

Article

Assessment of Heavy Metal Contamination in Coastal Sediments from the Red Sea: Environmental Impacts, Health Risks and Source Identification

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Abstract

Sustainable coastal environmental management relies on continuous assessment of sediment quality. In the Saudi Arabian Red Sea, such sediments function as both sinks and potential secondary sources of heavy metals (HMs) originating from natural processes and anthropogenic activities. The present study investigated the concentrations of HMs in surface sediments from Jeddah and Rabigh. Contamination levels, as well as possible natural and anthropogenic inputs and potential risks to human health through ingestion, dermal contact, and inhalation pathways, were evaluated. The results indicated that Fe is the most abundant metal at both sites (1570.40 mg/kg at Jeddah and 1804.11 mg/kg at Rabigh). Cu, Ni, and Zn are present in the sediments at concentrations ranging between 3.12 and 4.49 mg/kg, while Cd and Pb remain below the detection limits in all samples. Generally, the contamination index values indicated low levels in both regions. The evaluation of human health risks identified ingestion as the primary exposure pathway. Non-carcinogenic risk levels were within safe limits for both adults and children. However, the carcinogenic risk assessment of nickel (Ni) indicated that all values fall within the acceptable range (10^{-6} – 10^{-4}), although children consistently showed higher risks than adults. Despite the overall low levels of pollution, the moderate enrichment of Cu, Ni, and Zn in Jeddah and Cu in Rabigh, along with the higher non-carcinogenic risks to children at the Rabigh site, highlights the need for continuous environmental monitoring and further investigation to support the sustainable management of coastal ecosystems.

Keywords: heavy metals; coastal sediments; risk assessment; health risks; Red Sea; environmental pollution



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1. Introduction

Sustainable management of coastal ecosystems requires the continuous assessment of sediment quality, as marine sediments play a critical role in preserving ecosystem health, protecting public health, and supporting evidence-based environmental decision-making [1,2]. Marine sediments in coastal areas serve as important sinks for heavy metals (HMs) and metalloids derived from both natural and anthropogenic activities, including industrial discharges, sewage effluents, and shipping waste [3,4]. The accumulation of

these elements in sediments may pose serious environmental threats to marine organisms and health threats to humans via the food chain or through direct exposure, particularly in densely populated coastal regions [5,6]. The Red Sea coast of Saudi Arabia, which extends for more than 1800 km, is increasingly exposed to HM inputs due to rapid coastal development, industrial expansion, and maritime activities [7].

Evaluating the status of aquatic ecosystems is essential to identify the degree of HM contamination [8]. Contamination indices serve as essential tools for determining the degree of sediment contamination. In the process of evaluating contamination levels in sediments, both individual and composite indices are typically employed [9]. Individual indices focus on the specific impact of each metal, including the contamination factor (CF-HM), enrichment factor (EF-HM), ecological risk factor (Er-HM), and geoaccumulation index (Igeo) [10–12]. In contrast, composite indices such as the pollution load index (PLI-HM) and potential ecological risk (RI-HM) assess the cumulative effects of heavy metals [13,14]. Such contamination poses ecological threats to sensitive habitats, including mangroves, coral reefs, and seagrass beds, and may extend to human health risks through seafood consumption and direct exposure.

HMs are essential to ecosystems, playing significant roles in sediment fertility and the functioning of living organisms. However, their concentrations should remain within internationally recognized safe limits, as excessive levels of metals such as Cd, Pb, and Ni may pose serious risks to environmental quality and human health [15,16]. Consuming high levels of certain heavy metals on a daily basis is associated with various health issues, such as cancer, peripheral vascular disease, fatal cardiac arrest, and liver disease [16,17]. HMs released into water bodies often accumulate in marine sediments, posing an ecological threat to filter-feeding organisms and eventually impacting humans [18–20]. These metals can enter the human body through air inhalation, ingestion of sediment or dust, and skin contact [21,22].

Previous studies have reported elevated levels of HM contamination along the Saudi Arabian Red Sea coast [18,23,24]. Heavy metal assessment in coastal sediments aligns closely with the principles of sustainable development, as it provides essential scientific evidence for long-term environmental monitoring, pollution prevention, ecosystem conservation, and the protection of public health. Such assessments support informed decision-making and contribute to the sustainable management of coastal resources in accordance with environmental sustainability goals. However, comprehensive studies that simultaneously evaluate HM levels, sediment characteristics, ecological risk, and human health risk across various locations along the Saudi Arabian Red Sea coast, particularly in Jeddah and Rabigh, remain limited. Such integrated assessments are essential for supporting sustainable coastal environmental management, pollution prevention, and evidence-based decision-making aimed at protecting marine ecosystems and public health.

Therefore, the present study aims to (1) determine the levels of seven HMs (Ni, Cu, Fe, Zn, Mn, Cd, and Pb), together with carbonate and soil organic matter (SOM) contents, in surface sediments from the Jeddah and Rabigh regions; (2) evaluate sediment contamination using the enrichment factor (EF), contamination factor (CF), geoaccumulation index (Igeo), ecological risk factor (Er), pollution load index (PLI), and potential ecological risk index (RI); (3) assess non-carcinogenic and carcinogenic health risks for adults and children through multiple exposure pathways using chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), cancer risk (CR), and lifetime cancer risk (LCR); and (4) identify the potential natural and anthropogenic sources of HMs using multivariate statistical analyses and examine their relationships with carbonate and SOM contents.

2. Materials and Methods

2.1. Study Area and Sampling Preparation

Jeddah and Rabigh are located in western Saudi Arabia along the eastern coast of the Red Sea (Figure 1). These regions are major industrial and commercial centers. Rabigh is home to several industrial activities, including the Rabigh Refining and Petrochemical Company and the Arabian Cement Factory. Similarly, Jeddah is characterized by intensive anthropogenic activities, including power generation facilities, seawater desalination plants, port operations, shipping activities, and other industrial and urban developments that may contribute to coastal environmental contamination [25].

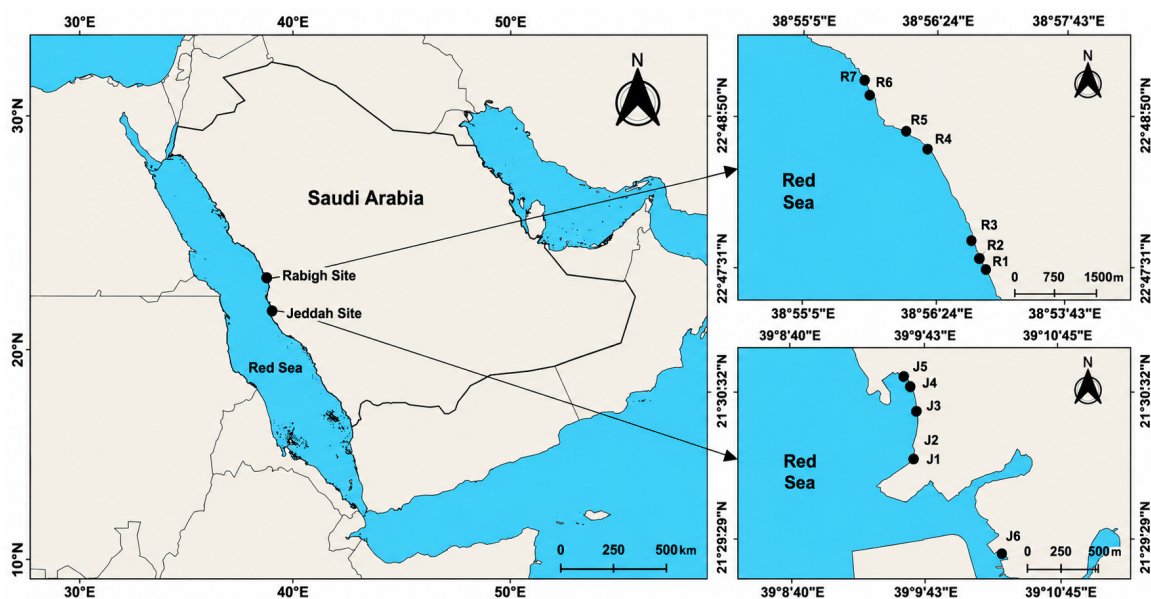


Figure 1. A map showing the study area and the locations of sediment sampling stations for each site along the Red Sea of Saudi Arabia (Jeddah and Rabigh).

Thirteen surface sediment samples (0–5 cm) were collected using a stainless-steel grab sampler from two Red Sea coastal sites during April 2025: six from Jeddah and seven from Rabigh. The sampling locations were determined using GPS and are presented in Figure 1. The samples were then transported to the laboratory in an icebox. In the laboratory, 50 g of each sample was oven-dried for 24 h, gently ground using a mortar and pestle, homogenized, and sieved through a 63 μm mesh prior to analysis.

2.2. Analytical Methods

2.2.1. HM Determination in Sediments

In total, 0.5 g of each dried sediment sample was digested using a MARS-6 microwave digestion system (CEM Corporation, Matthews, NC, USA) following U.S. EPA Method 3051 A [26]. Each sample was sieved (<63 μm) and then placed into a digestion vessel, before 10 mL of concentrated HNO_3 (69%) was added. The mixture was left for 15 min under a fume hood prior to sealing to avoid rapid pressure buildup. The vessels were then sealed and heated to $175 \pm 5^\circ\text{C}$ for approximately 10 min. After cooling, the digested samples were diluted with 18 M Ω deionized water to a final volume of 50 mL. The concentrations of Ni, Cu, Zn, Mn, Fe, Cd, and Pb were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; PerkinElmer Avio 220 Max, PerkinElmer, Inc., Waltham, MA, USA). Calibration curves were formulated for the studied elements using certified standard solutions (CPAchem Ltd., Stara Zagora, Bulgaria), with correlation coefficients (R^2) ≥ 0.999 . Blanks were analyzed to check for contamination during sample analysis.

The instrumental detection limits (IDLs) for the analyzed elements ranged from 0.0001 to 0.0005 mg/L, while the recovery rates ranged from 92% to 98%.

2.2.2. Carbonate and Organic Matter in Sediments

Carbonate content ($\text{CaCO}_3\%$) was determined using the geometric method according to ASTM D4373-21 [27]. Samples were oven-dried at $110 \pm 5^\circ\text{C}$ for 24 h and then disaggregated using a mortar and pestle. Approximately 1 g of dried sediment was placed in a reaction cylinder (reactor), and then 20 mL of 1 M HCl was added. The reactor was sealed and gently shaken to allow the reaction between HCl and the sample to take place. Then, the CO_2 gas evolved from the reaction was captured and measured by the pressure gauge mounted on the reactor. The measured pressure of CO_2 was used to determine carbonate % using calibration curves established with known amounts of CaCO_3 (reagent grade).

Soil organic matter (SOM %) was measured using the loss-on-ignition (LOI) technique according to ASTM D2974-20 [28], with a slight modification to the ignition temperature as described by Heiri et al. [29]. Approximately 5 g of each sediment sample was oven-dried at 105°C for 24 h, weighed (W_{105}), ignited at 550°C for 4 h, and reweighed (W_{550}). The SOM % content was calculated using the following equation:

$$\text{SOM \%} = ((W_{105} - W_{550}) / W_{105}) \times 100 \quad (1)$$

where W_{105} indicates the dry weight of the sample at 105°C and W_{550} represents the sample weight after heating to 550°C .

2.3. Environmental Risk Assessment

To assess the degree of HM pollution in sediments, several indices were applied, including the contamination factor (CF-HM), the enrichment factor (EF-HM), the geoaccumulation index (Igeo-HM), the pollution load index (PLI-HM), and the potential ecological risk index (RI-HM) [13,30].

The contamination factor (CF-HM) measures the degree of HM contamination in the sediment relative to their natural background values reported by Turekian and Wedepohl [31]. The CF-HM classifications are as follows: Class 1 ($\text{CF-HM} < 1$, indicating low pollution levels), Class 2 ($1 \leq \text{CF-HM} < 3$, suggesting moderate pollution), Class 3 ($3 \leq \text{CF-HM} < 6$, representing considerable pollution), and Class 4 ($\text{CF-HM} \geq 6$, indicating extremely high pollution levels) [32]. The CF-HM was determined using the following equation (Equation (2)) [33]:

$$\text{CF-HM} = C_m / B_m \quad (2)$$

where C_m is the measured HM concentration in the sediment, and B_m is the HM concentration in the natural background levels.

The enrichment factor (EF-HM) is a widely accepted geochemical index used to evaluate the degree of HM enrichment and to differentiate between natural and anthropogenic sources. The enrichment levels were categorized as follows: Class 1 ($\text{EF-HM} < 2$, ranging from deficiency to minimal enrichment), Class 2 ($\text{EF-HM} = 2\text{--}5$, indicating moderate enrichment), Class 3 ($\text{EF-HM} = 5\text{--}20$, denoting significant enrichment), Class 4 ($\text{EF-HM} = 20\text{--}40$, representing very high enrichment), and Class 5 ($\text{EF-HM} > 40$, indicating extremely high enrichment) [34]. EF-HM was estimated using the following equation (Equation (3)) [35]:

$$\text{EF-HM} = (C_m / C_{\text{Fe}})_{\text{sample}} / (B_m / B_{\text{Fe}})_{\text{crust}} \quad (3)$$

where C_m is the metal level in the sediment, C_{Fe} is the level of Fe in the sediment, B_m is the metal level in the crust, and B_{Fe} is level of Fe in the crust. Fe was selected as the normalizing element for EF-HM calculations because it is one of the most widely used

lithogenic reference elements in sediment geochemistry and is commonly employed to distinguish anthropogenic from natural metal enrichment [36,37].

The geoaccumulation index (Igeo-HM) was employed to assess the level of sediment contamination relative to their natural background concentrations. Based on Igeo-HM values, contamination was grouped into seven classes: Class 1 (Igeo < 0, uncontaminated), Class 2 (0–1, unpolluted to moderately contaminated), Class 3 (1–2, moderately polluted), Class 4 (2–3, moderately to strongly contaminated), Class 5 (3–4, strongly contaminated), Class 6 (4–5, strongly to extremely contaminated), and Class 7 (Igeo > 5, extremely contaminated). Igeo was calculated using the following equation (Equation (4)) [38]:

$$\text{Igeo-HM} = \log_2 (C_m / 1.5 \times B_m) \quad (4)$$

where C_m refers to the measured concentration of metals in the sediment, while B_m is the metal level in the crust. The factor 1.5 is used to account for fluctuations that might arise from natural lithogenic contributions [39].

The pollution load index (PLI) was applied to assess the overall degree of metal contamination in sediments [40]. According to its interpretation, PLI-HM < 1 denotes no pollution, whereas $\text{PLI-HM} \geq 1$ indicates pollution. PLI-HM was estimated using the following equation [41]:

$$\text{PLI-HM} = (\text{CF}_{\text{Fe}} \times \text{CF}_{\text{Cu}} \times \text{CF}_{\text{Zn}} \times \text{CF}_{\text{Ni}} \times \text{CF}_{\text{Mn}})^{1/n} \quad (5)$$

where CF is the contamination factor, and n is the number of metals studied.

The ecological risk factor (Er-HM) and potential ecological risk index (RI-HM) were used to assess the potential ecological risk of HMs in sediments. Er-HM and RI were calculated using the following equations (Equations (6) and (7)) [33]:

$$\text{Er-HM} = \text{CF} \times \text{Tr} \quad (6)$$

$$\text{RI-HM} = \sum \text{Er} \quad (7)$$

where Er is the ecological risk factor for each metal, CF-HM is the contamination factor, Tr is the toxicity coefficient of each element (Cu and Ni = 5; Zn and Mn = 1), and RI is the sum of Er for each metal. The ecological risk levels are categorized as follows: low risk is signified by Er-HM values less than 40, moderate risk is indicated by values between 40 and less than 80, considerable risk is shown by values ranging from 80 to less than 160, severe risk is identified by values between 160 and less than 320, and extremely high risk is represented by values above 320. The RI-HM classification is as follows: low ecological risk is denoted by RI-HM values under 150, moderate risk by values from 150 to less than 300, considerable risk by values between 300 and less than 600, and very high ecological risk by values of 600 or above [33].

2.4. Human Health Risk Assessment

Human exposure through ingestion (ing), dermal contact (derm), and inhalation (inh) of sediment particles was evaluated following internationally accepted human health risk assessment frameworks, as these represent the primary pathways of exposure to environmental contaminants. The potential carcinogenic and non-carcinogenic health risks for both adults and children were assessed based on the following indices: chronic daily intake (CDI-HM), hazard quotient (HQ-HM), hazard index (HI-HM), cancer risk (CR-HM), and total lifetime cancer risk (LCR-HM). These indices were estimated according to the following formulas:

Chronic daily intake (CDI-HM) was calculated to estimate the average daily exposure dose of HMs through ingestion (CDI-ing), dermal contact (CDI-derm), and inhalation (CDI-inh) of sediment particles. This parameter was used to evaluate the potential exposure levels of adults and children and to support the assessment of non-carcinogenic and carcinogenic health risks associated with HM contamination. The following equations were applied to calculate the CDI-HM values for different exposure pathways:

$$\text{CDI-ing} = (\text{Cm} \times \text{IngR} \times \text{EF} \times \text{ED}) / (\text{BW} \times \text{AT}) \times 10^{-6} \quad (8)$$

$$\text{CDI-derm} = (\text{Cm} \times \text{SA} \times \text{AFS} \times \text{ABS} \times \text{EF} \times \text{ED}) / (\text{BW} \times \text{AT}) \times 10^{-6} \quad (9)$$

$$\text{CDI-inh} = (\text{Cm} \times \text{EF} \times \text{ET} \times \text{ED} / \text{PEF} \times \text{BW} \times \text{AT}) \quad (10)$$

The exposure factors applied in the human health risk assessment through ingestion (CDI-ing), dermal contact (CDI-derm), and inhalation (CDI-inh) pathways were adopted from Hakanson [33], El-Sorogy et al. [42], and Miletić et al. [43]. For adults and children, the ingestion rates (IngR) were 100 and 200 mg/day, respectively, while the exposure frequency (EF) was 350 days/year. The exposure duration (ED) was assumed to be 24 years for adults and 6 years for children, with body weights (BW) of 70 and 15 kg and averaging times (AT) of 8760 and 2190 days, respectively. Skin surface area (SA) was considered to be 5700 cm² for adults and 2800 cm² for children, whereas the sediment adherence factor (AFS) was 0.07 and 0.2 mg/cm²/day, respectively. A dermal absorption factor (ABS) of 0.001, an exposure time (ET) of 20 h/day, and a particle emission factor (PEF) of 1.36×10^9 m³/kg were used for both exposure groups [33,42,43].

The hazard quotient (HQ-HM) was calculated to evaluate the potential non-carcinogenic risk associated with heavy metal exposure through ingestion, dermal contact, and inhalation pathways. The HQ value represents the ratio between the estimated chronic daily intake (CDI-HM) and the corresponding reference dose (RfD) for each metal. This parameter indicates whether the exposure level may pose potential adverse health effects to adults and children. The following equations were applied to calculate the HQ-HM values for different exposure pathways:

$$\text{HQ-ing} = \text{CD-ing} / \text{RfD-ing} \quad (11)$$

$$\text{HQ-derm} = \text{CDI-derm} / \text{RfD-derm} \quad (12)$$

$$\text{HQ-inh} = \text{CDI-inh} / \text{RfD-inh} \quad (13)$$

$$\text{T-HQ} = \text{HQ-ing} + \text{HQ-derm} + \text{HQ-inh} \quad (14)$$

The reference dose (RfD) values for Mn, Fe, Zn, Cu, and Ni via ingestion (RfD_ing), dermal contact (RfD_der), and inhalation (RfD_inh) were adopted from published studies and the USEPA guidelines [43–47]. The corresponding RfD_ing values were 0.14, 0.70, 0.30, 0.04, and 0.02 mg/kg/day, whereas the RfD_der values were 0.0056, 0.42, 0.06, 0.012, and 0.0008 mg/kg/day, and the RfD_inh values were 0.00005, 0.70, 0.30, 0.012, and 0.000014 mg/kg/day, respectively.

The hazard index (HI-HM) was calculated to assess the cumulative non-carcinogenic risk associated with exposure to multiple heavy metals through different pathways, including ingestion, dermal contact, and inhalation of sediment particles. The HI-HM value represents the sum of the individual hazard quotients (HQ-HM) for all analyzed heavy metals and exposure pathways, providing an overall estimation of potential health risks for adults and children. The following equation was applied to calculate the HI-HM values:

$$\text{HI-ing} = \sum \text{HQ-ing} \quad (15)$$

$$\text{HI-derm} = \sum \text{HQ-derm} \quad (16)$$

$$HI_{inh} = \Sigma HQ_{ing} \quad (17)$$

$$HI = HI_{ing} + HI_{derm} + HI_{inh} \quad (18)$$

Cancer risk (CR-HM) was calculated to estimate the probability of developing cancer over a lifetime due to exposure to carcinogenic heavy metals through different pathways, including ingestion, dermal contact, and inhalation of sediment particles. The CR-HM value was determined by multiplying the chronic daily intake (CDI-HM) by the corresponding cancer slope factor (CSF) for each metal. This parameter provides an estimation of the potential carcinogenic risk associated with long-term exposure to heavy metals in sediment. The following equation was applied to calculate the CR-HM values:

$$CR-Ni_{ing} = CDI_{ing} \times CSF-Ni_{ing} \quad (19)$$

$$CR-Ni_{inh} = CDI_{derm} \times CSF-Ni_{derm} \quad (20)$$

$$CR-Ni_{derm} = CDI_{inh} \times CSF-Ni_{inh} \quad (21)$$

where $CSF-Ni_i$ values are 1.7 mg/kg/day ($CSF-Ni_{ing}$), 22.5 mg/kg/day ($CSF-Ni_{derm}$), and 0.84 mg/kg/day ($CSF-Ni_{inh}$), as mentioned by Turhan et al. [47].

Total lifetime cancer risk (LCR) was calculated to estimate the overall carcinogenic risk resulting from simultaneous exposure to multiple heavy metals through ingestion, dermal contact, and inhalation of sediment particles over a lifetime. The LCR value was obtained by summing the individual cancer risk (CR) values for all exposure pathways and carcinogenic metals, providing an overall assessment of lifetime cancer risk for adults and children. The following equation was applied to calculate the LCR values:

$$LCR-Ni = CR-Ni_{ing} + CR-Ni_{inh} + CR-Ni_{derm} \quad (22)$$

If the LCR is below 10^{-6} , there is no risk of developing cancer. When the LCR falls between 1×10^{-6} and 10^{-4} , the risk of cancer is considered tolerable or acceptable. However, if the LCR exceeds 10^{-4} , the risk of cancer becomes unacceptable [43].

2.5. Statistical Analysis

Bivariate and multivariate analyses were applied to the dataset for the study area to investigate the relationships among the variables (HM concentrations, carbonate %, and SOM %). For this purpose, correlation analysis was conducted to examine linear relationships among the variables and identify possible sources of contamination. Moreover, principal component analysis (PCA) was used to decrease data dimensionality and identify the major contributing factors influencing metal accumulation. All statistical analyses were conducted using Python (version 3.12).

3. Results and Discussion

3.1. HM Concentrations in Sediments

The average concentrations of HMs (Ni, Cu, Zn, Mn, Fe, Cd, and Pb) in surface sediments from the two studied coastal sites along the Saudi Arabian Red Sea were evaluated to characterize their spatial distribution, assess the degree of contamination, and provide baseline information for environmental monitoring and sustainable coastal management (Table 1). At the Jeddah site, the concentration of Fe was the highest at 1570.40 mg/kg, whereas Ni had the lowest concentration at 3.77 mg/kg. The overall order of average concentrations for this site was $Ni < Cu < Zn < Mn < Fe$. Both Cd and Pb were below the detection limit (BDL) at all sampling points and were therefore excluded from analysis. Regarding the Rabigh site, the highest concentration was observed for Fe (1804.11 mg/kg),

and the lowest concentration was obtained for Zn (3.12 mg/kg). The order of average HM concentrations was $Zn < Cu < Ni < Mn < Fe$; Cd and Pb remained below the detection limits (BDL) throughout the site. The persistent absence of Cd and Pb (BDL) at both sites highlights their negligible contribution to sediment contamination in the studied areas. Overall, Ni, Cu, and Zn concentrations in Jeddah sediments were higher than those in Rabigh, while Fe and Mn concentrations were lower in Jeddah.

Table 1 also shows a comparison of the average concentrations of HMs in the studied sediment samples with those reported in previous investigations. Nickel (Ni) is an essential trace element that plays a role in various enzymatic processes; however, it can become toxic at elevated concentrations, posing ecological and human health risks [48]. In the present study, Ni concentrations in surface sediments along the Saudi Red Sea ranged from 3.43 mg/kg at Rabigh to 3.77 mg/kg at Jeddah. These values are slightly higher than those reported previously along the Red Sea coast of Egypt, where Abbas et al. [49] recorded an average Ni concentration of 2.57 mg/kg, comparable to the levels reported by Halawani et al. [50] in other areas of the Saudi Arabian Red Sea (3.68 mg/kg). When compared globally, Ni levels in the present study are markedly lower than those measured in the Black Sea (27.29 mg/kg) by Kodat and Tepe [51], the Gulf of Pozzuoli, Italy (10.40 mg/kg), by Armiento et al. [52], and the Caspian Sea, Russia (14.00 mg/kg), by De Mora et al. [53]. The values are also well below levels found for background shale (68 mg/kg) by Turekian and Wedepohl [31] and the average Earth's crust values (75 mg/kg) by Taylor [54]. Generally, the low Ni levels in both sites suggest limited contamination when compared with heavily impacted coastal regions worldwide.

Copper (Cu) is an essential micronutrient for many enzymatic and physiological processes in living organisms, although excessive accumulation in sediments can pose ecological risks [55]. In the present study, Cu concentrations ranged from 3.14 mg/kg at Rabigh to 3.92 mg/kg at Jeddah. These levels are higher than those reported along the Red Sea coast of Egypt (1.17 mg/kg) by Abbas et al. [49], but lower than the values recorded in other parts of the Saudi Arabian Red Sea by Halawani et al. [50], who reported 9.18 mg/kg for Cu. Compared to other global regions, Cu concentrations in this study are considerably lower than those measured in the Black Sea (45.66 mg/kg) by Kodat and Tepe [51], the Gulf of Pozzuoli, Italy (18.40 mg/kg), by Armiento et al. [52], and the Caspian Sea, Russia (8.30 mg/kg), by De Mora et al. [53]. Furthermore, they are well below background levels for shale (45 mg/kg) detected by Turekian and Wedepohl [31] and average values for the Earth's crust (55 mg/kg) found by Taylor [54]. Overall, Cu values in the studied area indicate minimal contamination in comparison with heavily impacted coastal zones worldwide.

Iron (Fe) is a major essential element in marine sediments, playing a key role in geochemical cycling and serving as an indicator of natural and anthropogenic inputs [56]. In the present study, Fe concentrations in the sediments ranged from 1570.40 mg/kg at Jeddah to 1804.11 mg/kg at Rabigh. These values are comparable to previous measurements made by Alharbi et al. along the Red Sea coast of Egypt (1539 mg/kg) [49] and the Arabian Gulf coast of Saudi Arabia (1525 mg/kg) [57]. Globally, Fe levels at the studied sites are significantly lower than those reported in the Black Sea (27,646 mg/kg) by Kodat and Tepe [51], the Gulf of Pozzuoli, Italy (26,378 mg/kg), by Armiento et al. [52], and the Caspian Sea, Russia (5520 mg/kg), by De Mora et al. [53]. They also remain below background levels for shale (47,200 mg/kg) detected by Turekian and Wedepohl [31] and the Earth's crust values (56,300 mg/kg) noted by Taylor [54].

Table 1. Descriptive statistics of HM concentrations (mg/kg) in the studied sediments and comparison with local and worldwide investigations.

Reference		Ni	Cu	Fe	Zn	Mn	Cd	Pb
Jeddah (present study)	Average	3.77	3.92	1570.4	4.49	24.52		
	SD	1.03	1.79	957.64	2.57	16.27		
	Min.	2.11	0.76	279	1.43	3.92	BDL	BDL
	Max.	4.91	5.65	2802.44	9.05	45.3		
Rabigh (present study)	Average	3.43	3.14	1804.11	3.12	35.91		
	SD	1.63	1.7	1369.92	1.47	20.36		
	Min.	1.89	1.07	426.24	1.46	11.39	BDL	BDL
	Max.	6.41	5.57	4093.67	5.62	61.54		
Red Sea, Egypt [49]		2.57	1.17	1539	15.47	56.27	BDL	2.23
Red Sea, Saudi Arabia [50]		3.68	9.18	--	18.02	36.52	--	77.34
Black Sea [51]		27.29	45.66	27,646	94.16	571.87	0.2	60.64
Arabian Gulf coast, Saudi Arabia [57]		--	--	1525	5.7	33.6	--	--
Gulf of Pozzuoli, Italy [52]		10.4	18.4	26,378	70.3	651	0.21	17.3
Caspian Sea, Russia [53]		14	8.3	5520	--	200	0.06	4.19
Background shale [31]		68	45	47,200	95	850	--	--
Earth's crust [54]		75	55	56,300	70	850	--	--

Zinc (Zn) is an essential trace metal involved in enzymatic functions and biological processes; however, it can pose ecological risks at elevated concentrations [58]. In the present study, Zn concentrations in the sediments ranged from 3.12 mg/kg at Rabigh to 4.49 mg/kg at Jeddah. These values are notably lower than those reported along the Red Sea coast of Egypt (15.47 mg/kg) by Abbas et al. [49] and in other areas of the Saudi Arabian Red Sea (18.02 mg/kg) by Halawani et al. [50]. Globally, Zn levels in the studied sites are far below those measured in the Black Sea (94.16 mg/kg) by Kodat and Tepe [51], the Gulf of Pozzuoli, Italy (70.30 mg/kg), by Armiento et al. [52], background shale (95 mg/kg) by Turekian and Wedepohl [31], and average values for the Earth's crust (70 mg/kg) reported by Taylor [54].

Manganese (Mn) is a trace element found naturally in marine sediments, where it plays an essential role in redox reactions and biogeochemical cycling; however, elevated concentrations may indicate anthropogenic influence [59]. In the present study, Mn concentrations in the surface sediments ranged from 24.52 mg/kg at Jeddah to 35.91 mg/kg at Rabigh. These values are lower than those reported along the Red Sea coast of Egypt (56.27 mg/kg) by Abbas et al. [49] and comparable to those reported for other areas of the Saudi Arabian Red Sea (36.52 mg/kg) as reported by Halawani et al. [50]. On a global scale, Mn concentrations in the studied sites are considerably lower than those measured in the Black Sea (571.87 mg/kg) by Kodat and Tepe [51], the Gulf of Pozzuoli, Italy (651 mg/kg), by Armiento et al. [52], and the Caspian Sea, Russia (200 mg/kg), by De Mora et al. [53]. They also remain below measured levels for background shale (850 mg/kg) by Turekian and Wedepohl [31] and average values for the Earth's crust (850 mg/kg) by Taylor [54].

3.2. Carbonate and Organic Matter

Carbonate and SOM are key sediment characteristics that influence the geochemical behavior of heavy metals and contribute to understanding sediment quality. Therefore, their contents were evaluated to examine their potential role in heavy metal distribution to support the sustainable environmental assessment of the Red Sea coastal ecosystem. The average carbonate content in Jeddah sediments (16.01%) was much lower than in Rabigh sediments (63.60%); by contrast, the SOM% content average was relatively comparable between the two regions (1.04% for Jeddah and 2.58% for Rabigh) (Table 2).

Table 2. Descriptive statistics of carbonate% and SOM% content in sediments from the study locations.

Location		Carbonate %	SOM%
Jeddah	Average	16.01	1.04
	SD	28.60	0.70
	Minimum	2.87	0.30
	Maximum	74.16	2.11
Rabigh	Average	63.60	2.58
	SD	12.62	0.79
	Minimum	42.58	1.84
	Maximum	76.13	3.53

3.3. Sediment Contamination Assessment

Sediment contamination assessment is a fundamental tool for evaluating environmental quality, identifying pollution sources, and supporting sustainable coastal management. Therefore, contamination indices were applied to assess the degree of HM contamination in the investigated coastal sediments, identify potential sources, and evaluate the associated environmental risks. In this study, several indices were employed to evaluate the environmental status of the study area, including the contamination factor (CF-Hm), geoaccumulation index (Igeo-Hm), enrichment factor (EF-Hm), pollution load index (PLI-Hm), ecological risk factor (Er-Hm), and potential ecological risk index (RI-Hm). Table 3 shows that the average values of CF-Hm, Igeo-Hm, and PLI-Hm for the analyzed metals in both the Jeddah and Rabigh regions are <1, <0, and <1, respectively, suggesting that the sediments at both sites have low concentrations and are unpolluted. Similarly, the average Er-Hm and RI-Hm values of Jeddah and Rabigh are below 40 and 150, respectively, suggesting that the sediments are at low ecological risk. However, the average EF-Hm values show that Ni, Cu, and Zn in Jeddah sediments and Cu in Rabigh sediments are moderately enriched. This suggests these metals are the most affected by anthropogenic inputs. The remaining EF-Hm average values show minimal enrichment for Mn in Jeddah sediments and Ni, Zn, and Mn in Rabigh sediments (Table 3).

Table 3. Environmental risk indices (CF, Igeo, EF, Er, PLI, and RI) of the heavy metals in sediment samples from Jeddah and Rabigh regions.

		Contamination Factor (CF)						
		Ni	Cu	Fe	Zn	Mn	PLI	RI
Jeddah	Minimum	0.03	0.02	0.01	0.02	0.005	0.01	0.32
	Maximum	0.07	0.13	0.06	0.10	0.05	0.08	1.14
	Average	0.06	0.09	0.03	0.047	0.03	0.05	0.79
Rabigh	Minimum	0.03	0.02	0.01	0.015	0.01	0.02	0.39
	Maximum	0.09	0.12	0.09	0.059	0.07	0.08	1.72
	Average	0.05	0.07	0.04	0.033	0.04	0.04	0.96
		Geoaccumulation Index (Igeo)						
Jeddah	Minimum	−5.74	−6.77	−8.24	−5.64	−8.35	-	-
	Maximum	−4.52	−3.87	−4.91	−4.42	−4.82	-	-
	Average	−4.95	−4.64	−6.09	−4.85	−6.1	-	-
Rabigh	Minimum	−5.9	−6.26	−7.63	−5.8	−6.81	-	-
	Maximum	−4.13	−3.89	−4.37	−4.03	−4.37	-	-
	Average	−5.17	−4.93	−5.97	−5.07	−5.4	-	-

Table 3. Cont.

Enrichment Factor (EF)								
Jeddah	Minimum	1.32	1.89	-	1.7	0.74	-	-
	Maximum	7.98	4.53	-	4.12	1.35	-	-
	Average	2.78	2.91	-	2.65	1.01	-	-
Rabigh	Minimum	1.10	1.2	-	1.10	1	-	-
	Maximum	3.36	5.55	-	3.12	1.81	-	-
	Average	1.90	2.37	-	1.82	1.52	-	-
Ecological Risk Factor (Er)								
Jeddah	Minimum	0.16	0.08	-	0.02	0.005	-	-
	Maximum	0.36	0.63	-	0.1	0.053	-	-
	Average	0.28	0.44	-	0.05	0.029	-	-
Rabigh	Minimum	0.06	0.12	-	0.24	0.013	-	-
	Maximum	0.19	0.62	-	1.3	0.072	-	-
	Average	0.1	0.35	-	0.76	0.042	-	-

3.4. Bivariate Correlation and Principal Component Analysis

Bivariate correlation and principal component analysis (PCA) were employed to examine the geochemical associations, source origins, and dominant hosting phases of heavy metals in the sediments [60]. The results of the bivariate analysis reveal interrelationships among the variables of interest, suggesting distinct trends at both locations (Figures 2 and 3). At Jeddah, Ni, Cu, and Zn are moderately correlated ($r > 0.63$); however, these relationships are not statistically significant ($p > 0.05$). In contrast, Ni and Zn both show high and significant correlations with Fe and Mn ($r > 0.82$, $p < 0.05$), and Fe is significantly associated with Mn ($r = 0.96$, $p < 0.01$). Based on their EF values (suggesting moderate enrichment) and their statistical significance ($p > 0.05$), Ni, Cu, and Zn may have different anthropogenic contributions to Jeddah sediments. By contrast, Fe and Mn are likely of natural origin. Additionally, all heavy metals are weakly related to carbonate% and SOM%, suggesting limited influence of these fractions on metal distribution. At the Rabigh location, all metals are positively and moderately to strongly correlated with each other ($r > 0.76$, $p < 0.05$), with weak-to-moderate negative correlations with carbonate% and SOM%. The significant relationships among Ni, Zn, Fe, and Mn in Rabigh sediments ($r > 0.9$, $p < 0.01$), besides their low concentrations and EF values, indicates that these metals are naturally transported to the Rabigh environment. In contrast, Rabigh is enriched in Cu sediments, as indicated by its EF value, suggesting a probable contribution from anthropogenic sources. The bivariate analysis supports this suggestion by showing that Cu in Rabigh sediments has the weakest correlations with other metals compared to correlations identified for the remaining metals (Figures 2 and 3).

Principal component analysis (PCA) results show that the first principal component (PC1) explains most of the total variance in the dataset in both regions (Table 4). Based on the low average concentrations of HMs and their low associated contamination indices in both regions, PC1 is suggested to represent natural sources. For Jeddah, Ni, Cu, Fe, Zn, and Mn are positively loaded on PC1, which explains 62.6% of the total variance. PC2 in the Jeddah region accounts for 30% of the total variance and is mainly associated with carbonate% and SOM%. Both PC1 and PC2 have eigenvalues greater than one. For Rabigh, PC1 accounts for 87.3% of the total variance and has high positive loadings for Ni, Cu, Fe, Zn, and Mn, and high negative loadings for carbonate % and SOM% with an eigenvalue greater than one. The heavy metals in Jeddah sediments are highly correlated and grouped on PC1, while the carbonate% and SOM% are highly loaded on different components (PC2).

In Rabigh sediments, heavy metals are positively and significantly loaded on PC1, whereas carbonate% and SOM% are highly and negatively loaded on PC1.

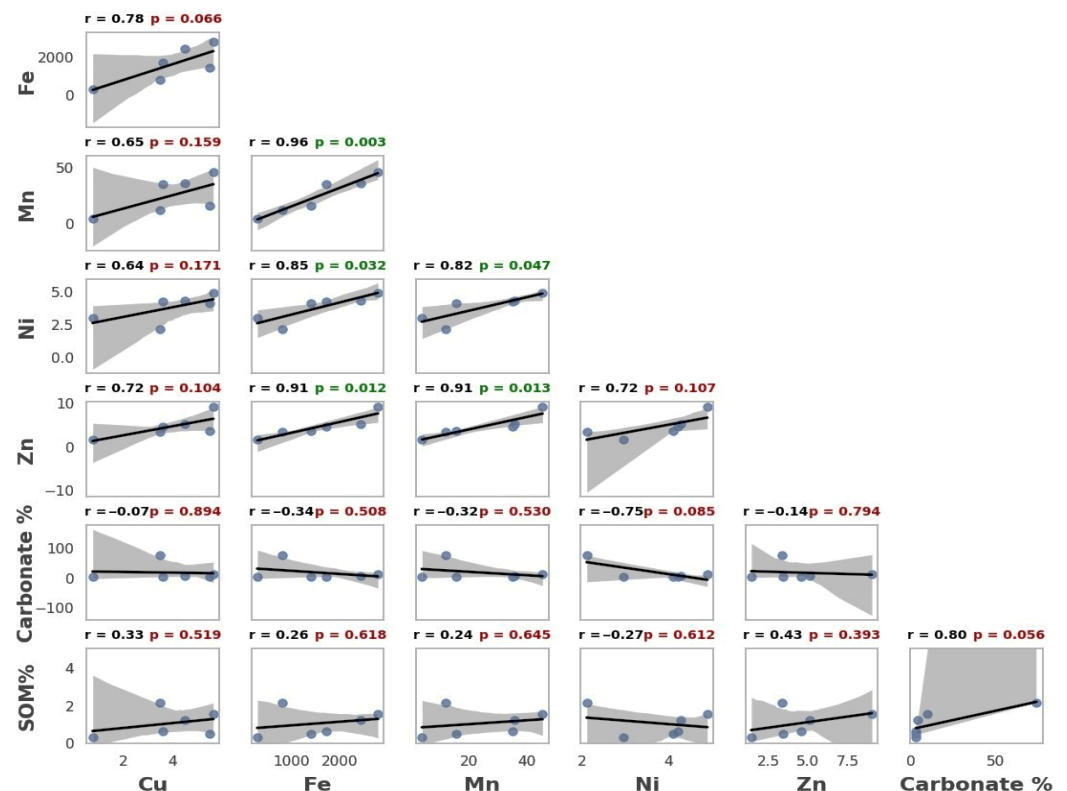


Figure 2. Scatterplot matrices for Jeddah showing the linear relationships (r values) between the metal concentrations (Cu, Zn, Ni, Mn, and Fe) and sediment properties (carbonate % and SOM %) in the Jeddah sediments. Green p -values indicate statistically significant correlations ($p < 0.05$), while red p -values show non-significant correlations.

The high loadings of Fe, Ni, Zn, Cu, and Mn on PC1 (natural sources) in both regions indicate that these HMs are likely influenced by similar geochemical processes and/or common environmental controls. Likewise, the separation of carbonate% and SOM% from the HM group in Jeddah, together with their negative loadings in Rabigh, suggests that these sediment characteristics play only a limited role in controlling the distribution of the investigated HMs. Although Cu is also loaded on PC1 in both regions, its comparatively lower loading than those of the other HMs suggests that it may, to some extent, be influenced by anthropogenic inputs in addition to natural sources (Table 4).

Table 4. Principal component analysis of HMs, SOM %, and carbonate % in sediments from the study areas.

Variable	Jeddah		Rabigh
	PC1	PC2	PC1
Cu	0.81	0.25	0.90
Fe	0.98	0.07	0.95
Mn	0.95	0.06	0.99
Ni	0.90	−0.43	0.95
Zn	0.92	0.27	0.96
Carbonate %	−0.40	0.91	−0.89
SOM%	0.17	0.97	−0.90
Variance %	62.60	30.00	87.30
Cumulative %	92.60	−	87.30
Eigenvalue	4.38	2.10	6.11

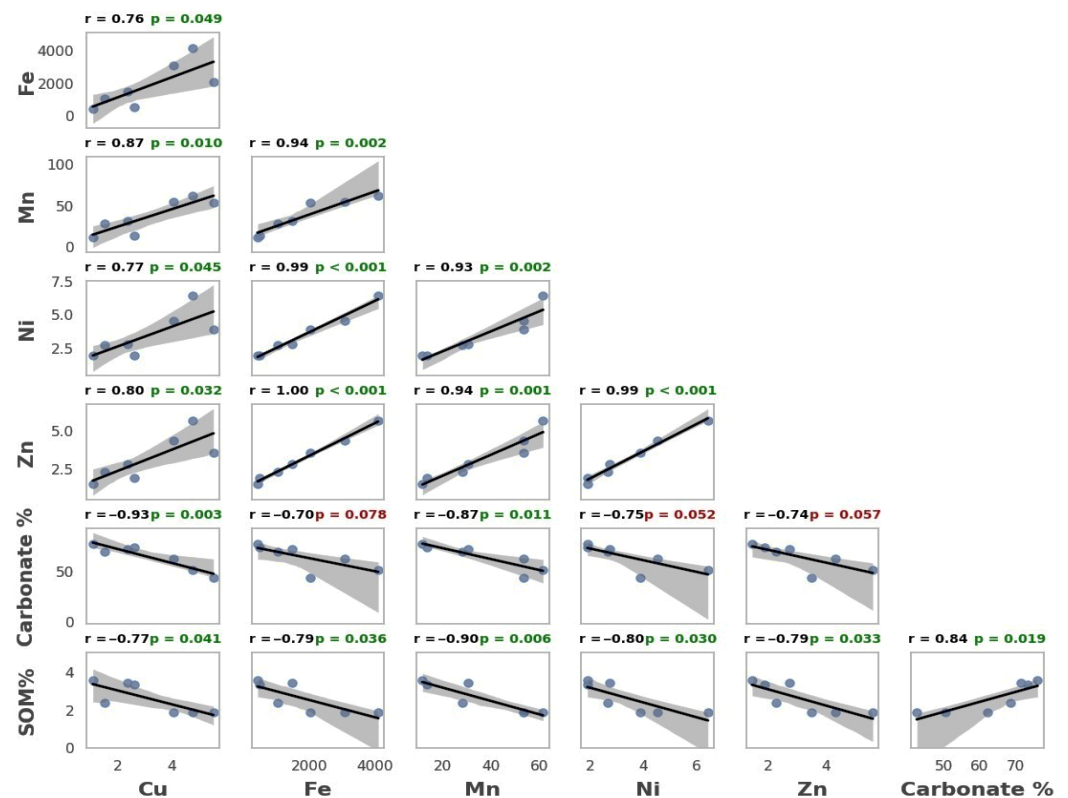


Figure 3. Scatterplot matrices for Rabigh showing the linear relationships (r values) between the metal concentrations (Cu, Zn, Ni, Mn, and Fe) and sediment properties (carbonate % and SOM %) in the Rabigh sediments. Green p -values indicate statistically significant correlations ($p < 0.05$), while red p -values show non-significant correlations.

The bivariate analysis supports these interpretations by showing that carbonate% and SOM% have a limited effect on metal accumulation. It also indicates that Cu behaves differently from the other HMs, consistent with the possibility of additional anthropogenic contributions (Figures 2 and 3). Overall, the agreement between the PCA and bivariate analyses provides additional support for the proposed interpretation of the geochemical behavior and potential sources of the studied HMs.

3.5. Human Health Risks

Human health risk assessment is an essential component of sustainable environmental management, as it evaluates the potential adverse health effects associated with exposure to environmental contaminants. An assessment of human health risks was performed using the U.S. EPA framework to analyze possible exposure routes, including ingestion, skin contact, and inhalation, for both adults and children [44]. Therefore, the chronic daily intake (CDI-HM), hazard quotient (HQ-HM), and hazard index (HI-HM) for non-carcinogenic risks, as well as cancer risk (CR-HM) and Lifetime Cancer Risk (LCR-HM) for carcinogenic risks, were applied to assess the potential health risks associated with heavy metal exposure in the investigated coastal sediments.

3.5.1. Non-Carcinogenic Risk

CDI-HM Values

Chronic daily intake (CDI-HM) was calculated to estimate potential long-term human health risks associated with exposure to HMs from sediments via ingestion, dermal absorption, and inhalation. The assessment was performed for both adults and children at Jeddah and Rabigh (Table 5). In Jeddah, ingestion (CDI_{ing}) represented the primary pathway

of exposure, where Fe showed the highest values (2.15×10^{-3} for adults; 2.01×10^{-2} for children), while Ni recorded the lowest values in adults (5.16×10^{-6}) and children (4.82×10^{-5}). In the dermal pathway (CDI_{derm}), Fe again dominated (8.58×10^{-6} for adults; 5.62×10^{-5} for children), whereas Ni contributed the lowest values (2.06×10^{-8} in adults; 1.35×10^{-7} in children). For inhalation (CDI_{inh}), Fe also ranked highest (3.16×10^{-13} in adults; 1.48×10^{-12} in children), while Ni was consistently lowest (7.59×10^{-16} and 3.54×10^{-15} , respectively). At Rabigh, a similar pattern was observed, with Fe showing the maximum CDI values across all pathways (2.47×10^{-3} for adults and 2.31×10^{-2} for children via ingestion; 9.86×10^{-6} and 6.46×10^{-5} via dermal absorption; 3.63×10^{-13} and 1.70×10^{-12} via inhalation). The lowest CDI-HM values were mainly attributed to Cu in the dermal and inhalation pathways (1.72×10^{-8} and 6.33×10^{-16} in adults; 1.13×10^{-7} and 2.96×10^{-15} in children) and to Zn in the ingestion pathway (4.27×10^{-6} in adults; 3.99×10^{-5} in children). Overall, the CDI-HM results revealed a consistent dominance of Fe across all pathways and age groups, highlighting its strong bioavailability in sediments. In contrast, Ni, Cu, and Zn generally had the lowest contributions, depending on the exposure pathway for Jeddah. These findings suggest that while Fe is the primary metal influencing chronic exposure, overall intake levels remain low and within safe limits.

Table 5. Chronic daily intake (CDI-HM) values through ingestion, dermal, and inhalation pathways for adults (Ad) and children (Ch) at Jeddah and Rabigh.

		CDI-HM				
Site		Ni	Cu	Fe	Zn	Mn
Jeddah						
CDI_{ing}	Ad	5.16×10^{-6}	5.37×10^{-6}	2.15×10^{-3}	6.15×10^{-6}	3.36×10^{-5}
	Ch	4.82×10^{-5}	5.01×10^{-5}	2.01×10^{-2}	5.74×10^{-5}	3.14×10^{-4}
CDI_{derm}	Ad	2.06×10^{-8}	2.14×10^{-8}	8.58×10^{-6}	2.45×10^{-8}	1.34×10^{-7}
	Ch	1.35×10^{-7}	1.40×10^{-7}	5.62×10^{-5}	1.61×10^{-7}	8.78×10^{-7}
CDI_{inh}	Ad	7.59×10^{-16}	7.89×10^{-16}	3.16×10^{-13}	9.04×10^{-16}	4.94×10^{-15}
	Ch	3.54×10^{-15}	3.68×10^{-15}	1.48×10^{-12}	4.22×10^{-15}	2.31×10^{-14}
Rabigh						
CDI_{ing}	Ad	4.69×10^{-6}	4.31×10^{-6}	2.47×10^{-3}	4.27×10^{-6}	4.92×10^{-5}
	Ch	4.38×10^{-5}	4.02×10^{-5}	2.31×10^{-2}	3.99×10^{-5}	4.59×10^{-4}
CDI_{derm}	Ad	1.87×10^{-8}	1.72×10^{-8}	9.86×10^{-6}	1.70×10^{-8}	1.96×10^{-7}
	Ch	1.23×10^{-7}	1.13×10^{-7}	6.46×10^{-5}	1.12×10^{-7}	1.29×10^{-6}
CDI_{inh}	Ad	6.90×10^{-16}	6.33×10^{-16}	3.63×10^{-13}	6.28×10^{-16}	7.23×10^{-15}
	Ch	3.22×10^{-15}	2.96×10^{-15}	1.70×10^{-12}	2.93×10^{-15}	3.38×10^{-14}

HQ-HM Values

The hazard quotient (HQ-HM) and total hazard quotient (THQ-HM) were utilized to assess the non-carcinogenic risks associated with HM exposure for both adults and children at the two locations through ingestion, dermal contact, and inhalation (Table 6). At Jeddah, ingestion was the predominant pathway, with Fe showing the highest HQ values (3.07×10^{-3} in adults; 2.87×10^{-2} in children), while Zn contributed the lowest values. For dermal exposure, Mn and Fe showed the highest HQ-HM values (2.39×10^{-5} and 2.04×10^{-5} in adults; 1.57×10^{-4} and 1.34×10^{-4} in children), whereas Cu was the lowest. Inhalation was negligible for all metals, with Mn showing the highest values and Zn the lowest. The THQ-HM results indicated that Fe was the main contributor to non-carcinogenic risk, particularly for children, where THQ-HM values reached 2.88×10^{-2} compared to 3.09×10^{-3} in adults. At Rabigh, ingestion similarly dominated, with Fe recording the highest HQs-HM values (3.53×10^{-3} in adults; 3.30×10^{-2} in children),

while Zn had the lowest contribution. For dermal absorption, Mn (3.51×10^{-5} in adults; 2.30×10^{-4} in children) and Fe (2.35×10^{-5} in adults; 1.54×10^{-4} in children) were the most significant, with Cu consistently showing the lowest values. Inhalation risks remained negligible, with Mn again showing the highest HQ-HM value. The results obtained from HQ-HM values confirmed that Fe and Mn were the major contributors, with children exhibiting higher risk levels (HQ-Fe: 3.31×10^{-2} ; HQ-Mn: 3.51×10^{-3}). Comparatively, Rabigh generally exhibited higher HQ-HM and THQ-HM values than Jeddah, particularly in children, reflecting their greater exposure to Fe and Mn. Across both sites, ingestion was the primary exposure pathway, dermal absorption contributed minimally, and inhalation posed almost no risk. Overall, Fe was identified as the main driver of non-carcinogenic risk, while Mn also played a significant role, especially in Rabigh. Children were consistently more vulnerable than adults, with higher THQ-HM values across metals, underscoring the importance of monitoring and managing risks to protect sensitive populations from exposure.

Table 6. The hazard quotient (HQ-HM) and hazard index (HI-HM) values of HMs through ingestion, dermal, and inhalation pathways for adults (Ad) and children (Ch) at Jeddah and Rabigh.

		HQ-HM					HI
		Ni	Cu	Fe	Zn	Mn	
Jeddah							
HQ _{ing}	Ad	2.58×10^{-4}	1.34×10^{-4}	3.07×10^{-3}	2.05×10^{-5}	2.40×10^{-4}	3.73×10^{-3}
	Ch	2.41×10^{-3}	1.25×10^{-3}	2.87×10^{-2}	1.91×10^{-4}	2.24×10^{-3}	3.48×10^{-2}
HQ _{derm}	Ad	2.58×10^{-5}	1.78×10^{-6}	2.04×10^{-5}	4.09×10^{-7}	2.39×10^{-5}	7.23×10^{-5}
	Ch	1.69×10^{-4}	1.17×10^{-5}	1.34×10^{-4}	2.68×10^{-6}	1.57×10^{-4}	4.74×10^{-4}
HQ _{inh}	Ad	5.42×10^{-11}	6.58×10^{-14}	4.52×10^{-13}	3.01×10^{-15}	9.88×10^{-11}	1.54×10^{-10}
	Ch	2.53×10^{-10}	3.07×10^{-13}	2.11×10^{-12}	1.41×10^{-14}	4.61×10^{-10}	7.17×10^{-10}
THQ-HM	Ad	2.84×10^{-4}	1.36×10^{-4}	3.09×10^{-3}	2.09×10^{-5}	2.64×10^{-4}	3.80×10^{-3}
	Ch	2.58×10^{-3}	1.26×10^{-3}	2.88×10^{-2}	1.94×10^{-4}	2.40×10^{-3}	3.52×10^{-2}
Rabigh							
HQ _{ing}	Ad	2.35×10^{-4}	1.08×10^{-4}	3.53×10^{-3}	1.42×10^{-5}	3.51×10^{-4}	4.24×10^{-3}
	Ch	2.19×10^{-3}	1.00×10^{-3}	3.30×10^{-2}	1.33×10^{-4}	3.28×10^{-3}	3.96×10^{-2}
HQ _{derm}	Ad	2.34×10^{-5}	1.43×10^{-7}	2.35×10^{-5}	2.84×10^{-7}	3.51×10^{-5}	8.24×10^{-5}
	Ch	1.53×10^{-4}	9.38×10^{-7}	1.54×10^{-4}	1.86×10^{-6}	2.30×10^{-4}	5.39×10^{-4}
HQ _{inh}	Ad	4.93×10^{-11}	5.28×10^{-14}	5.19×10^{-13}	2.09×10^{-15}	1.45×10^{-10}	1.95×10^{-10}
	Ch	2.30×10^{-10}	2.46×10^{-13}	2.42×10^{-12}	9.77×10^{-15}	6.75×10^{-10}	9.08×10^{-10}
THQ-HM	Ad	2.58×10^{-4}	1.08×10^{-4}	3.55×10^{-3}	1.45×10^{-5}	3.86×10^{-4}	4.32×10^{-3}
	Ch	2.34×10^{-3}	1.01×10^{-3}	3.31×10^{-2}	1.35×10^{-4}	3.51×10^{-3}	4.01×10^{-2}

HI-HM Values

The hazard index (HI-HM) is a widely used parameter to evaluate the potential non-carcinogenic health risks from exposure to HMs through ingestion, skin absorption, and inhalation. An HI value below one indicates that exposure levels are within the safe limit and are unlikely to pose health risks; in contrast, $\text{HI-HM} \geq 1$ suggests a potential health concern, particularly for sensitive groups such as children. The HI-HM values were calculated for adults and children at both study sites across the three exposure pathways: ingestion, dermal absorption, and inhalation (Table 6). At Jeddah, HI_{ing} was the dominant exposure pathway, with values of 3.73×10^{-3} for adults and 3.48×10^{-2} for children. Dermal absorption contributed marginally (7.23×10^{-5} in adults; 4.74×10^{-4} in children), and inhalation posed negligible risk (1.54×10^{-10} in adults; 7.17×10^{-10} in children). The total HI-HM values reached 3.80×10^{-3} for adults and 3.52×10^{-2} for children, both of which are well below the safety threshold ($\text{HI-HM} < 1$). At Rabigh, ingestion again represented the primary pathway, with HI_{ing} values of 4.24×10^{-3} in

adults and 3.96×10^{-2} in children. Dermal absorption was slightly higher in Rabigh than Jeddah (8.24×10^{-5} in adults; 5.39×10^{-4} in children), while inhalation risks remained negligible (1.95×10^{-10} in adults; 9.08×10^{-10} in children). The overall HI-Hm values were 4.32×10^{-3} in adults and 4.01×10^{-2} in children, which remain below the risk threshold. Comparative analysis indicates that Rabigh showed slightly higher HI-HM values than in Jeddah for both adults and children, though ingestion remained the dominant pathway at both sites. Compared to adults, children consistently showed higher HI-HM values, indicating their greater vulnerability to HM exposure. Overall, the results confirm that the non-carcinogenic health risks from sediment-associated HMs at both sites are within safe limits ($\text{HI-HM} < 1$). However, children remain more susceptible than adults, and Rabigh has a relatively greater potential risk, underscoring the significance of continuous monitoring and the implementation of preventive management strategies.

3.5.2. Carcinogenic Risk

CR-HM and LCR-HM Values

Cancer risk (CR-HM) indicates the likelihood of developing cancer over a lifetime due to exposure to carcinogenic contaminants via ingestion, dermal absorption, and inhalation. The lifetime cancer risk (LCR-HM) combines all these exposure routes to offer a comprehensive estimate. According to the USEPA, acceptable cancer risk ranges between 1.0×10^{-6} and 1.0×10^{-4} . In the present study (Figure 4A–D), ingestion was identified as the dominant pathway at both sites. At Jeddah, the average CR-HM via ingestion was 8.78×10^{-6} in adults and 8.19×10^{-5} in children, while dermal absorption contributed 4.64×10^{-7} in adults and 3.04×10^{-6} in children. Inhalation risks were negligible ($\leq 1.0 \times 10^{-15}$). Consequently, the average LCR-HM reached 9.24×10^{-6} in adults and 8.50×10^{-5} in children. Similarly, at Rabigh, ingestion accounted for the highest contribution, with average CR-HM values of 7.98×10^{-6} in adults and 7.45×10^{-5} in children. Dermal exposure was minor (4.21×10^{-7} in adults and 2.76×10^{-6} in children), and inhalation was again negligible. The corresponding average LCR-HM was 8.40×10^{-6} in adults and 7.72×10^{-5} in children. Overall, children consistently showed higher CR and LCR values than adults, emphasizing their greater vulnerability. Although Jeddah had slightly higher risks than Rabigh, all LCR-HM values remained within the USEPA's acceptable range (1.0×10^{-6} – 1.0×10^{-4}). These findings highlight the necessity for continuous monitoring to minimize long-term carcinogenic risks, particularly among sensitive populations such as children.

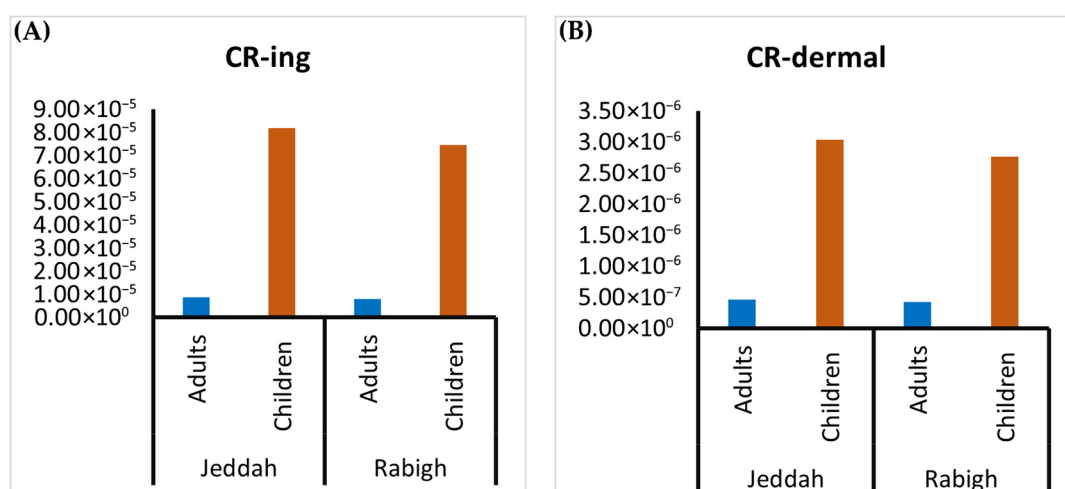


Figure 4. Cont.

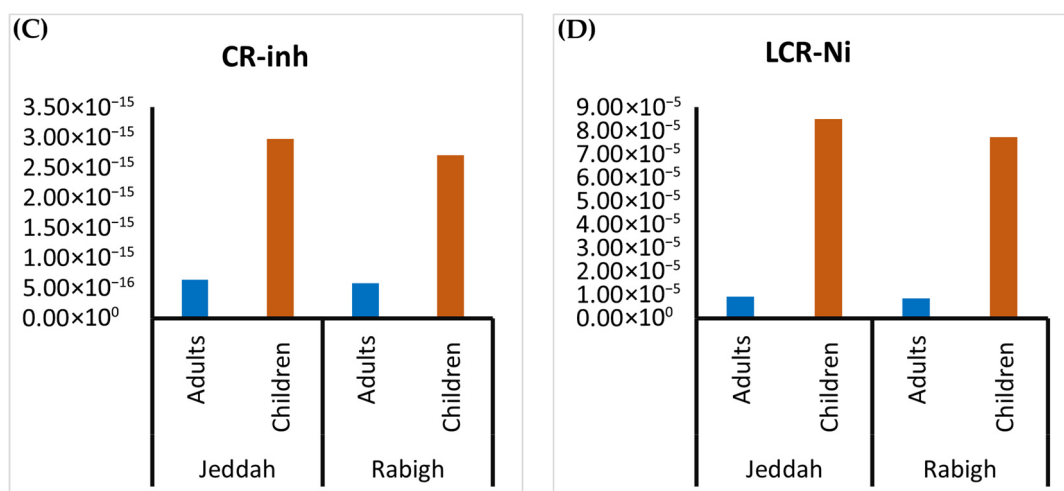


Figure 4. CR-Ni values of HMs through ingestion ((A) for CR-ing), dermal contact ((B) for CR-dermal), and inhalation ((C) for CR-inh) pathways and LCR-Ni values, (D) for adults and children at Jeddah and Rabigh.

Future studies are encouraged to incorporate seasonal sampling, offshore gradients, and sediment grain-size analysis to provide a more comprehensive understanding of the spatial and temporal distribution of heavy metals and their associated ecological and human health risks along the Saudi Arabian Red Sea coast.

4. Conclusions

This study provides a comprehensive assessment of heavy metal contamination, ecological risk, and human health risk in coastal sediments from Jeddah and Rabigh along the Saudi Arabian Red Sea. The findings contribute to the scientific basis for sustainable coastal environmental management and pollution prevention. The results show that Jeddah and Rabigh have relatively similar contamination levels and generally low pollution and ecological risk, based on their average HM concentrations and associated risk indices. EF values, supported by statistical analysis, revealed that although neither region is contaminated, Jeddah sediments are moderately enriched in Ni, Cu, and Zn. In contrast, Rabigh sediments are moderately enriched in Cu, suggesting a probable contribution from anthropogenic sources. The remaining HMs (Fe and Mn for Jeddah and Ni, Zn, Fe, and Mn for Rabigh) have likely been naturally transported to the sediments, as indicated by the statistical analysis and low-risk index values. Based on the statistical analysis, carbonate % and SOM % content appear to have minimal impacts on the distribution of HMs in sediments for both sites. Human health risk assessment identified ingestion as the primary exposure pathway, with non-carcinogenic risks remaining within safe limits for both adults, and children. Carcinogenic risk values (CR and LCR) were within the acceptable USEPA range, although they were consistently higher in children than in adults. Although both regions currently pose no environmental risk, the moderate enrichment of Cu in both regions, as well as Ni and Zn in Jeddah sediments, indicates localized concern. Furthermore, the potential health risks for children represent an additional concern. Therefore, further studies are encouraged to support and expand these findings through seasonal sampling, sediment grain-size analysis, and broader spatial coverage. Such investigations will provide a more comprehensive understanding of HM distribution and contribute to long-term environmental monitoring and evidence-based decision-making for the sustainable management of the Saudi Arabian Red Sea coastal environment.

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