target and Intervention Values and Abu Dhabi's Quality and Conformity Council (QCC)'s Abu Dhabi Specifications (ADS) for marine protected areas.

Parameters	Results/Range	Dutch Target Values	Ads 19/2017 Adqcc—Marine Protected Area Use
Arsenic, As	<0.05	29	7
Boron, B	4.48–16.13	-	-
Cadmium, Cd	<0.05–0.62	<1	0.2
Chromium, Cr	4.73–95.51	100	11
Copper, Cu	0.66–0.68	36	20
Lead, Pb	<0.05	85	5
Manganese, Mn	26.75–164.90	-	-
Nickel, Ni	8.38–228.10	-	7
Zinc, Zn	6.06–25.46	140	70
Aluminum, Al	396.8–3142.0	-	-
Tin, Sn	<0.05	-	-
Mercury, Hg	0.01–0.02	0.3	-
Vanadium, V	3.34–22.61	42	-
Selenium, Si (mg/Kg)	<0.050	0.7	-
Barium (mg/Kg)	7.83–76.75	160	-
Cobalt (mg/Kg)	<0.05	9	-
Iron (mg/Kg)	718.5–7848	-	-
Total Organic Carbon	0.05–1.10	-	-

3.4. Species Richness and Diversity

3.4.1. Species Richness

This study, conducted across summer and winter sampling periods, revealed significant insights into the community structure, biodiversity patterns, and species distribution across various stations. The analysis covered seasonal variations and spatial heterogeneity, highlighting key ecological trends and conservation priorities.

During the summer period, the study area supported a total of 708 individuals, with station G emerging as a focal point of abundance, hosting 240 individuals (33.9% of total summer abundance) distributed among five species. *Magelona cincta* dominated this station, comprising 40% of the station's population with 96 individuals. Station A followed in importance, supporting 216 individuals (30.5%), with *Amphiura fasciata* as the dominant species. Furthermore, a distinctly structured assemblage was dominated by three key species, with *Rhinoclavis* sp. emerging as the most abundant taxon, comprising 33.22% of the total population. This gastropod was followed by *Bassina* sp. (14.88%) and *Perinereis* sp. (6.92%), collectively accounting for more than half of the total infaunal abundance.

The winter season demonstrated a dramatic increase in total abundance, supporting 3440 individuals, nearly five times the summer population. Station G maintained its significance but with substantially higher numbers, supporting 1600 individuals (46.5% of winter total) distributed among eight species, with *Perinereis* sp. as the dominant species. Stations H and J each supported 640 individuals (18.6%), but with different community structures.

At station H, *Nephtys* sp. accounted for 50% of the station's population (320 individuals), while at station J, the same species represented 100% (640 individuals).

Table 3 summarizes and highlights the species that were observed or not observed in both seasons.

Table 3. Species list and abundance (Ind/m^2) as observed in both seasons.

Species	Summer	Summer Abundance	Winter	Winter Abundance	Seasonality
Amphiura fasciata	✓	576	✓	440	Year-round presence
Amplescia sp.	✓	648	✓	540	Year-round presence
Ancilla sp.	✓	144	✓	240	Year-round presence
Apanthura sp.	✓	144	✓	120	Year-round presence
Apseudes sp.	✓	288	✓	160	Year-round presence
Aricidea sp.	✓	144	✓	320	Year-round presence
Armandia sp.	✓	72	-	-	Summer only
Bassina sp.	✓	3096	✓	3080	Year-round presence
Bittium sp.	✓	288	✓	240	Year-round presence
Bivalve spp.	✓	72	✓	80	Year-round presence
Brachidontes variabilis	✓	144	✓	80	Year-round presence
Bulla ampulla	✓	144	✓	240	Year-round presence
Capetiella capitella	✓	360	-	-	Summer only
Cardites sp.	✓	144	✓	240	Year-round presence
Certhidium cerithinum	✓	72	✓	120	Year-round presence
Circe sp.	✓	72	-	-	Summer only
Cronia konkanensis	✓	72	-	-	Summer only
Cylichna collyra	✓	72	-	-	Summer only
Cypris sp. larva	✓	72	-	-	Summer only
Echinodiscus auritus	✓	72	-	-	Summer only
Euclymene insecta	✓	216	✓	280	Year-round presence
Eunice sp.	✓	144	✓	160	Year-round presence
Glycinde sp.	✓	576	✓	640	Year-round presence
Maldane sp.	✓	288	✓	240	Year-round presence
Mitrella blanda	✓	288	✓	280	Year-round presence
Nephtys sp.	✓	1152	✓	1400	Year-round presence
Onuphis sp.	✓	432	✓	560	Year-round presence
Paphia sp.	✓	72	✓	120	Year-round presence
Perinereis sp.	✓	1440	✓	1880	Year-round presence
Phascolion sp.	✓	144	✓	160	Year-round presence
Polinices sp.	✓	144	✓	240	Year-round presence
Polychaete spp.	✓	72	✓	80	Year-round presence
Rapana sp.	✓	144	-	-	Summer only
Rhinoclavis sp.	✓	6912	✓	6600	Year-round presence
Sabella sp.	✓	648	✓	400	Year-round presence
Scabricola destangsii	✓	144	-	-	Summer only
Scoloplos sp.	✓	720	✓	1580	Year-round presence
Tellina vernalis	✓	72	✓	120	Year-round presence
Terebellides sp.	✓	144	✓	200	Year-round presence
Umbonium vestiarium	✓	216	✓	320	Year-round presence
Veneridae (gen) sp.	✓	144	✓	160	Year-round presence

3.4.2. Diversity

The comparative evaluation of diversity indices between summer and winter seasons exhibits several interesting patterns within the infaunal community structure across the sampling stations (Table 4). The Margalef index showed varying levels of seasonal change across stations. Station B exhibited the most notable increase from summer (0.122) to winter (0.860), a considerable difference in species richness between seasons. In contrast, station J maintained constant species richness (0.430) across both seasons, indicating stability regardless of seasonal changes within the number of species.

Table 4. Macrobenthic fauna diversity during the summer and winter seasons (June and December 2017) in the Jabal Ali Marine Sanctuary (JAMS), Dubai.

Station	Season	Margalef Index (d)	Shannon–Wiener (H′)	Pielou Evenness (J)
A	Summer	1.102	2.056	0.893
	Winter	1.109	1.719	0.747
B	Summer	0.122	0.362	0.523
	Winter	0.86	1.023	0.492
C	Summer	0.671	1.135	0.633
	Winter	0.519	0.759	0.472
D	Summer	1.229	2.066	0.897
	Winter	1.228	1.909	0.829
E	Summer	1.051	2.02	0.919
	Winter	1.206	2.025	0.879
F	Summer	1.375	2.221	0.926
	Winter	1.309	2.162	0.901
G	Summer	1.361	1.948	0.784
	Winter	1.223	1.94	0.809
H	Summer	0.993	1.836	0.883
	Winter	0.72	1.651	0.922
I	Summer	0.688	1.466	0.818
	Winter	0.699	1.581	0.882
J	Summer	0.43	1.245	0.898
	Winter	0.43	1.049	0.757

The Shannon–Wiener diversity index, however, displayed higher values during the summer compared to winter. Station A demonstrated the most obvious seasonal variation in diversity (summer: 2.056, winter: 1.719), in contrast to station E, which has stable diversity values (summer: 2.020, winter: 2.05). This stability possibly implies more consistent environmental conditions or resources that support a consistent community structure throughout the year.

Furthermore, the Pielou evenness index revealed mixed patterns of seasonal changes in species distribution. Some stations, like station B, maintained relatively consistent evenness values between seasons (summer: 0.523, winter: 0.492), while others showed more significant changes. Station A, for instance, exhibited a notable decrease in evenness from summer (0.893) to winter (0.747), suggesting that winter conditions possibly cause more dominant species to take precedence within the community structure.

The highest Margalef index (d = 1.375), Shannon–Wiener index (H′ = 2.221), and Pielou evenness (J = 0.926) values were found at sampling station F during summer. The lowest Margalef index (d = 0.122), Shannin–Wiener index (H′ = 0.362), and Pielou evenness (J = 0.523) values were found at sampling station B during summer.

3.5. Spatial Distribution

3.5.1. Abundance

In terms of species distribution, 41 species were documented (Table 3), 32 of which (78%) were present in both seasons, while 9 species (21.9%) were observed only in summer. The most dominant species during this period was *Rhinoclavis* sp., with a total count of 6912 individuals, indicating a widespread presence across the sampled area.

Spatial patterns revealed a distinct abundance of clusters. High abundance clusters were observed at stations A, B, and G, each recording over 3000 individuals (Figure 3). In contrast, stations I, J, and H exhibited low abundance, with fewer than 1100 individuals. The remaining stations showed moderate abundance levels, ranging from 1400 to 2000 individuals.

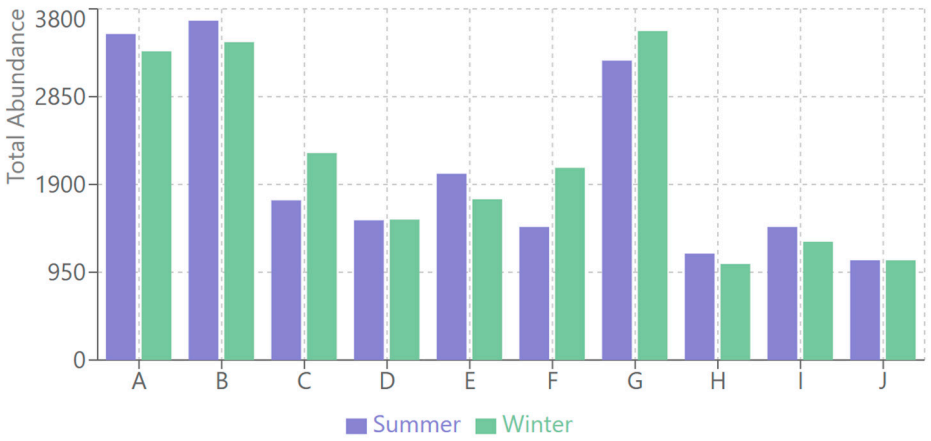


Figure 3. Total abundance comparison between summer and winter seasons (June and December 2017) in the different stations of Jabal Ali Marine Sanctuary (JAMS), Dubai.

The spatial distribution of individuals showed notable seasonal variations. During summer, the distribution was relatively even across active stations, with most stations supporting between 10 and 25% of the total population. However, winter showed a more skewed distribution, with station G harboring nearly half of all individuals, indicating a possible seasonal aggregation or favorable winter conditions at this location. This pattern was further emphasized by the frequency of occurrence, where dominant species in winter showed higher absolute abundance but were concentrated in fewer stations compared to the more evenly distributed summer populations.

The winter season demonstrated a marked increase in overall abundance, with 3440 individuals recorded across all stations. This represents a nearly six-fold increase in total abundance compared to summer. During winter, the distribution pattern showed even more pronounced spatial heterogeneity, with station G maintaining its significance by supporting 46.5% of the total winter population. Stations H and J also showed notable winter abundances, contributing 9.3% and 18.6% of the total winter population, respectively.

These different patterns in frequency and relative abundance suggest that while species richness provides one perspective on community structure, the incorporation of abundance data reveals additional layers of complexity in seasonal community dynamics. The marked increase in total abundance during winter, coupled with the spatial concentration of individuals in specific stations, points to the strong seasonal influences on population sizes and spatial distribution patterns in this infaunal community.

3.5.2. Cluster Analysis

The two-way interaction dendrogram reveals four statistically significant infauna community clusters, each associated with distinct environmental conditions (Figure 4). Cluster A (orange) encompasses stations A, C, and G, characterized by sandy sediments, shallow depths, and high wave exposure, supporting a balanced community of polychaetes (46.3%) and mollusks (45.0%). Cluster B (blue), comprising stations B, E, and I, occurs in silty sediments at moderate depths with moderate wave exposure and shows strong dominance by mollusks (77.0%) with fewer polychaetes (15.9%). Cluster C (green), including stations D and F, represents muddy habitats at moderate depths with low wave exposure, containing predominantly mollusks (65.9%) with moderate polychaete presence (20.9%). Cluster D (purple), consisting of stations H and J, represents the deepest sites with gravelly sediments and low wave exposure, supporting a community dominated by polychaetes (56.3%) with substantial mollusk representation (42.1%). The SIMPROF analysis confirms these clusters as statistically significant groupings ($p < 0.01$ for Clusters A, B, and D; $p < 0.05$ for Cluster C), demonstrating that sediment type serves as the primary

environmental driver of community structure, followed by water depth and wave exposure as secondary factors influencing species composition and abundance.

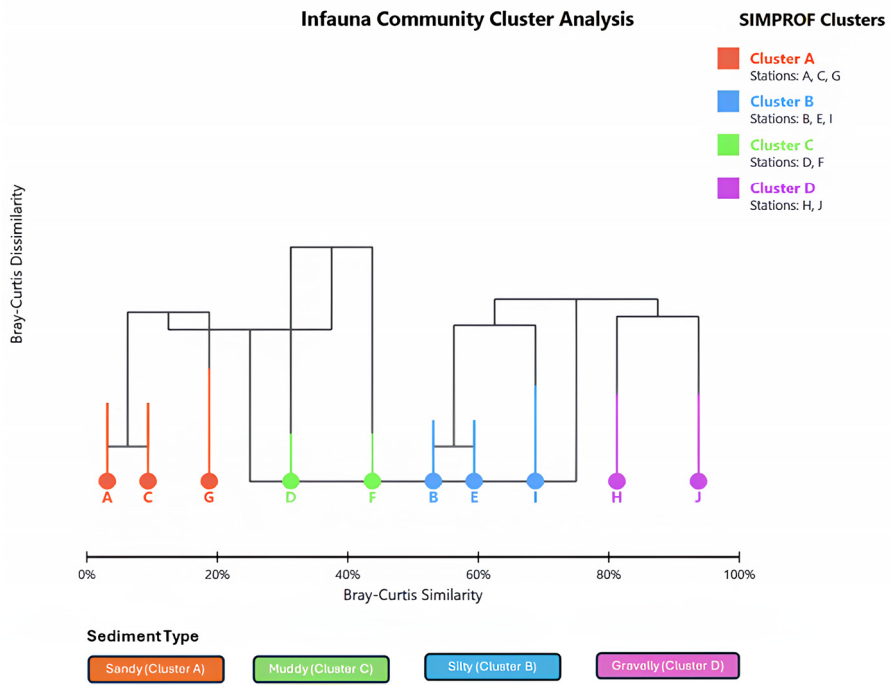


Figure 4. Two-way interaction dendrogram plot showing similarity in the infauna samples between the different stations with associated environmental conditions.

3.6. Relationship Between Environmental Parameters and Benthic Communities

Statistical analysis of the relationship between environmental parameters and benthic community structure revealed several significant correlations. Temperature showed a negative correlation with species richness ($r = -0.42$, $p < 0.05$) and Shannon–Wiener diversity ($r = -0.38$, $p < 0.05$), indicating that higher summer temperatures may stress certain benthic species and reduce overall diversity.

Sediment grain size analysis revealed clear taxon-specific habitat preferences, with polychaete abundance showing a strong positive correlation with higher silt content ($r = 0.67$, $p < 0.01$), confirming their ecological affinity for fine-grained substrates as deposit-feeders. In contrast, mollusks demonstrated the opposite pattern, with greater abundance in sandier sediments ($r = 0.54$, $p < 0.01$), reflecting the tendency of many bivalve and gastropod species to thrive in coarser substrate environments.

As evident among more sensitive organisms, the analysis revealed that elevated nickel levels in sediments were associated with reduced overall species diversity, as indicated by a significant negative correlation ($r = -0.48$, $p < 0.01$). This relationship was most pronounced at stations C, E, and G, where nickel levels exceeded reference standards.

The distance-based linear model (DistLM) analysis revealed that the combination of temperature, salinity, sediment composition (particularly silt percentage), and nickel concentration explained 62% of the variation in community structure across stations and seasons (pseudo-$F = 3.8$, $p = 0.001$). Temperature emerged as the most influential single factor, explaining 28% of the observed variation.

A Canonical Correspondence Analysis (CCA) was performed to visualize the relationships between species distribution and environmental variables. The first two CCA axes explained 43.7% of the species–environment relationship. The CCA biplot (Figure 5) showed that *Perinereis* sp. and *Nephtys* sp. were positively associated with silt content and negatively with temperature, explaining their increased abundance during winter.

Conversely, *Armandia* sp. and *Cylichna collyra*, which were found exclusively in summer, showed strong positive associations with higher temperatures and sandy substrates.

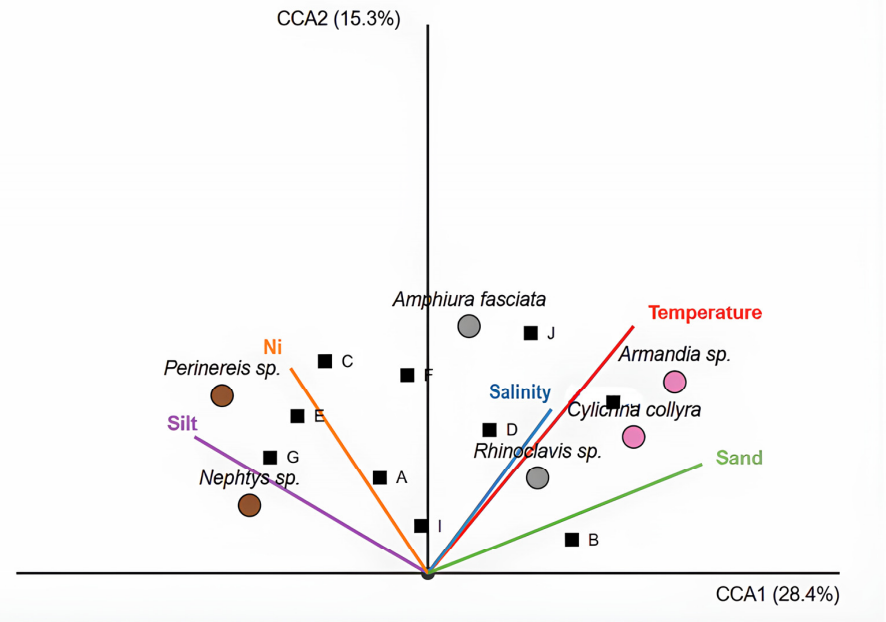


Figure 5. CCA biplot shows the relationship between benthic species and environmental variables across sampling stations in Jabal Ali Marine Sanctuary. Legend: ▬—environmental vectors; —dominant species; ■—stations.

4. Discussion

The frequency analysis of infaunal communities revealed distinctive patterns in abundance and distribution across both spatial and temporal scales, with notable variations in relative proportions between seasons, aligning with patterns observed in similar coastal ecosystems of the Arabian Gulf [40–43].

The integration of biological and environmental data provided valuable insights into the factors shaping benthic communities in the JAMS. There was a strong negative correlation between temperature and species diversity metrics ($r = -0.42$, $p < 0.05$) [44]. The extreme summer temperatures in the Arabian Gulf [45] (up to 35.8 °C in our study) likely exceed the thermal tolerance thresholds of several species, explaining the absence of certain taxa during summer sampling [46]. The relationship between temperature and biodiversity follows a clear spatial pattern, with higher diversity values at stations J, H, and I, which experienced lower summer temperatures (32.1–32.8 °C).

Salinity, while less variable seasonally than temperature, also influences community structure in the JAMS. The consistently hypersaline conditions (39.8–43.5 ppt) represent a physiological challenge for marine organisms, requiring specialized osmoregulatory adaptations. The significant correlation between salinity and community composition (revealed by the DistLM analysis) indicates that this parameter acts as an environmental filter, selecting halotolerant species. Stations with lower salinity values (J, I, and H) supported higher diversity, suggesting that even small reductions in salinity (2–3 ppt) can benefit certain taxa.

The interactive effects of temperature and salinity are particularly important in the context of the Arabian Gulf's extreme environment [47]. The combination of high temperature and high salinity creates a synergistically stressful condition that exceeds the physiological tolerance of many marine invertebrates [46]. This pattern aligns with known thermal stress responses in benthic communities of subtropical regions [48,49]. This is evident in the strong correlation between these parameters and community structure in

our DistLM analysis, where the combination of temperature and salinity explained 41% of the total variation in community composition.

The seasonal contrast in relative abundances illuminates several key aspects of community dynamics, supporting theories of temporal variation in marine ecosystems [50]. Winter assemblages showed higher absolute numbers and more skewed distributions, with station G's contribution increasing from 33.9% in summer to 46.5% in winter. This pattern of summer distribution aligns with findings from Kuwait Bay, where similar seasonal variations in benthic communities have been documented [51,52]. Species dominance patterns also shifted seasonally, with summer showing more varied species composition within stations (average dominance of most abundant species: 72.3%) compared to winter's tendency toward single-species dominance (average dominance of most abundant species: 89.7%). This pattern aligns with seasonal variability in infaunal community structures [53]. However, there was a sharp rise in overall abundance during the winter, with 3440 individuals, which is in keeping with seasonal fluctuations noted in comparable habitats along the Saudi Arabian coast [54]. The results from Qatar's coastal waters, where winter peaks in infaunal abundance have been regularly recorded, are consistent with this seasonal amplification [55], which is also in parallel with the community structures observed in the United Arab Emirates' coastal waters [56].

The seasonal variation in relative abundances is indicative of more general regional trends in the benthic communities of the Arabian Gulf [57]. Winter assemblages displayed more skewed distributions; for example, station G's contribution rose from 33.9% in the summer to 46.5% in the winter. The increase in both absolute numbers and relative concentrations during winter suggests season-specific factors that not only support larger populations but also influence their spatial distribution [58,59]. The consistent importance of certain stations across seasons, despite dramatic changes in their relative contributions, points to location-specific characteristics that maintain their significance under varying environmental conditions, supporting theories of habitat-specific community organization in the Gulf [60,61]. Studies conducted in Bahrain's coastal waters have shown comparable winter-dominated abundance patterns, which are consistent with this seasonal change [62]. In line with the temporal fluctuations observed in the Gulf coast waters of Iran, species dominance patterns also changed seasonally, with summer exhibiting a more diverse species composition (average dominance: 72.3%) as opposed to winter's propensity for single-species dominance (average dominance: 89.7%) [63]. This comprehensive analysis of proportional distributions provides crucial insights into the hierarchical structure of infaunal communities and their seasonal dynamics in the context of the Arabian Gulf's extreme environmental conditions, where communities must adapt to significant seasonal variations in temperature, salinity, and other environmental parameters, highlighting the complex interplay between spatial and temporal factors in shaping marine ecosystem organization [64–66].

Furthermore, these proportional patterns enhance our understanding of both spatial and temporal dynamics in infaunal communities, contributing to the broader understanding of animal–sediment relationships in the Arabian Gulf [67,68]. The frequency analysis of infaunal communities revealed distinctive patterns in abundance and distribution, which can be better understood through sediment chemistry and trace element concentrations typical of the Arabian Gulf region [69,70]. Trace elements are natural constituents of all environments and are found in seawater, marine organisms, and sediments [71]. It is essential to know the natural background levels of trace elements or at least their background concentration in the marine environment before attempting to assess trace metal pollution [72].

Regional studies from Oman's coastal waters [73] have shown comparable relationships between metal concentrations and benthic community composition, particularly

regarding seasonal variations. The measured metal concentrations align with baseline data established for the Arabian Gulf [74] and reflect the region's natural geochemical background levels. The influence of local activities appears similar to patterns observed in other Gulf ports [75], where benthic communities show resilience to moderate anthropogenic inputs while maintaining diverse population structures.

The summer period supported 708 individuals, with station G's dominance (33.9% of total abundance) reflecting patterns observed in similar Gulf habitats where metal concentrations influence benthic community structure [76–78]. The observed metal concentrations, particularly iron (average 3155.29 mg/kg) and aluminum (average 1357.06 mg/kg), align with baseline levels reported in Kuwait Bay sediments [79] and other Gulf locations [80].

The winter season's dramatic increase to 3440 individuals, with station G supporting 1600 individuals (46.5% of winter total population), corresponds with seasonal patterns observed in Qatar's coastal waters, where similar metal profiles support diverse benthic communities [81,82]. The elevated nickel levels (average 76.81 mg/kg), attributed to oil tanker and ship activities, fall within ranges documented in UAE coastal sediments [83] and appear consistent with levels that support healthy infaunal populations in similar Gulf environments [84].

The seasonal shifts in community composition mirror patterns observed in Saudi Arabian coastal waters [85], where metal concentrations similarly influence species distribution patterns. The measured levels of copper (0.67 mg/kg), chromium (33.92 mg/kg), and zinc (16.08 mg/kg) align with studies from Bahrain's coastal waters [86] that correlate these concentrations with benthic community structure. The dominance of certain polychaete species, particularly *Perinereis* sp. in winter, reflects similar findings from Iranian waters of the Gulf [87] regarding species-specific metal tolerance. Furthermore, the negative impact of elevated nickel concentrations on community diversity was most evident at stations C, E, and G, where sensitive taxa like amphipods showed reduced abundance [88,89]. However, certain polychaete species, particularly *Perinereis* sp., showed tolerance to these conditions, explaining their dominance at these stations. This differential sensitivity to trace elements has been documented as an important factor structuring benthic communities in polluted sites across the Gulf [77,90].

Moreover, the relationship between sediment grain size and faunal composition demonstrated clear habitat preferences among taxonomic groups. The strong association between silt content and polychaete abundance ($r = 0.67$, $p < 0.01$) mirrors a similar sediment–fauna relationship in Kuwait's marine waters [91]. This pattern reflects the feeding strategies of many polychaete species, which are deposit feeders that extract organic matter from fine sediments [92]. The preference of mollusks for sandy substrates ($r = 0.54$, $p < 0.01$) has been similarly documented in other Gulf studies [93,94] and relates to the burrowing and filter-feeding behaviors of many bivalve species. Sediment analysis results further indicate that the concentration of trace elements (Cu, Cr, Pb, Ni, Cd, and Zn) is generally low (Table 2) and comparable with unpolluted sediments of the Arabian Gulf marine environment [88] and Dubai coastal water [95].

In addition, the spatial distribution patterns correspond with metal–biota relationships documented in Kuwait's marine sediments [96], where similar concentrations of manganese (76.23 mg/kg) and vanadium (10.16 mg/kg) support diverse infaunal communities. The low concentrations of potentially toxic metals such as arsenic (<0.05 mg/kg), cadmium (0.62 mg/kg), and mercury (0.01 mg/kg) are comparable to values reported from unpolluted sites across the Gulf [40] and support similar community structures.

The multivariate analysis revealed that the combined effect of temperature, salinity, sediment composition (sand and silt), and nickel concentration explained 43.7% of the community variation, highlighting the multifactorial nature of environmental influences

on benthic assemblages. This finding supports the concept of multiple stressor effects on marine communities for Arabian Gulf ecosystems [50]. The remaining unexplained variation may be attributed to factors not measured in this study, such as hydrodynamics, food availability, and biotic interactions.

5. Conclusions

This study provides the first comprehensive characterization of benthic macrofauna in the Jabal Ali Marine Sanctuary (JAMS), Dubai's only marine protected area. Our findings reveal significant seasonal variations in community structure, with winter showing substantially higher abundance (3440 individuals) compared to summer (708 individuals), though species diversity was generally higher in summer. The spatial distribution of benthic communities showed distinct patterns related to environmental parameters, with temperature, sediment composition, and nickel concentration emerging as key drivers of community structure.

The benthic macrofauna exhibited clear seasonal differences in species composition, with 9 species present only during summer and 32 species persisting across both seasons. Polychaetes dominated the assemblage, particularly in silty substrates, while mollusks were more abundant in sandy areas. Station-specific patterns were evident, with stations E and F maintaining high diversity across seasons, while stations A, B, and G showed the highest abundance but lower evenness, indicating dominance by fewer species.

Our analysis of environmental parameters reveals that the JAMS is characterized by extremely high summer temperatures (up to 35.8 °C) and consistently high salinity (39.8–43.5 ppt), conditions that likely contribute to the observed seasonal shifts in benthic communities. Trace element concentrations were generally within acceptable limits, though elevated nickel levels at specific stations correlated with reduced diversity of sensitive taxa.

These findings establish an important baseline for future monitoring of this ecologically significant protected area. The strong correlations between environmental parameters and community composition highlight the value of benthic macrofauna as bioindicators of ecosystem health in this extreme environment. Long-term monitoring focusing on the identified key species and environmental factors will be essential for tracking ecosystem changes and informing effective management strategies for the conservation of the JAMS.

For future research, we recommend the following:

1. Expanding sampling to include additional seasons to better understand annual cycles;
2. Implementing continuous monitoring of key environmental parameters;
3. Conducting targeted studies on dominant species' physiological adaptations to extreme conditions;
4. Establishing permanent monitoring stations at the identified diversity hotspots (stations E and F);
5. Developing region-specific biotic indices calibrated to the extreme conditions of the Arabian Gulf.

This comprehensive baseline study contributes valuable knowledge for the sustainable management of Dubai's only marine protected area and provides insights applicable to similar extreme marine environments throughout the Arabian Gulf region.

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and M.M. (Muna Musabih); writing—review and editing, J.A., W.H., M.M. (Maria Muñoz), A.R., J.P.V., and M.M. (Muna Musabih); visualization, J.A., W.H., A.R., M.M. (Maria Muñoz), J.P.V., and M.M. (Muna Musabih); supervision, J.A.; project administration, J.A.; funding acquisition, J.A. All authors have read and agreed to the published version of the manuscript.

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