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Evaluation of Pollution Status and Risk Assessment Along the Al-Shuaibah Coastline, the Red Sea, Saudi Arabia

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ABSTRACT

This study aimed to assess the pollution status and conduct a risk assessment on the Shuaibah coast of the Red Sea, Saudi Arabia. The results indicated generally favorable water quality conditions characterized by acceptable pH levels for aquatic organisms and low turbidity values. However, slight reductions in dissolved oxygen (DO) levels and moderate organic pollution were observed. Metal concentrations in the water samples were generally low. The study encompassed an evaluation of the physicochemical parameters and metal concentrations in sediments. The analysis of the sediments indicated minimal pollution levels, characterized by low levels of organic matter and phosphorus. While. the metal concentrations in the sediments largely conformed to background levels, slightly increased concentrations of specific metals were identified. These findings suggest the presence of localized contamination sources, notably including silver (0.7mg/ L in site 1 and 0.3mg/ L in site 2). Additionally, this study compared contamination factors, contributions of different elements, degrees of contamination, modified degrees of contamination, enrichment factors, pollution index, modified pollution index, potential ecological risk index (PERI), and Geo-accumulation Index (Igeo) values in the study area. The results indicated varying contamination factors ranging from considerable contamination to very high contamination. Similarly, degrees of contamination varied between low and moderate levels. The PERI values indicated a low ecological risk associated with the presence of metals in both stations. The Igeo values suggested an unpolluted for the majority of investigated metals. Overall, this study provided valuable insights into the water quality and sediment characteristics of the study area, emphasizing the importance of continuous monitoring and effective management practices to ensure the preservation of aquatic ecosystems.

INTRODUCTION

The Red Sea, spanning 280 kilometers in width and 1,930 kilometers in length, covers an approximate surface area of 437,000 square kilometers. With a mean depth of

490 meters, the Red Sea supports a diverse range of marine life, including prominent coral reefs and a multitude of invertebrate species. Studies by **Hassan *et al.* (2002**) and **Fahmy *et al.* (2003)** have reported over a thousand species of marine organisms, with a particular focus on delicate and hard coral reefs. However, the quality of seawater in the Red Sea has become a significant concern due to the potential presence of contaminants and waste elements.

The Red Sea is known for its rich biodiversity and unique ecological features, making it a globally significant marine ecosystem. However, the increasing anthropogenic activities, such as industrial discharges, wastewater effluents, and shipping operations, pose a potential threat to the delicate balance of this ecosystem **(Soliman *et al.*, 2020; Hanafy *et al.*, 2021)**.

Introducing contaminants and waste elements into the marine ecosystem poses severe health risks and has observable impacts on the environment **(Younis *et al.*, 2023a)**. Increased levels of pollutants and waste elements, including trace metals, have been detected in sediments, organisms, and water, leading to reduced productivity and adverse effects on the marine ecosystem **(Younis, 2019; Elnaggar *et al.*, 2022; Younis *et al.*, 2023b)**. These environmental concerns have significant economic implications, particularly for the tourism and fisheries industries, as the degradation of environmental conditions affects their profitability **(El-Naggar, *et al.*, 2021; Younis *et al*, 2023c)**. Moreover, the bioaccumulation and toxic effects of metals further exacerbate the impact of human activities on marine ecosystem-induced anthropogenic activities, such as nitrogen emissions resulting from the expansion of agricultural practices, which contribute to the presence of nutrient contaminants, particularly nitrogen and phosphorus compounds, which are detrimental to human health **(Younis, 2020; Younis *et al.*, 2022; Younis *et al.*, 2023d)**. Eutrophication, characterized by excessive growth of algae and subsequent oxygen depletion, is a pervasive issue in the Red Sea. In their study, **Palaniappan *et al.* (2012)** highlighted the role of human and industrial activities in the production of nitrogen and phosphorus pollutants.

Understanding the pollution status in the Shuaibah area is essential for effective environmental management and implementing appropriate mitigation measures to prevent further degradation.

In light of these environmental challenges, the primary objectives of this research were to observe and evaluate the physical and chemical properties of the marine ecosystem in the Shuaibah coastal water area of Saudi Arabia along the Red Sea coast. The study focused on assessing trace element contamination and the eutrophication status in this region. By comprehensively understanding the pollution levels and environmental conditions, this study aimed to contribute valuable insights to the scientific knowledge base and guide future management and conservation efforts in Saudi Arabia's Red Sea coastal area. The findings of this study would provide valuable insights for policymakers, environmental agencies, and stakeholders to implement sound management practices and ensure the long-term protection and sustainability of this vital marine ecosystem.

MATERIALS AND METHODS

1. Study area

The Shuaibah area is located in the western part of Saudi Arabia along the Red Sea coastline, with a latitude ranging from approximately 21° 30' N to 22° 30' N. At the same time, the longitude spans from around 38° 30' E to 39° 30' E. The Shuaibah area, situated along the coastline of the Red Sea in Saudi Arabia, has experienced substantial industrial and urban development over the past decades. This growth has brought numerous economic benefits, however it has also raised concerns about potential pollution and its adverse effects on the marine environment. The need to evaluate and monitor the pollution status in this area is crucial to ensure the protection of marine ecosystems and the sustainability of the local community and industries.

To assess the pollution status in the Shuaibah area, a comprehensive scientific analysis is necessary. This analysis should encompass various water quality parameters, including physical and chemical indicators to provide the pollution levels and their potential impacts. Parameters such as pH, turbidity, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrients, heavy metals, and organic pollutants were examined to evaluate the overall water quality and identify potential pollution sources.

In addition to water quality analysis, the assessment considered the impact of pollution on the local ecosystem. The ecological consequences of pollution can have far-reaching effects on the Red Sea ecosystem's biodiversity, resilience, and productivity. Therefore, a comprehensive evaluation of the pollution status would help identify sensitive areas and prioritize conservation efforts.

2 Sampling and chemical analysis

Four locations were selected for sampling in Shuaibah, a coastal water of the Saudi Red Sea, and duplicate samples were taken from each station for each sampling site (Table 1 & Fig. 1). The collected samples were stored in 0.5-liter polyethylene containers, preserved in an icebox, and subjected to *in vitro* analysis.

In each location, various analytical instruments, such as CTD (YSI-6000), were used to measure salinity, pH, and dissolved oxygen (DO) content.

Nutrient salt samples were separated using GF/C filters and stored in a cryogenic state for later analysis using calorimetric methods **(Grasshoff, 1976)**. Nitrate (NO_3/N)

was analyzed using a reduction column and color reagent (sulphanilamide and N-(1-naphthyl)-ethylene diamine dihydrochloride), as specified by the guidelines of **APHA (1998)**.

Ammonia in water was determined in the field without filtration using Valderrama's indophenol blue colourimetry method **Valderrama (1981)**. Shimadzu UV-150-02 double beam UV/V is a spectrophotometer used to analyze nutrient compounds.

Heavy metals in seawater were analyzed, according to the method of **Martin (1972)**, while trace metals were extracted and subsequently analyzed. A 750ml water sample was filtered through a 0.45μm membrane filter. Diluted HCl (pH 4-5) was used to adjust the pH of the water sample, according to the method of **Martin (1972)** and **Boniforti *et al.* (1984)**. APDC-MIBK was used as a solvent extraction agent to chelate trace metals. The complexation reaction between methyl isobutyl ketone (MIBK) and the extracted metals was initiated using ammonium pyrrolidine thiocarbamate (APDC). The contamination of the final extracts with heavy metals (Ca, Na, Al, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Ag, Zn, V, and Hg) was identified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Table 1. Location of sampling stations

Water sample (1)	Opposite to/ near intake channel of Shuaibah independent water and power plant (phase 3)
Water sample (2)	Opposite to/ near outfall pipe of Shuaibah independent water plant (phase 4)
Water sample (3)	Opposite to/ near discharge channel of Shuaibah independent water and power plant (phase 3)
Water sample (4)	Outfall sample from discharge channel of Shuaibah independent water and power plant (phase 3)

Fig. 1. Geographical distribution of collected samples

Using a Peterson grab sampler, two surface sediment samples were simultaneously taken with water samples within the depth range of 0 to 20cm. The collected samples were immediately transferred into clean and airtight polythene bags, ensuring their preservation. Subsequently, the samples were transported to the laboratory and stored at a temperature of -20°C until further analysis. Prior to utilization, the sampler underwent a thorough rinsing with distilled water to prevent any unnecessary contamination. The total organic carbon of sediments was determined using the wet oxidation method, following the methodology established by **Loring and Rantala (1992)**. Wet digestion was performed to determine the total metal levels in the sediment.

The analysis of metal concentrations was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), as described by **Oregioni and Aston (1984)**. The examination of total phosphorus (TP) involved subjecting the samples to a temperature of 550°C for 2.5 hours, followed by a 1M HCl extraction for 16 hours, following the procedure outlined by **Aspila *et al*. (1976)**.

3 Statistical analysis

Multiple methodologies were employed to assess and analyze pollution, which included the utilization of enrichment factor (EF), contamination factor (Cf), pollution index (PI), potential ecological risk index (PERI), degree of contamination (C_d), modified degree of contamination (mCd), geo-accumulation index (Igeo), and modified pollution index (MPI) for evaluation purposes.

RESULTS AND DISCUSSION

1. Sea water

1.1 Water quality parameters

Table (2) shows the water quality parameters in the area of study. By analyzing various parameters, including pH, turbidity, TDS, DO, BOD, COD, TOC, oil and grease, ammonia, SO_4, Cl, $CaCO_3$, Na, sulfide, and total Haydrocarbns, we can gain insights into the overall water quality and potential environmental impacts. The measured pH values ranged from 6.7 to 8.2, indicating slightly acidic to slightly alkaline conditions in the water samples. These pH values fall within an acceptable range for most aquatic organisms, suggesting that the water is generally suitable for supporting aquatic life. However, the sample with a pH of 6.7 may be due to the discharge from the Shuaibah Independent Water and Power Project (SIWPP) cooling system. Turbidity levels were consistently low across all samples, with a recorded value of 1NTU. This indicates that the water in the study area is relatively clear and free from suspended particles. Low turbidity values favor water quality, suggesting a reduced presence of particulate matter that can negatively impact aquatic ecosystems. The TDS concentrations ranged from

38,600 to 48,400mg/ L, indicating a high presence of dissolved salts in the water. These elevated TDS levels can be attributed to the Red Sea's geographical location, known for its high salinity. Dissolved oxygen (DO) values ranged from 6.67 to 7.58mg/ L, indicating an adequate oxygen level to support aquatic life. However, the sample with a DO value of 6.67mg/ L suggests a potential decrease in oxygen levels, and this may be due to the pollution from human activities, such as industrial discharges in the study area. Minor variations in dissolved oxygen (DO) content were observed. The transfer of oxygen (O_2) from the atmosphere to the surface water is accountable for the elevated DO levels in the surface water.

Table 2. Hydrographic parameters in the coastal surface water of Shuaibah, Saudi Arabia, the Red Sea during 2022

Parameter	Unit	Sample 1	Sample 2	Sample 3	Sample 4
pH	-	8.02	8.2	6.7	8
Turbidity	NTU	< 1	< 1	< 1	< 1
TDS	mg/ L	38600	36400	40800	46000
DO	mg/ L	6.84	6.67	6.82	7.58
BOD	mg/ L	5	8	4	8
COD	mg/ L	16	25	12	38
TOC	mg/ L	5	5	5	12
Oil and grease	mg/ L	< 1	< 1	< 1	< 1
Ammonia	mg/ L	0.1	0.06	0.03	0.11
SO_4	mg/ L	3400	2600	3000	8900
Cl	mg/ L	15000	13500	15800	35000
$CaCO_3$	mg/ L	3000	4700	6100	11500
Na	mg/ L	9100	8870	9580	23100
Sulfide	mg/ L	0.02	0.01	0.01	0.01
Total HC	mg/ L	0.02	0.02	0.02	0.02

The photosynthetic activity of algae facilitates this **process (Abu-Zied *et al.*, 2013)**. Conversely, decreased DO concentrations in surface water may be attributed to the respiration of marine organisms, as well as biochemical reactions and organic matter decomposition. BOD values ranged from 4 to 8mg/ L, suggesting a moderate level of organic pollution in the water samples. COD values ranged from 12 to 38mg/ L, indicating the presence of organic and potentially some inorganic pollutants in the water samples. TOC values ranged from 5 to 12mg/ L, indicating the presence of organic matter in the water samples. All samples' measured concentrations of oil and grease were recorded as 1, suggesting low hydrocarbon contamination levels. Ammonia concentrations ranged from 0.03 to 0.11mg/ L, indicating low ammonia levels in the water samples. Ammonia is a common pollutant associated with wastewater discharges and can harm aquatic organisms. The low concentrations observed in the samples suggest a minimal impact from ammonia pollution, which is favorable for the local marine environment. Sulfate (SO_4) concentrations ranged from 2,600 to 8,900mg/ L. Chloride (Cl) concentrations ranged from 13,500 to 35,000mg/ L, indicating a high presence of chloride ions in the water due to the discharge with high levels of desalination plant of the study area. Calcium carbonate ($CaCO_3$) concentrations ranged from 3,000 to 11,500mg/ L, indicating the presence of calcium carbonate in the water samples. Sodium (Na) concentrations ranged from 8,870 to 23,100mg/ L, indicating a significant presence of sodium ions in the water samples. This study's findings agree with the results obtained by **Al-Mur (2020)**.

1.2 Distribution of trace metals

Table (3) presents the distribution of metal concentrations in the surface water of the study area, with samples labelled as Sample 1, Sample 2, Sample 3, and Sample 4. The concentrations of various metals, including Al, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Ni, Ag, and Zn, were analyzed. Comparing the results with previous work, it is evident that the metal concentrations in the surface water of the study area remain relatively low. Metal concentrations across the samples were consistently within the < 0.001 to 0.08 range, indicating low levels of metal pollution in the surface water.

Some notable observations can be made from the comparison. The metal concentrations of Al, As, Ba, Cr, Co, Cu, Pb, Ag, and Zn remained consistently low across all the samples, suggesting minimal contamination of these metals in the surface water. These findings are consistent with previous studies, indicating a stable and unpolluted state of the water with respect to these metals **(Hanna & Muir, 1990)**.

Table 3. Metal concentration (mg/ L) distribution in the surface water of the study area

Parameter	Sample 1	Sample 2	Sample 3	Sample 4
Al	< 0.001	< 0.001	< 0.001	< 0.001
As	< 0.001	< 0.001	< 0.001	< 0.001
Ba	< 0.001	< 0.001	< 0.001	< 0.001
Cd	< 0.001	0.003	< 0.001	< 0.001
Cr	< 0.001	< 0.001	< 0.001	< 0.001
Co	< 0.001	< 0.001	< 0.001	< 0.001
Cu	< 0.001	< 0.001	< 0.001	< 0.001
Fe	0.08	< 0.001	< 0.001	< 0.001
Pb	< 0.001	< 0.001	< 0.001	< 0.001
Mn	0.008	< 0.001	< 0.001	0.006
Hg	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Ni	0.06	0.05	< 0.001	0.003
Ag	< 0.001	< 0.001	< 0.001	< 0.001
Zn	< 0.001	< 0.001	< 0.001	< 0.001

However, slight variations were observed in the concentrations of Cd, Mn, and Ni across the samples. Sample 2 exhibited slightly higher concentrations of Cd (0.003mg/ L) compared to the other samples. Sample 1 showed a slightly elevated concentration of Mn (0.008mg/ L), Ni (0.06mg/ L) and Fe (0.08mg/ L). These variations could be attributed to localized sources of contamination or natural fluctuations in metal concentrations.

When compared to the findings of the previous study conducted by **Martin and Whitfield (1983)**, the concentrations of dissolved iron and manganese in the Red Sea within the study region were generally lower. Specifically, the iron and manganese levels were measured at 50 and 20mg/ L, respectively, which were below the minimum acceptable concentrations outlined by the water quality standard **(WQC, 1972)** for safe water quality. Additionally, the concentrations of dissolved nickel were also found to be below the lower threshold defined by the water quality standards for nickel **(WQC, 1972),** which is set at 7mg/ L.

It is important to note that the metal concentrations observed in this study should be considered in the context of regulatory guidelines and the specific ecological sensitivity of the study area. The low metal concentrations indicate a relatively clean environment, which is favorable for maintaining aquatic ecosystems.

2. Sediment

2.1 Physicochemical parameters

This study investigated the distribution of metal concentrations in the surface sediments of the Shuaibah coast in the Red Sea, Saudi Arabia. The results revealed various characteristics of the sediments in the area (Table 4). The total organic carbon (TOC) values ranged from 6 to 7%, indicating the presence of organic matter resulting from biological decomposition processes in the study area. However, the proportion of organic matter remained minimal, suggesting negligible pollution levels.

The total phosphorus (P) concentrations ranged from 0.08 to 0.88%, which can be attributed to the involvement of organisms in the phosphorus cycle in the marine environment, where phosphorus plays a crucial role. The study also found nitrate (NO_3) concentrations ranging from 0.5 to 2.7mg/ L, sulfate (SO_4) concentrations ranging from 139 to 147mg/ L, chloride (Cl) concentrations ranging from 3000 to 3088mg/ L, and sulfide concentrations ranging from 0.01 to 0.02mg/ L, indicating the presence of sulfide in the sediments.

These observations can be explained by the deposition processes of total suspended matter in the sediments and the decomposition processes occurring at the seafloor. Nevertheless, despite these natural processes, the analysis of the physicochemical properties of the sediments did not reveal any significant pollution levels within the study area.

Table 4. Physicochemical parameters in the coastal surface sediments of Shuaibah, Saudi Arabia, the Red Sea during 2022

Parameter	Unit	Sample 1	Sample 2
TOC	%	6	7
P (total)	mg/ L	0.1	0.01
NO_3	mg/ L	0.5	2.7
SO_4	mg/ L	147	139
Cl	mg/ L	3088	3000
Sulfide	mg/ L	0.01	0.02

2.2 Assessment of trace metals in sediments

In this study, we conducted an analysis of metal concentrations in the surface sediments of the Shuaibah coast in the Red Sea, Saudi Arabia. Our results indicated that the concentrations of several metals, including Ca, Na, Al, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Ag, Zn, V and Hg, were within the range of background levels previously reported for Red Sea sediments. However, we observed slightly higher concentrations of certain metals, such as V, compared to the background levels.

The concentrations of Ca and Na in the sediments were consistent with the Red Sea's high salinity. Fig. (2) shows the concentration of other elements in two different stations. The elements are V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Ag, Al, Ba, Cd, Hg and Pb.

The concentration of elements in station 1 is generally higher than in station 2. This suggests that station 1 is more polluted or contaminated by these elements than station 2. The possible sources of these elements could be industrial activities. The higher concentration of elements in station 1 could negatively impact the water quality, aquatic life, and human health. The elements with the highest concentration in station 2 are Al, Cr, Fe, Mn, Ni and Zn, while those with the highest concentration in station 1 are Na, As, Ba, Cd, Cu, Pb, and Ag. Notably, both V. V and Cd are both toxic metals that can cause serious health problems if ingested or inhaled. V is mainly used as an alloying agent in steel and other metals, while Cd is used in alloys, batteries, metal coatings, solar cells, plastic stabilizers and pigments. The high concentration of V and Cd in station 1 could indicate the presence of metal industries near the station. Fe and Al are abundant elements in the earth's crust and are widely used in industry. The high concentration of Fe and Al in station 2 could indicate the influence of soil erosion or sedimentation from the surrounding land.

The elements with the lowest concentration in both stations are Co and Hg. These elements are relatively rare and have limited applications in various fields. Hg is used in thermometers, batteries, and dental fillings. Co is primarily used in lithium-ion batteries and in the manufacture of magnetic and wear-resistant batteries. The low concentration of these elements in both stations could indicate that they are not significant sources of pollution or contamination in the area.

To provide further context, we compared our results with a study conducted by **El-Sorogy *et al.* (2021)**, which analyzed metal concentrations in sediments along the Red Sea coast of Saudi Arabia. Their study found higher concentrations of Fe, Pb, Ni, As, Zn, Cu, Cr, Co, Al, Sb, and Cd compared to the reported background levels for the Red Sea sediments. Additionally, **Kahal *et al.* (2018)** reported that metals including Al, Fe, Cr, Cu, Zn, Ni, Co, Pb, Hg, and Cd in coastal surface sediments from the Red Sea in northwest Saudi Arabia originated from anthropogenic sources.

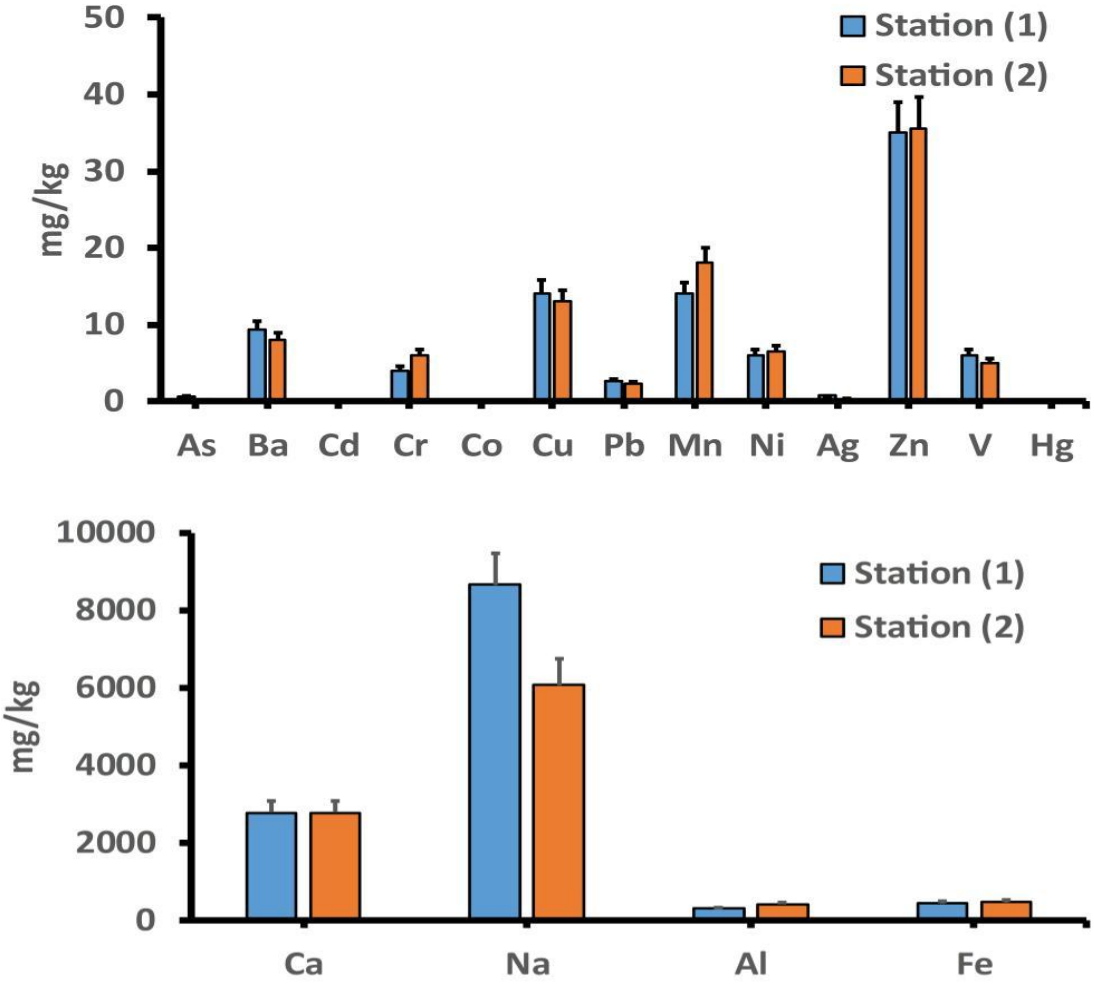

Fig. 2. Metal concentrations (mg/ kg, dry weight, ± SD) in the coastal surface sediments of Shuaibah, Saudi Arabia, the Red Sea during 2022

3. Evaluation of sediment pollution

3.1 Contamination factor (CF)

The contamination factor (CF) index, as described by **Hakanson (1980),** is employed to assess the level of contamination by a specific metal. According to **Loska *et al.* (1997)**, individual CF values are useful in evaluating pollution trends over time and determining the pollution status of specific compounds. It is calculated using the following ratio:

$$C_f = \frac{C_i}{C_b}$$

Where, Cb represents the concentration of the same metal at a background or reference site; Ci represents the concentration of the metal of interest at a particular site, and CF represents the contamination factor. In this study, the background levels of sedimentary metals were determined by considering the elemental concentrations found in average shale background concentrations of sediments worldwide **(Turekian & Wedepohl, 1961)**.

In the study of **Hakanson (1980)**, he categorized the contamination factor values (CF) into four groups: $Cf < 1$ low contamination factor, $1 \leq Cf < 3$ moderate contamination factors, $3 \leq Cf < 6$ considerable contamination factors, and $Cf \geq 6$ very high contamination factor.

The computed CF values are presented in Fig. (3). Fig. (3) shows that station 1 has a higher contamination factor than station 2. The contamination factor for station 1 is in the range of "very high contamination", while station 2 is in the range of "considerable contamination". This suggests that station 1 is more polluted than station 2.

In addition, Fig. (3) shows the contribution of different elements to the contamination factor. The elements are Ca, Al, Na, Fe, Mn, Cu, Zn, Pb, Ni, Cr, V, As, Ba, Ag and Cd. Additionally, some interesting patterns and differences are recorded between the two stations.

The elements with the highest contribution to the contamination factor in both stations are Pb, Zn, Cu, Cd, and Ag. These elements are known to be toxic and harmful to the environment and human health. The high contribution of these elements to the contamination factor in both stations could indicate the presence of industrial activities, urbanization, or waste disposal sites near the stations.

The elements with the lowest contribution to the contamination factor in both stations are Al, Fe, and Mn. These elements are relatively abundant and benign in the natural environment. Al is mainly found in clay, bauxite, and feldspar. Fe is mainly found in hematite, magnetite, and pyrite. Mn is mainly found in pyrolusite, rhodochrosite, and braunite. The low contribution of these elements to the contamination factor in both stations could indicate that they are not significant sources of pollution or contamination in the area.

The most varied elements contributing to the contamination factor between the two stations are Ag, Cd, Cu, and Pb. These elements contribute more to the contamination factor in station 1 than in station 2. These elements are also toxic and harmful to the environment and human health. The higher contribution of these elements to the contamination factor is found in station 1 than in station 2; this could indicate the presence of specific sources of pollution or contamination near station 1.

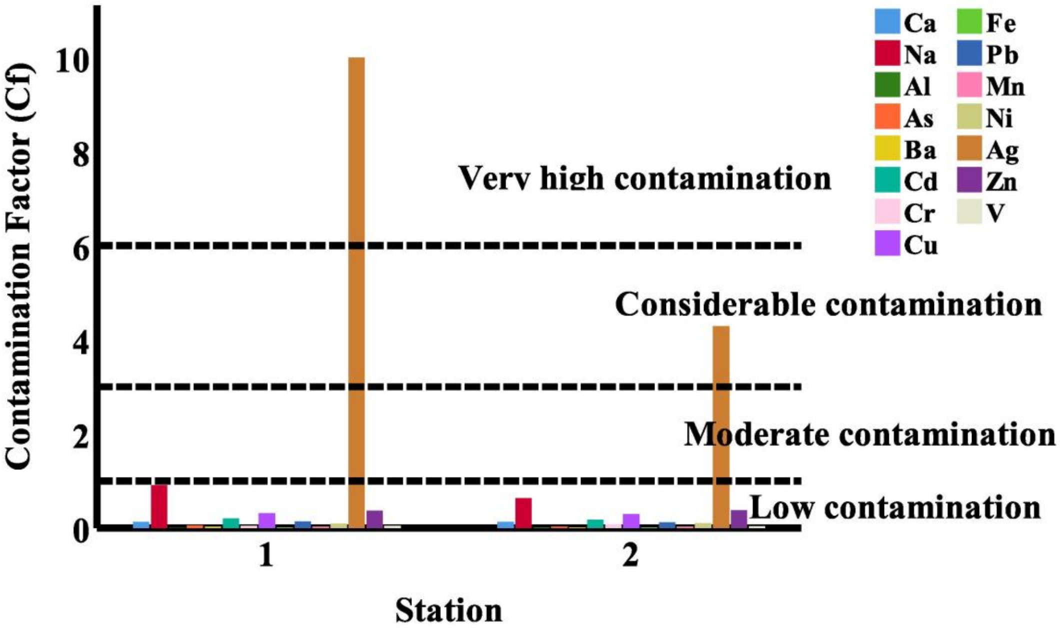

Fig. 3. Contamination factor of the coastal surface sediments in the area of study

Degree of contamination (C_d) is defined as the sum of all contamination factors for a given basin, as described by **Hakanson (1980)**, as follows:

$$C_d = \sum_{i=1}^{n} C_f^i$$

The degree of contamination defines the quality of the environment in the following way: Cd< 8 low degree of contamination; 8≤ Cd< 16 moderate degree of contamination; 16≤ Cd< 32 considerable degree of contamination, and Cd< 32 very high degree of contamination. The value of contamination degree may be utilized in characterizing the role of a given element in the global contamination of the reservoir by determining the proportion of a given element in the contamination, according to **Hakanson (1980)**.

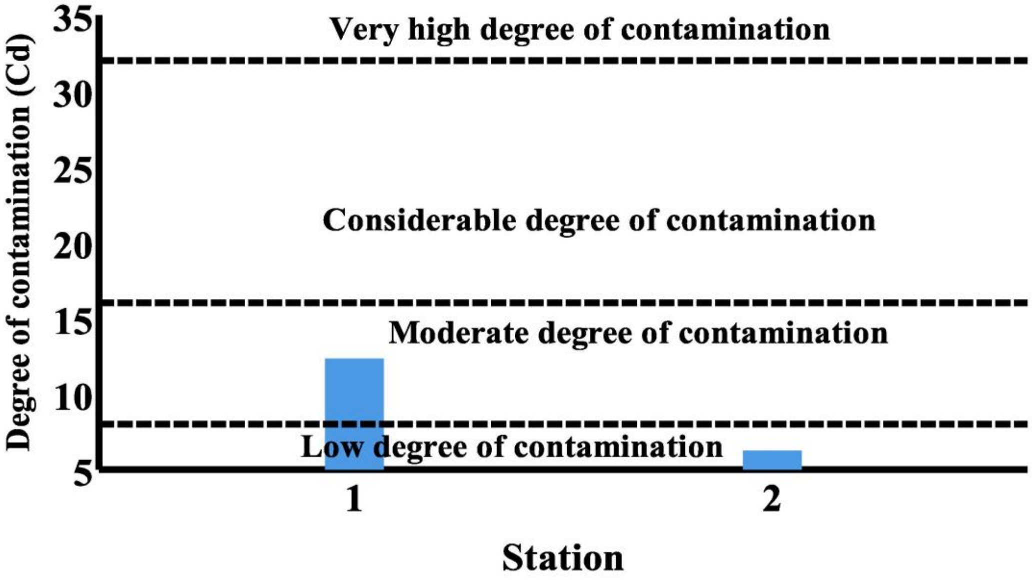

Fig. 4. Degree of contamination (C_d) of metals of the coastal surface sediments in the area of study

Fig. (4) shows that station 2 has a low degree of contamination, while station 1 has a moderate degree of contamination. This suggests that there is a difference in the level of contamination between the two stations. The metals with the highest contribution to the degree of contamination in both stations are Ag. Silver is capable of causing toxic and harmful to the environment and human health.

3.2 Modified degree of contamination (mC_d)

The Hakanson model, referred to as the modified degree of contamination, was further developed and improved by **Abrahim and Parker (2008)**. This index involves dividing the total number of pollutants by the sum of the contamination factors. To assess the degree of contamination, seven classes were established based on the mean values of the modified degree of contamination (Table 5). The updated equation for this index is as follows:

$$mC_d = \frac{\sum_{i=1}^{n} C_f}{n}$$

Table 5. Classification and description of the modified degree of contamination (mC_d)

Unpolluted	$mC_d < 1.5$
Slightly polluted	$1.5 < mC_d < 2$
Moderately polluted	$2 \leq mC_d < 4$
Moderately-heavily polluted	$4 \leq mC_d < 8$
Severely polluted	$8 \leq mC_d < 16$
Heavily polluted	$16 \leq mC_d < 32$
Extremely polluted	$mC_d > 32$

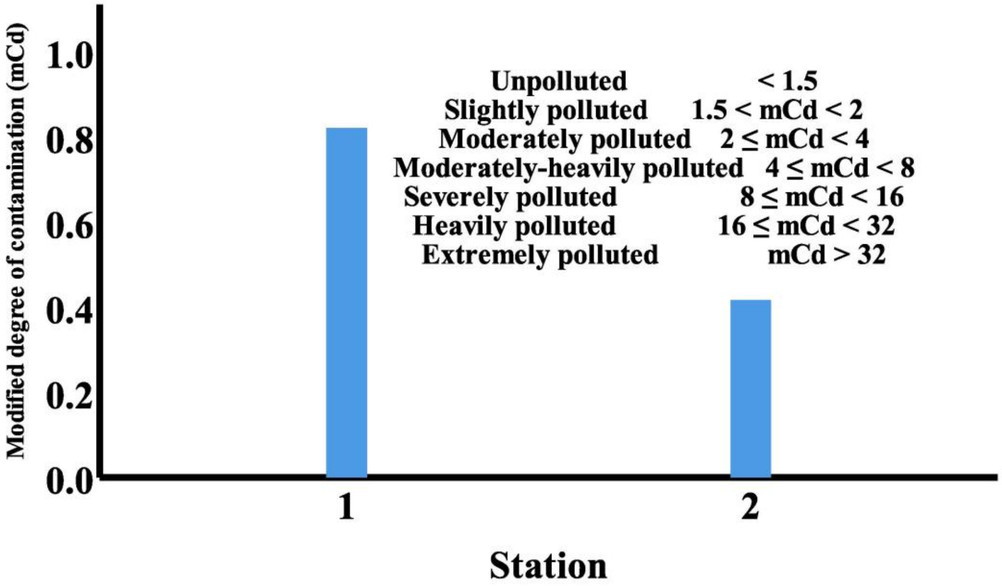

Fig. 5. Degree of contamination of metals in the coastal surface sediments in the study area

Fig. (5) shows that stations 1 and 2 have a low modified degree of contamination**.** Moreover, it shows that stations 1 and 2 fall into the unpolluted level**.**

3.3 Enrichment factor (EF)

The Enrichment Factor (EF) was determined using the equation implemented by **Muller (1981)**, as follows:

$$EF = \frac{\left(C_{sample} / Fe_{sample} \right)}{\left(C_{reference} / Fe_{reference} \right)}$$

Where, C_{sample} represents the concentration of the element in the sediment sample; Fe_{sample} represents the concentration of Fe in the sample, $C_{reference}$ denotes the concentration of the tested element in the reference environment, , as described by **Turekian and Wedepohl (1961)**, and $Fe_{reference}$ represents the concentration of Fe in the reference environment

For this study, the background values were obtained from **Turekian and Wedepohl (1961)**, and geochemical normalization was performed using Fe as the reference element. The values in mg/ kg were 47,200 for Fe, 80,000 for Al, 22,100 for Ca, 9600 for Na, 0.3 for Cd, 850 for Ba, 13 for As, 90 for Cr, 19 for Co, 68 for Ni, 0.07 for Ag, 95 for Zn, 130 for V, 45 for Cu, 850 for Mn, and 20 for Pb.

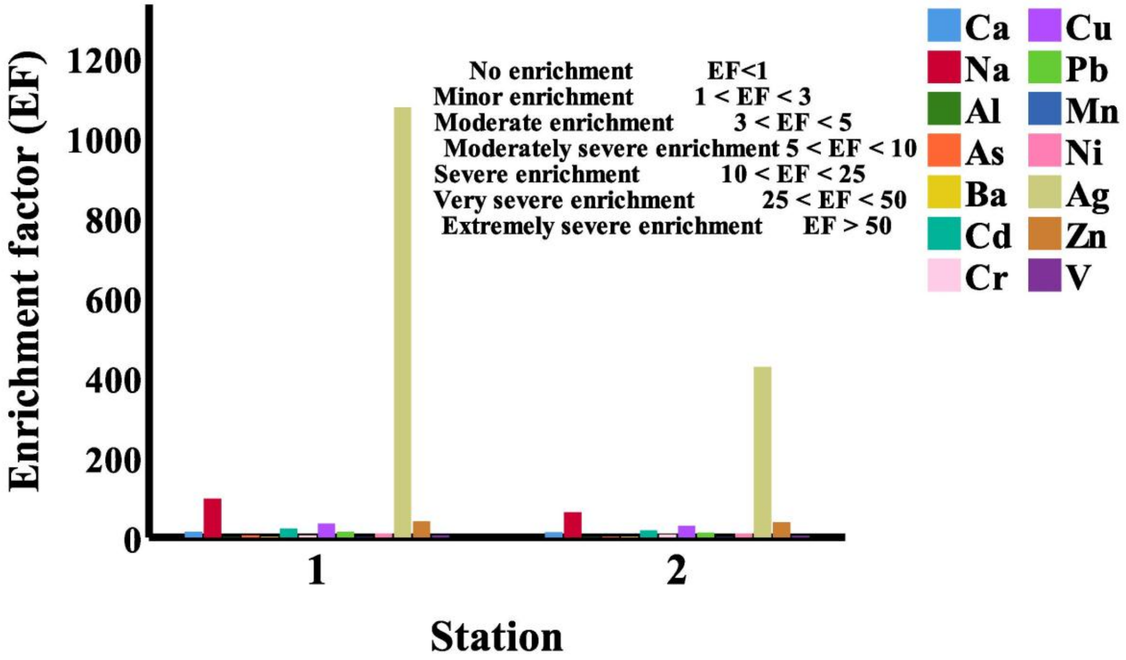

Fig. 6. Enrichment factor of metals in the coastal surface sediments in the area of study

The interpretation of EF values followed the recommendations provided by **Birch and Davies (2003)**. They classified EF values into seven classes: no enrichment (EF< 1), minor enrichment (EF< 3), moderate enrichment (EF= 3– 5), moderately severe enrichment (EF= 5– 10), severe enrichment (EF= 10– 25), very severe enrichment (EF= 25– 50), and extremely severe enrichment (EF> 50).

Fig. (6) shows that the enrichment factor for most metals is higher in station 1 than in station 2. This suggests that the sediment in station 1 is more contaminated with metals than in station 2. Metals with the highest enrichment factor in both stations are Ag, Cd, Pb, Cu and Zn. These metals are known to be toxic and harmful to the environment and human health. The metals with the lowest enrichment factor in both stations are Al and Mn. These metals are relatively abundant and benign in the natural environment.

The metals with the most variation in their enrichment factor between the two stations are Ag, Cd, Pb, Cu and Zn. These metals show a higher enrichment factor in station 1 than in station 2. This could indicate the presence of specific sources of pollution or contamination near station 1, such as metal industries.

3.4 Pollution index (PI) and modified pollution index (MPI)

Utilizing the Nemerow pollution index (PI) to assess sediment quality offers an alternative approach to address the limitations of the modified degree of contamination index. The PI incorporates a suite of elements' average contamination factors (Cf average), making it comparable to the modified degree of contamination index. However, it goes further by incorporating a weighted average that considers the highest contamination factor (Cf max), thereby accounting for the impact of individual elements' contamination. By employing a weighted average, the Nemerow pollution index provides a more comprehensive evaluation of sediment quality that considers the influence of specific elements **(Nemerow, 1991)**.

$$PI = \sqrt{\frac{\left(C_{f_{average}}\right)^2 + \left(C_{f_{max}}\right)^2}{2}}$$

Where, Cf^i, Cf average, and Cf max represent the contamination factor for an individual element, the average of contamination factors and maximum contamination factor, respectively.

According to the modified pollution index (MPI), sediments may exhibit non-conservative behavior due to normalization against elements like Al or Fe **(Brady *et al.*, 2015)**.

$$MPI = \sqrt{\frac{\left(EF_{average}\right)^2 + \left(EF_{max}\right)^2}{2}}$$

Where, $EF_{average}$ and EF_{max} represent an average of enrichment and maximum enrichment factors, respectively.

Table 6. Thresholds for sediment quality classification for multi-element indices (adapted from **Brady *et al.* (2015)**)

Class	Sediment qualification	PI	MPI
0	Unpolluted	PI< 0.7	MPI< 1
1	Slightly polluted	0.7< PI< 1	1< MPI< 2
2	Moderately polluted	1< PI< 2	2< MPI< 3
3	Moderately-heavily polluted	–	3< MPI< 5
4	Heavily polluted	2< PI< 3	5< MPI< 10
5	Severely polluted	PI> 3	MPI> 10

Fig. (7) reveals that station 1 has a higher pollution index and modified pollution index than station 2, indicating that station 1 is more polluted than station 2. This indicates a classification of severely polluted associated with the presence of metals at station 1, while heavily polluted at station 2 in the study area. Levels of MPI at all sites in the study area were in the severely polluted category of the classification (Table 6).

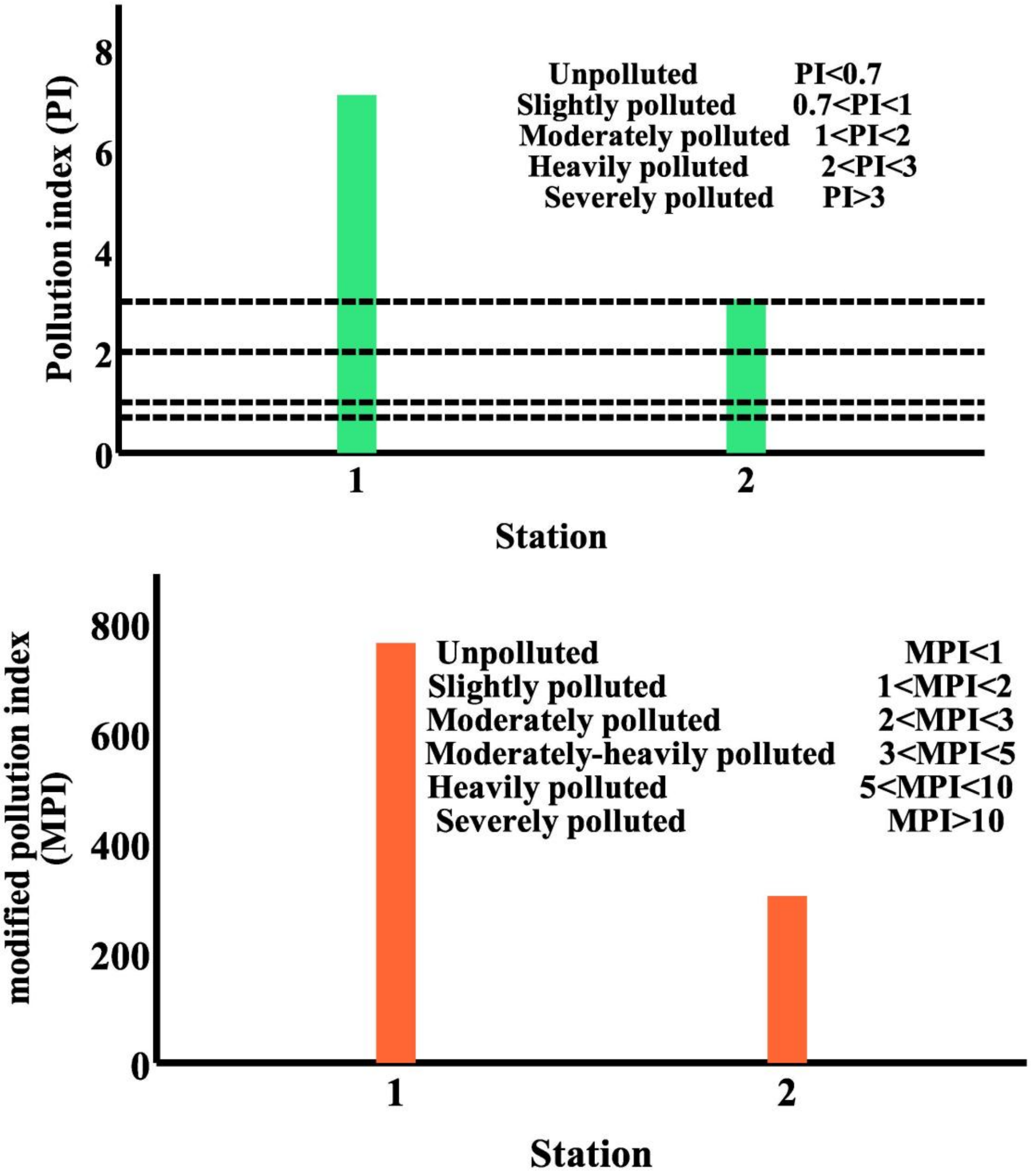

Fig. 7. Pollution index and modified pollution index of metals in the coastal surface sediments in the area of study

3.5 The Potential ecological risk index (PERI)

The potential ecological risk index (PERI), developed by **Hakanson (1980)**, was employed to assess the potential harmful effects of metals. The objective of this risk index is to evaluate the ecological health risk arising from the introduction of pollutants into the food chain. By utilizing this approach, the PERI calculates the combined potential ecological risk index resulting from the collective effects of metals and the potential ecological risk coefficient (E_r^i) for each individual metal. The calculations are performed using the following equations:

$$C_f^i = \frac{C_s^i}{C_n^i}$$

$$E_r^i = T_r^i X C_f^i$$

$$PERI = \sum_{i=1}^{n} E_r^i$$

Where, C_f^i represents the pollution coefficient of a single metal "i", C_s^i denotes the measured concentration of the metal in the sediment, C_n^i indicates the background level of the sedimentary metal, and T_r^i represents the toxicity coefficient for the specific metal "i". The toxicity coefficient provides information about the toxicity levels, pollution levels, and environmental sensitivity to metals **(Soliman *et al.*, 2015; Zhang *et al.*, 2016)**. For example, the toxicity coefficients for Pb, Cd, Cu, Cr, Ni, Zn, Hg, As, and Mn were determined as 5, 30, 5, 2, 5, 1, 40, 10 and 1, respectively **(Hakanson, 1980; Zheng *et al.*, 2008)**.

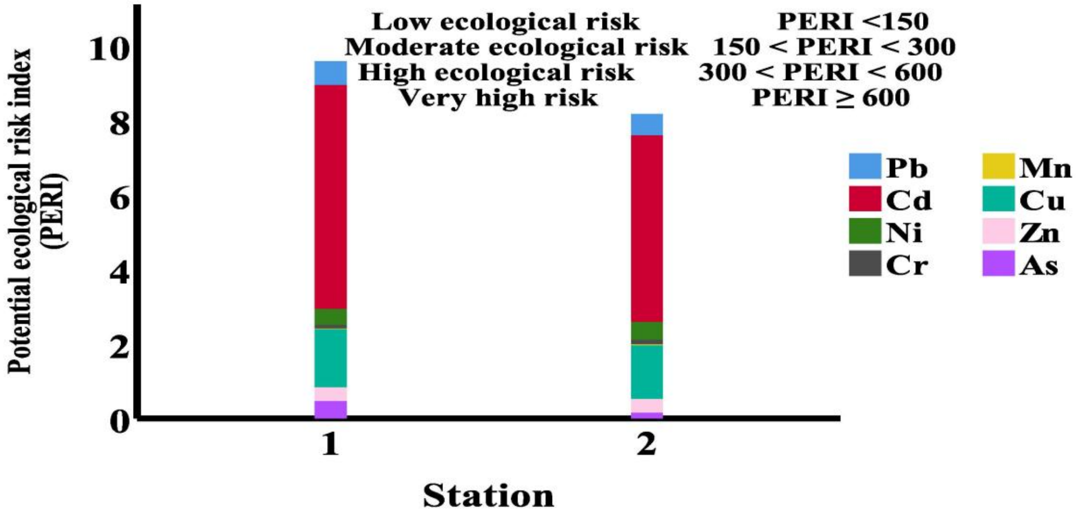

Fig. 8. Potential ecological risk index (PERI) of metals in the coastal surface sediments in the area of study

According to **Hakanson (1980)**, the PERI is categorized into four levels: PERI< 150 indicates a low ecological risk, 150< PERI< 300 suggests a moderate ecological risk, 300< PERI< 600 indicates a high ecological risk, and PERI≥ 600 signifies a significantly high ecological risk. The potential ecological risk index for each individual element is classified as either low risk (E_r^i< 40), moderate risk (40< E_r^i< 80), considerable risk (80< E_r^i< 160), high risk (160< E_r^i< 320), or very high risk (E_r^i> 320).

According to Fig (8), station 1 has a higher PERI than station 2. It was noticed that the metals Pb, Cd, Ni, Zn, Cu, and As are present in both stations, with Cd and Cu being the most abundant metals in station 1 and station 2.

Fig. (8) reveals some interesting patterns and differences between the two stations. The metal with the highest PERI in both stations is Cd, known to be toxic and harmful to the environment. However, these values indicate a classification of low ecological risk associated with the presence of metals and, consequently, a low potential impact of heavy metals on the environment and human health in the study area.

3.6 Geo-accumulation index (I_{geo})

The geo-accumulation index (Igeo) serves as a commonly used measure to assess trace metal pollution in sediments within the present study. **Müller (1969)** established the geo-accumulation index (Igeo) as a means to identify and characterize metal pollution in sediments. The formula below defines the geo-accumulation index (Igeo):

$$\text{Igeo} = \text{Log2}\left(\frac{C_n}{1.5\ X\ B_n}\right)$$

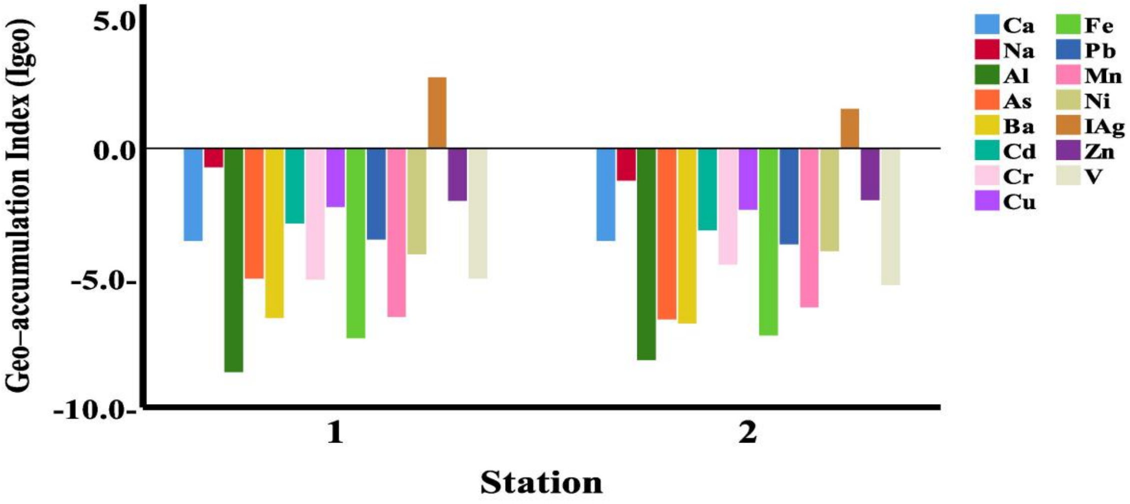

Fig. 9. Geo-accumulation index (Igeo) of metals in the coastal surface sediments in the area of study

Müller's classification divides the geo-accumulation index into seven classes, ranging from Class 0 (Igeo= 0) to Class 6 (Igeo> 5). Samples are categorized as follows: unpolluted (Igeo≤ 0), unpolluted to moderately polluted (0< Igeo≤ 1), moderately polluted (1< Igeo≤ 2), moderately to strongly polluted (2< Igeo≤ 3), strongly polluted (3< Igeo≤ 4), strongly to extremely polluted (4< Igeo≤ 5), and extremely polluted (Igeo> 5). Igeo is associated with a qualitative scale of pollution intensity.

The study findings reveal that the geo-accumulation index (Igeo) values were lower than zero for all metals except Ag (Fig. 9). This suggests that the sediments in the study area belong to category 0, which signifies an unpolluted area with all investigated metals. However, station 1 is classified as moderately to highly polluted (category 3), and station 2 as moderately polluted (category 2), both due to the presence of Ag in the area of study.

In conclusion, this study comprehensively assessed the pollution status and risk assessment on the Shuaibah coast of the Red Sea, Saudi Arabia. The findings reveal generally favorable water quality conditions characterized by acceptable pH levels for aquatic organisms and low turbidity values.

CONCLUSION

The analysis of metal concentrations in water samples indicated that the levels were low overall, suggesting a relatively low risk of metal pollution in the study area. Furthermore, evaluating sediment physicochemical parameters demonstrated minimal pollution levels with low organic matter and phosphorus content. While metal concentrations in sediments generally remained within background levels, slight elevations of certain metals, such as Ag (0.7mg/ L in sample 1 and 0.3mg/ L in sample 2), were detected. The results indicated that some areas exhibited considerable to very high contamination factors, emphasizing the importance of targeted efforts to control and reduce pollution in these locations. However, the PERI values provided reassurance regarding the low ecological risk associated with the presence of metals in the study area, indicating that the current metal concentrations are unlikely to harm the surrounding aquatic ecosystems. Additionally, the Igeo values suggested that the study area can be considered generally unpolluted except for Ag.

Overall, this study contributes valuable insights into the water quality and sediment characteristics of the Shuaibah coast of the Red Sea, Saudi Arabia. The findings underscore the need for continuous monitoring and effective management practices to preserve and conserve the local aquatic ecosystems. Implementing targeted pollution, control measures and remediation actions in areas with localized contamination sources are crucial for maintaining and improving the overall environmental health of the study area.

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