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Research article

Health risk assessment and contamination of lead and cadmium levels in sediments of the northwestern Arabian Gulf coast

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ABSTRACT

This environmental assessment focuses on the coastal sediments of the Al-Khafji area in the Saudi Arabian Gulf, with an analysis of the human health risks posed by lead (Pb) and cadmium (Cd) contamination. Single and integrated indices were used to detect contamination and evaluate these metals' non-carcinogenic and carcinogenic impacts on adults and children through ingestion, dermal contact, and inhalation pathways. Sediment quality guidelines and contamination indices indicated the absence of significant contamination levels. The moderate contamination observed in scattered samples did not imply adverse biological effects due to the presence of these two metals in Al-Khafji sediments. The average values of the chronic daily intake (CDI) for both Pb and Cd were higher in children than adults across all three pathways, with ratios of 9.4, 4.7, and 4.7 folds, respectively. The hazard index (HI) values for Pb and Cd were below 1, confirming that the sediments of Al-Khafji are considered acceptable and safe in terms of these potentially toxic elements (PTEs). The average lifetime cancer risk (LCR) values for Pb and Cd were higher in children compared to adults, with ratios of 9.3 and 9.4 folds, respectively. However, all detected LCR levels do not represent a potential carcinogenic health hazard. Nevertheless, a regular monitoring program aimed at detecting early signals of environmental health depletion is recommended.

1. Introduction

The concentration of potentially toxic elements (PTEs) in marine sediments has shown a significant increase, reaching levels that are five to ten times higher than those recorded half a century or a century ago [1–3]. This rise vividly reflects the impact of human activities and the discharge of PTEs into marine environments over the recent decades. The combination of rapid industrialization and economic development has led to a rise in metal contamination within the aquatic systems. Various sources, including municipal and domestic sewage discharges, industrial effluents, agricultural activities, offshore and onshore petroleum operations, as well as metalliferous mining and smelting, have contributed to the release of PTEs into the marine environments [4–7]. Consequently, this increasing presence of PTEs in the marine ecosystems started to pose potential risks to both the environment and human health. It is imperative to undertake efforts aimed at mitigating and managing metal contamination in aquatic systems to ensure the sustainable

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development and preservation of these invaluable ecosystems. Among the non-essential PTEs including Cd, As, Cr, Hg, and Pb, their high toxicity persists even at extremely low concentrations. These elements are non-biodegradable and impose severe toxic effects on living organisms. The dissolved forms of these elements contaminate aquatic environments through water pollutants, subsequently entering the food chain and ultimately reaching humans. As a result, they cause significant harm to the cellular system and significantly increase the risk of cancer [8–10]. Industrial activities, sewage sludge or superphosphate fertilization, lead gasoline usage, lead mining, and smelting are some of the main sources responsible for the widespread release of cadmium and lead contamination into coastal sediments [11–13]. Both Pb and Cd, when present in the human body, can reach the brain, and potentially contribute to the development of Alzheimer's disease [14]. Additionally, cadmium tends to accumulate in the kidneys, and therefore, urinary cadmium levels are often used as biomarkers to assess cadmium levels in humans [15]. The toxic effects of cadmium are well-documented, particularly on the excretory system, leading to renal cancer. Moreover, other systems can also be affected, resulting in gastric cancer, breast cancer, and lung cancer. The outbreak of the itai-itai disease in Japan during the first half of the 1900s serves as a notable example of the health issues caused by soil cadmium contamination [11–17].

The Al-Khafji area is in the northeastern part of the Arabian Gulf, within the Eastern Province of Saudi Arabia. It falls within the boundaries of the Arabian Plate, which covers a significant portion of the Arabian Peninsula and neighboring regions in the Middle East. The geological composition of the Al-Khafji area primarily comprises sedimentary rocks that were deposited during the Mesozoic era, spanning from approximately 252 to 66 million years ago. These rocks consist mainly of sandstone, shale, limestone, and dolomite [18,19]. The sedimentary rocks in the Al-Khafji area were deposited in various environments, including shallow marine, lagoon, and deltaic settings. One noteworthy rock formation in the area is the Khafji Formation, which is a sedimentary sequence consisting of sandstone, shale, and limestone that originated during the Early Cretaceous period, around 145 million years ago. The Khafji Formation is significant due to its substantial reserves of oil and gas. Another notable feature in the Al-Khafji area is the presence of salt domes, which are underground structures containing extensive salt deposits. These salt domes hold economic importance as they can serve as traps for oil and gas reserves [19,20]. The coastal environment in the Khafji region features a long coastline extending along the Arabian Gulf, making it an important location from both environmental and economic standpoints. The coastal area of Khafji contains rich biodiversity, including many species of fish, coral reefs, and migratory birds. It is also home to a variety of marine and beach plants. The region relies heavily on maritime activities such as fishing and maritime trade. The presence of offshore oil fields further enhances its economic importance. However, the Khafji region faces many environmental challenges, including pollution resulting from industrial and oil activities, as well as climate changes that affect sea levels and biodiversity. The coastal region of Khafji is one of the vital areas that requires constant attention to maintain its environmental balance and ensure the sustainability of its natural resources.

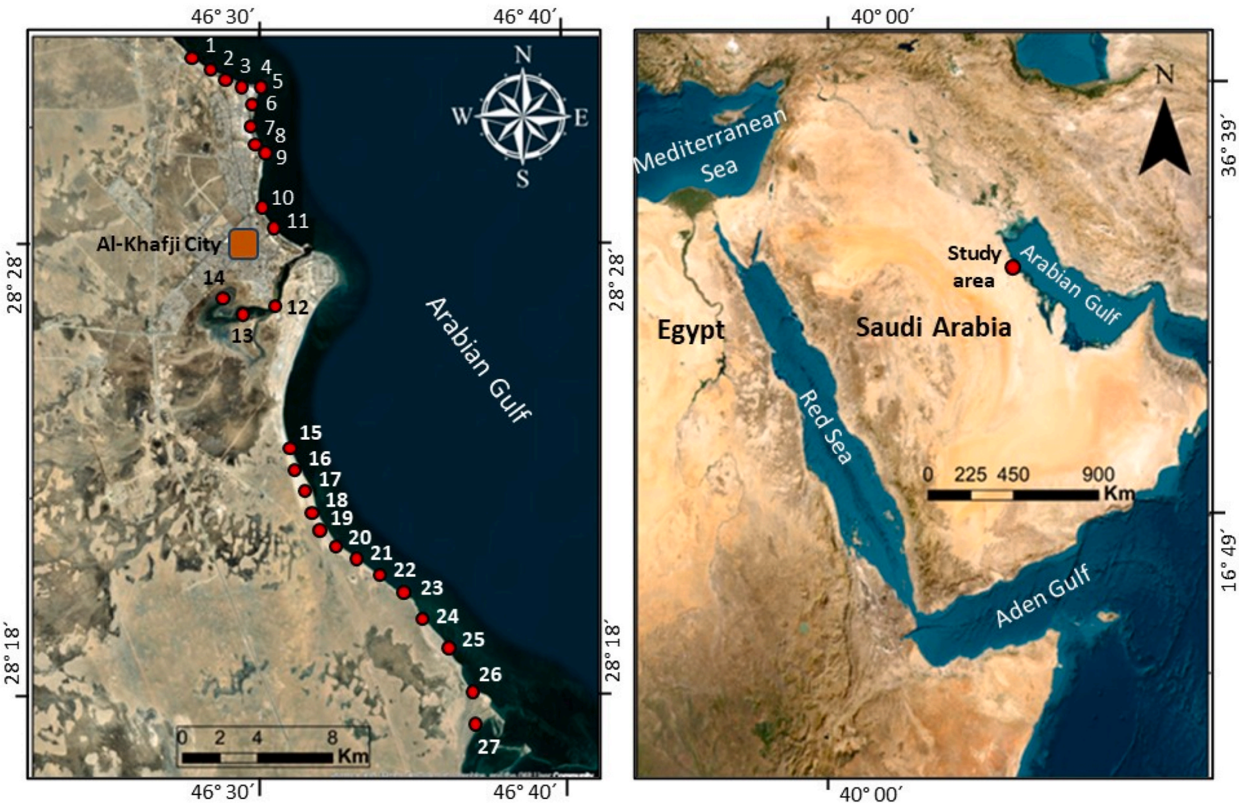

Fig. 1. Study area and sampling sites.

Over the past twenty years, there has been a notable increase in environmental research focused on the Saudi Arabian Gulf [21–24]. Many of these studies have aimed to assess the levels of PTEs contamination in sediment and to compare them to reference levels representing natural conditions, using several indices such as the enrichment factor, contamination factor, and pollution load index. More recently, studies have also started to investigate the adverse effects of PTEs on human health, revealing concerning levels of hazards [10,24,25].

The objective of this study is two folds. First, it aims to determine the levels, spatial distribution, and environmental risks associated with Cd and lead Pb in beach sediments in the Al-Khafji area of the Arabian Gulf. Second, it seeks to assess the carcinogenic and non-carcinogenic health risks posed to both adults and children through ingestion, dermal contact, and inhalation pathways. By examining these aspects, this study aims to provide valuable insights into the contamination status and potential health risks associated with Cd and Pb in the coastal sediments of the Al-Khafji area.

2. Material and methods

2.1. Study area and sampling

The city of Al-Khafji in Saudi Arabia is located on the northeastern side of the Arabian Gulf. The area encompasses a combination of natural and human-influenced landscapes, including residential and industrial zones, as well as oil and desalinization plants. The natural environment of Al-Khafji includes scattered evaporitic-saline deposits linked to the Sabkhas supratidal formations [26]. The coastal sediments in the region are composed of both terrigenous and biogenic components. The terrigenous fraction mainly consists of quartz grains and rock fragments, resulting from the erosion of Quaternary deposits in the hinterland. The biogenic portion includes various organisms such as foraminifers, bivalves, gastropods, echinoids, ostracods, corals, and algae. These biogenic components are transported from offshore areas to the beach during storms and tides [23].

For this study, three sediment samples per site were taken from 27 sites along the coast of Al-Khafji. The collection sites were geographically located between latitude N48° 27′ 57.31″ and N48° 37′ 26.9″, as well as longitude E28° 30′ 12.82″ and E28° 11′ 42.5" (Fig. 1). The sediment samples were collected from the upper 25 cm of the tidal level and stored in plastic bags. In the laboratory, the samples were dried in a drying oven at a temperature of 115 °C until a constant mass was reached. The fine fraction of the sediments was subsequently separated using a 63 μm mesh sieve for chemical analysis.

2.2. Analytical and statistical methods

The concentrations of Cd and Pb in each sediment sample were measured by extracting 1 g of powder from each sample and analyzed it using ICP-MS (NexION 300D, PerkinElmer, USA) at the laboratory of King Saud University. The analysis followed the protocols set by the US Environmental Protection Agency (EPA/CE-81-1 Protocol) to ensure compliance with international safety standards. To ensure the accuracy of the measurements, a blank method was employed, and some samples were repeated. Several quality assurance and quality control (QA/QC) measures are employed to ensure the accuracy and reliability of the results. These measures include instrument calibration, blank analysis to detect contamination, replicate analysis to verify precision, and the use of quality control samples to monitor both accuracy and precision. These procedures guarantee that the results are accurate, precise, and dependable.

Multiple studies around the world have demonstrated the importance of measuring single and integrated environmental indices to monitor environmental pollution in marine sediments. Therefore, these environmental indices were evaluated in the current study to assess potential pollution in the sediments of the coast of the Khafji region. To assess the contamination of Cd and Pb in the study area, five pollution indices were utilized: the pollution index (PI) used to assess the level of pollution in coastal sediments, and this allowed the comparison of different sampling locations or tracking changes in pollution levels over time. The formula for pollution index is PI= $(Cx)_{sample}/(Cb)_{background}$, where Cx_{sample} is the concentration of metal in the sample, and $Cb_{background}$ is the concentration of metal in the Earth's crust [27,28].

The Sediment Pollution Index (SPI) indicates the contamination status of sediments based on the concentrations of metals in sediments according to permissible levels set by Ref. [29]. The SPI is calculated using a formula: SPI = Ms/Mm, where Ms is the concentration of metal in the sample and Mm is the permissible levels of metals in sediments [25,30].

The Ecological Risk Index (E_r^i) is a multidimensional index that assesses the potential ecological risks associated with contaminants in coastal sediments. The E_r^i considers factors such as the concentration of contaminants, their toxicity, and the sensitivity of the ecosystem to be assessed. The E_r^i is calculated by: $E_r^i = T_r^i$ * Cf, where Ti is the toxic response factor and Cf is the monomial concentration factor [31,32].

Contamination Degree (C_{deg}) in coastal sediments refers to the extent or level of contamination present in the sediments along the coastline. It is a measurement used to assess the pollution or presence of harmful substances in the sediment, which can have significant environmental and ecological implications. The C_{deg} is calculated using the formula $C_{deg} = \sum_{i=1}^{n} Cf$, where Cf is the contamination factors [7,33].

The Pollution Load Index (PLI) provides a quantitative measurement of the overall contamination status of an area. The formula for calculating the PLI is as follows: PLI= $(CF1 \times CF2 \times CF3 \times \ldots CFn)^{1/n}$, where CF is the contamination factor and (n) is the number of metals. The PLI is a useful tool for environmental monitoring and management, as it allows for the assessment of pollution levels in coastal sediments over time and the identification of areas that may require remediation or further investigation [30,32].

Furthermore, the study area conducted an analysis of Cd and Pb to assess their carcinogenic and non-carcinogenic effects on both adults and children. This evaluation took into consideration ingestion, dermal contact, and inhalation pathways. Chronic Daily Intake (CDI) is a commonly used term in toxicology and risk assessment to quantify the potential risks associated with long-term exposure to a particular substance. CDI estimates the daily amount of a substance that an individual or population may ingest, inhale, or come into dermal contact with over an extended period without causing adverse health effects. The CDI is calculated using the following formulas:

For dermal exposure: $CDI_{der} = (Csediment.\ SA.\ AF.\ ABS.\ EF.ED\ /\ BW.\ AT)^{CF}$

For ingestion: $CDI_{Ing} = (Csediment.\ R_{Ing}.\ EF.\ ED\ /\ BW.\ AT)^{CF}$; and

For inhalation: $CDI_{Inh} = (Csediment.\ EF.\ ET.ED\ /\ PEF.\ BW.\ AT)$,

In these formulas, Csediment represents the concentration in soil (mg/kg); SA is the exposed skin area (cm^2); AF is adherence factor (mg. cm^2); ABS is the dermal absorption fraction; EF is the exposure frequency (d/y); ED is the exposure duration (adult or children); BW is the body weight of the exposed individual (kg); AT is the averaging time (days); R. is the rate of ingestion (mg/day); ET is the exposure duration (h/d); and PEF is the particle emission factor (Kg^{-1}), [34,35].

The Hazard Index (HI) is a measurement used to assess the potential health risks associated with exposure to multiple chemicals, particularly in the context of carcinogens. It is a tool commonly used in risk assessment to estimate the cumulative impact of exposure to multiple carcinogens and guide the decision-making process regarding exposure reduction strategies. The HI is calculated as follows: $HI = \sum HQ = HQ_{ing} + HQ_{der} + HQ_{inh}$, where HQ is used for the non-carcinogenic risk assessment of toxic metals [36,37].

The term "Total Cancer Risk" is often referred to as Lifetime Cancer Risk (LCR), which estimates an individual's likelihood of developing cancer over their lifetime. The formula for calculating LCR is as follows: $LCR = \Sigma\ CR_{ing} + CR_{der} + CR_{inh}$, where CR represents the cancer risk for metal [29,37].

3. Results and discussion

3.1. Distribution and contamination assessment

The average concentrations of Cd and Pb (dry weight) were 0.39 μg/g and 1.80 μg/g, respectively (Table 1). The lowest levels of Cd (0.18 μg/g) and Pb (0.54 μg/g) were found in samples 5 and 6, located in the northern part of the study area. In contrast, samples 23

Table 1
Concentration (μg/g) and pollution indices calculated for Cd and Pb in the Al-Khafji coastal sediment.

S.N.	Longitude	Latitude	Cd	Pb	SPI		PI		ERI		Cdeg	PLI
					Pb	Cd	Pb	Cd	Pb	Cd		
1	48° 27′ 57″	28° 30′ 12″	0.53	1.87	0.187	0.005	0.094	1.767	0.468	53	1.860	0.406
2	48° 28′ 29″	28° 30′ 0.5″	0.42	2.08	0.208	0.004	0.104	1.400	0.520	42	1.504	0.382
3	48° 29′ 5″	28° 29′ 49″	0.30	2.31	0.231	0.003	0.116	1.000	0.578	30	1.116	0.340
4	48° 29′ 34″	28° 29′ 42″	0.44	1.88	0.188	0.004	0.094	1.467	0.470	44	1.561	0.371
5	48° 29′ 53″	28° 29′ 33″	0.18	1.35	0.135	0.002	0.068	0.600	0.338	18	0.668	0.201
6	48° 29′ 48″	28° 28′ 54″	0.22	0.54	0.054	0.002	0.027	0.733	0.135	22	0.760	0.141
7	48° 29′ 46″	28° 28′ 27″	0.32	0.65	0.065	0.003	0.033	1.067	0.163	32	1.099	0.186
8	48° 29′ 49″	28° 28′ 14″	0.38	1.06	0.106	0.004	0.053	1.267	0.265	38	1.320	0.259
9	48° 29′ 58″	28° 28′ 4″	0.28	1.65	0.165	0.003	0.083	0.933	0.413	28	1.016	0.278
10	48° 29′ 56″	28° 26′ 29″	0.50	1.98	0.198	0.005	0.099	1.667	0.495	50	1.766	0.406
11	48° 30′ 2″	28° 26′ 10″	0.36	2.24	0.224	0.004	0.112	1.200	0.560	36	1.312	0.367
12	48° 30′ 12″	28° 23′ 22″	0.48	2.02	0.202	0.005	0.101	1.600	0.505	48	1.701	0.402
13	48° 29′ 38″	28° 23′ 27″	0.40	2.44	0.244	0.004	0.122	1.333	0.610	40	1.455	0.403
14	48° 28′ 32″	28° 23′ 28″	0.51	2.70	0.270	0.005	0.135	1.700	0.675	51	1.835	0.479
15	48° 30′ 43″	28° 19′ 49″	0.36	1.78	0.178	0.004	0.089	1.200	0.445	36	1.289	0.327
16	48° 31′ 27″	28° 18′ 41″	0.39	1.98	0.198	0.004	0.099	1.300	0.495	39	1.399	0.359
17	48° 31′ 41″	28° 18′ 18″	0.42	2.12	0.212	0.004	0.106	1.400	0.530	42	1.506	0.385
18	48° 31′ 52″	28° 17′ 45″	0.30	1.62	0.162	0.003	0.081	1.000	0.405	30	1.081	0.285
19	48° 32′ 5″	28° 17′ 20″	0.45	2.68	0.268	0.005	0.134	1.500	0.670	45	1.634	0.448
20	48° 32′ 24″	28° 16′ 55″	0.52	1.52	0.152	0.005	0.076	1.733	0.380	52	1.809	0.363
21	48° 33′ 4″	28° 16′ 23″	0.30	2.08	0.208	0.003	0.104	1.000	0.520	30	1.104	0.323
22	48° 34′ 4″	28° 15′ 44″	0.32	1.46	0.146	0.003	0.073	1.067	0.365	32	1.140	0.279
23	48° 34′ 37″	28° 15′ 20″	0.54	2.14	0.214	0.005	0.107	1.800	0.535	54	1.907	0.439
24	48° 35′ 18″	28° 14′ 41″	0.33	2.06	0.206	0.003	0.103	1.100	0.515	33	1.203	0.337
25	48° 35′ 57″	28° 14′ 6″	0.40	1.87	0.187	0.004	0.094	1.333	0.468	40	1.427	0.353
26	48° 37′ 8″	28° 12′ 33″	0.51	1.54	0.154	0.005	0.077	1.700	0.385	51	1.777	0.362
27	48° 37′ 26″	28° 11′ 42″	0.37	1.31	0.131	0.004	0.066	1.233	0.328	37	1.299	0.284
Min.			0.18	0.54	0.054	0.002	0.027	0.600	0.135	18	0.668	0.141
Max.			0.54	2.70	0.270	0.005	0.135	1.800	0.675	54	1.907	0.479
Aver.			0.39	1.80	0.180	0.004	0.090	1.290	0.450	38.8	1.380	0.340

and 14, located in the southern and central parts of the area, respectively, showed the highest concentrations for both elements (0.54 μg/g and 2.7 μg/g for Cd and Pb, respectively) (Fig. 2). According to the findings of [26], the increased concentration of Pb in sample 14 can be attributed to two factors: landfilling from new construction activities and the discharge of industrial sewage from brick factories in the area. These activities likely contributed to the higher levels of Pb observed in that specific sample.

A comparison of the average Cd and Pb values in the study area with those from various other coastal regions is provided in Table 2. The average value of Pb (1.80 μg/g) was lower than those observed along the Red Sea and Mediterranean coast [38,39], Arabian Gulf coast [40], Gokcekaya Dam Lake in Turkey [41], the background levels in the Earth's crust [42], and shale deposits [27]. On the other hand, the average Cd value (0.39 μg/g) was lower than the levels recorded in Choghakhor Wetland, Iran [43], Red Sea, Egypt [38], Duba area, Red Sea coast [44], and the Mediterranean Sea, specifically Rosetta beach in Egypt [39]. However, it was higher than the average values found in Arabian Gulf coast [40], Gokcekaya Dam Lake, Turkey [41], the background levels in the Earth's crust [42], and shale deposits [27].

The average concentrations of Cd (0.39 μg/g) and Pb (1.80 μg/g) detected in the sediments of Al-Khafji were found to be below the threshold effects level (TEL) values for these metals, which are 0.68 μg/g and 30.2 μg/g, respectively. These TEL values are commonly used as sediment quality guidelines (SQGs) to assess whether the presence of metals in sediments poses a potential threat to aquatic ecosystems and can result in adverse biological impacts. Since the average concentrations of Cd and Pb in Al-Khafji sediments fall below their respective TEL values, it indicates that the presence of these metals is not expected to cause adverse biological effects in the studied aquatic ecosystem [47–49]. This suggests that the levels of Cd and Pb in the sediments of Al-Khafji are within acceptable ranges and do not pose a significant risk to the ecosystem.

PI, estimating the degree of single metal contamination in sediments [4], showed average values of 0.09 for Pb and 1.29 for Cd, respectively indicating no pollution with Pb (below the pollution threshold of 1.0) and low pollution with Cd (Table 3), whereas SPI indicated low contamination levels both for Pb (average: 0.18) and Cd (average: 0.004). The average values of ERI for Pb and Cd were 0.45 and 38.79, respectively, suggesting no-to-low risk for these two metals in the study area. However, some individual samples (e.g., S1, S4, S10, S12, S14, S17, S19, S20, S23, S26) showed moderate risk [23,50]. Similarly, the average value of C_{deg} (1.38), indicated a low degree of contamination for the investigated sediment. The average value of PLI, applied to evaluate the combined effect of metals on coastal sediments in the study area [51,52], resulted 0.34, indicating no pollution problem (PLI <1).

Even without immediate effects, the long-term ecological impacts of Pb and Cd contamination can be severe. These metals persist for decades, accumulating in soil, water, and organisms. This bioaccumulation can lead to toxic levels in plants and animals, disrupting ecosystems. Pb and Cd can inhibit plant growth and cause neurological, reproductive, and kidney damage in animals [53]. As top predators consume contaminated prey, the effects magnify, leading to population declines and biodiversity loss [54]. Disrupted soil microbes impair nutrient cycling and soil fertility, destabilizing ecosystems [55].

The sources of Pb and Cd contamination in the Al-Khafji area can be attributed to both natural and anthropogenic factors. Natural sources include geological weathering of rocks and soils that contain these metals, although their contribution to environmental levels is typically limited. Anthropogenic sources, however, play a significant role, particularly from industrial activities such as metal smelting, mining, battery manufacturing, and improper disposal of electronic waste. In urban areas, vehicular emissions from leaded gasoline (though phased out in many places) and cadmium in brake linings contribute to atmospheric deposition. Agricultural practices, including the use of phosphate fertilizers containing cadmium, can also lead to soil contamination. Identifying and mitigating these anthropogenic sources through stricter regulations, cleaner production technologies, and improved waste management practices are crucial steps in reducing Pb and Cd contamination and protecting environmental and public health in the region.

3.2. Non-carcinogenic health risk assessment

The chronic daily intake (CDI) of Pb and Cd, has been done as first step in non-carcinogenic and carcinogenic assessment of these PTEs on human health. These values were calculated considering the ingestion, dermal, and inhalation pathways based on the beach sediments of the Al-Khafji area (Table 4). The CDI values for Pb and Cd for adults and children are presented in Table 5. For adults, the maximum and minimum CDI values for Pb through the three pathways were as follows: ingestion (3.70E-06 - 7.40E-07), dermal

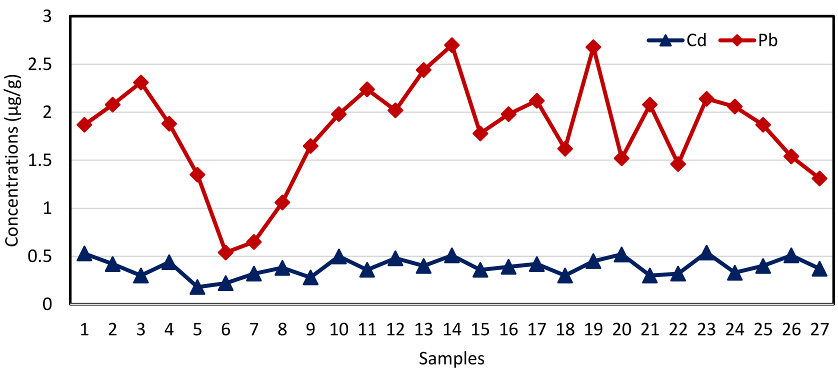

Fig. 2. Distribution of Pb and Cd in the coastal sediments along the Al-Khafji area.

Table 2
Comparison between Pb and Cd (ug/g) in the present area and other worldwide sites.

Location	Cd	Pb	Reference
Al-Khafji area, Saudi Arabian Gulf	0.39	1.8	Present Study
Red Sea Coast, Egypt	1.38	30.4	[38]
Aqeer coastline, Arabian Gulf	3.88	0.07	[45]
Red Sea coast, Saudi Arabia	3.50	0.18	[44]
Arabian Gulf, Saudi Arabia	0.23	5.36	[40]
Choghakhor Wetland, Iran	1.10	1.82	[43]
Gokcekaya Dam Lake, Turkey	0.007	74.4	[41]
Mediterranean Sea, Egypt	28.88	384.7	[39]
Background shale	0.30	20	[27]
Background continental crust	0.20	12.5	[42]
Sediment quality guidelines (TEL)	0.68	30.20	[46]

TEL is the threshold effects level.

Table 3
Thresholds values for environmental indices.

PI	Pollution	*SPI*	Contamination
<1	No	≤1	Low
1–2	Low	1 l 3	Moderate
2–3	Moderate	>3)	High
3–5	High		
PLI	Pollution	*Cdeg*	Pollution
≤1	unpolluted	<8	Low
1–3	moderate	8–16	Moderate
3–5	high	16–32	Considerable
>5	very high	>32	High
ERI	Ecological risk		
<40	low ecological risk		
40–80	moderate ecological risk		
80–160	moderate to high ecological risk		
160–320	high ecological risk		
≥320	very high ecological risk		

contact (1.48E-08 - 2.95E-09), and inhalation (6.53E-16 - 1.31E-16). Similarly, for Cd, the maximum and minimum CDI values were ingestion (7.40E-07 - 2.47E-07), dermal contact (2.95E-09 - 9.84E-10), and inhalation (1.31E-16 - 4.35E-17). For children, the maximum and minimum CDI values for Pb were as follows: ingestion (3.45E-05 - 6.90E-06), dermal contact (6.89E-08 - 1.38E-08), and inhalation (3.05E-15 - 6.09E-16). Similarly, for Cd, the maximum and minimum CDI values were ingestion (6.90E-06 - 2.30E-06), dermal contact (1.38E-08 - 4.59E-09), and inhalation (6.09E-16 - 2.03E-16). In general, the average CDI values for both Pb and Cd were significantly higher in children compared to adults, being 9.4-fold, 4.7-fold, and 4.7-fold in the three pathways, respectively. The chronic daily intake of Pb and Cd is especially concerning in children, posing significant public health risks. Children are more susceptible due to their developing nervous systems and higher absorption rates. Chronic Pb exposure can cause cognitive impairments, behavioral issues, and decreased IQ even at low levels [56]. Cd exposure can lead to kidney damage, skeletal abnormalities, and impaired growth [57]. The heightened vulnerability in children underscores the need for stringent regulations and public health interventions to prevent long-term developmental and health issues.

The Hazard Index (HI) assesses potential health risks from exposure to toxic substances like Pb and Cd. It is calculated by summing the ratios of estimated exposure levels of each contaminant to its reference dose (RfD), the maximum acceptable oral dose of a toxic substance. An HI value greater than 1 indicates that combined exposure to multiple contaminants exceeds safe levels, suggesting potential adverse health effects. For Pb and Cd, HI values over 1 imply significant health risks, including neurological, renal, and skeletal damage, particularly for vulnerable populations like children and pregnant women. Therefore, HI values are critical indicators for public health authorities to implement risk management strategies and minimize exposure to these hazardous substances. In the study area the maximum and minimum HI values for Pb in adults and children were 1.08E-03/2.16E-04 and 9.86E-03/1.97E-03, respectively, and for Cd, the corresponding HI values were 7.56E-03 - 2.52E-03 and 6.90E-02 - 2.30E-02. The average HI values for Pb and Cd in children exceeded those in adults by 9.3-fold. Notably, the highest HI values were observed in samples 14 and 6 for Pb, and samples 23 and 5 for Cd (Fig. 3). It is important to note that the HI values for both Pb and Cd remained below 1, indicating that the sediments of Al-Khafji coast are deemed acceptable and safe in terms of these PTEs [58].

3.3. Carcinogenic health risk assessment

The evaluation of carcinogenic health risk due to Pb and Cd concentrations in Al-Khafji beach sediments, assessed through

Table 4
Chronic daily intake (CDI) values for both adults and children through ingestion, dermal and inhalation pathways in the beach sediments of Al-Khafji area.

SN	Der/adults		Der/children		Ing/adults		Ing/children		Inh/adults		Inh/children	
	Pb	Cd	Pb	Cd	Pb	Cd	Pb	Cd	Pb	Cd	Pb	Cd
1	1.02E-08	2.90E-09	4.77E-08	1.35E-08	2.56E-06	7.26E-07	2.39E-05	6.78E-06	4.52E-16	1.28E-16	2.11E-15	5.98E-16
2	1.14E-08	2.30E-09	5.31E-08	1.07E-08	2.85E-06	5.75E-07	2.66E-05	5.37E-06	5.03E-16	1.02E-16	2.35E-15	4.74E-16
3	1.26E-08	1.64E-09	5.89E-08	7.65E-09	3.16E-06	4.11E-07	2.95E-05	3.84E-06	5.58E-16	7.25E-17	2.61E-15	3.38E-16
4	1.03E-08	2.40E-09	4.80E-08	1.12E-08	2.58E-06	6.03E-07	2.40E-05	5.63E-06	4.54E-16	1.06E-16	2.12E-15	4.96E-16
5	7.38E-09	9.84E-10	3.44E-08	4.59E-09	1.85E-06	2.47E-07	1.73E-05	2.30E-06	3.26E-16	4.35E-17	1.52E-15	2.03E-16
6	2.95E-09	1.20E-09	1.38E-08	5.61E-09	7.40E-07	3.01E-07	6.90E-06	2.81E-06	1.31E-16	5.32E-17	6.09E-16	2.48E-16
7	3.55E-09	1.75E-09	1.66E-08	8.16E-09	8.90E-07	4.38E-07	8.31E-06	4.09E-06	1.57E-16	7.74E-17	7.33E-16	3.61E-16
8	5.79E-09	2.08E-09	2.70E-08	9.69E-09	1.45E-06	5.21E-07	1.36E-05	4.86E-06	2.56E-16	9.19E-17	1.20E-15	4.29E-16
9	9.02E-09	1.53E-09	4.21E-08	7.14E-09	2.26E-06	3.84E-07	2.11E-05	3.58E-06	3.99E-16	6.77E-17	1.86E-15	3.16E-16
10	1.08E-08	2.73E-09	5.05E-08	1.28E-08	2.71E-06	6.85E-07	2.53E-05	6.39E-06	4.79E-16	1.21E-16	2.23E-15	5.64E-16
11	1.22E-08	1.97E-09	5.71E-08	9.18E-09	3.07E-06	4.93E-07	2.86E-05	4.60E-06	5.41E-16	8.70E-17	2.53E-15	4.06E-16
12	1.10E-08	2.62E-09	5.15E-08	1.22E-08	2.77E-06	6.58E-07	2.58E-05	6.14E-06	4.88E-16	1.16E-16	2.28E-15	5.41E-16
13	1.33E-08	2.19E-09	6.22E-08	1.02E-08	3.34E-06	5.48E-07	3.12E-05	5.11E-06	5.90E-16	9.67E-17	2.75E-15	4.51E-16
14	1.48E-08	2.79E-09	6.89E-08	1.30E-08	3.70E-06	6.99E-07	3.45E-05	6.52E-06	6.53E-16	1.23E-16	3.05E-15	5.75E-16
15	9.73E-09	1.97E-09	4.54E-08	9.18E-09	2.44E-06	4.93E-07	2.28E-05	4.60E-06	4.30E-16	8.70E-17	2.01E-15	4.06E-16
16	1.08E-08	2.13E-09	5.05E-08	9.95E-09	2.71E-06	5.34E-07	2.53E-05	4.99E-06	4.79E-16	9.43E-17	2.23E-15	4.40E-16
17	1.16E-08	2.30E-09	5.41E-08	1.07E-08	2.90E-06	5.75E-07	2.71E-05	5.37E-06	5.12E-16	1.02E-16	2.39E-15	4.74E-16
18	8.85E-09	1.64E-09	4.13E-08	7.65E-09	2.22E-06	4.11E-07	2.07E-05	3.84E-06	3.92E-16	7.25E-17	1.83E-15	3.38E-16
19	1.46E-08	2.46E-09	6.84E-08	1.15E-08	3.67E-06	6.16E-07	3.43E-05	5.75E-06	6.48E-16	1.09E-16	3.02E-15	5.08E-16
20	8.31E-09	2.84E-09	3.88E-08	1.33E-08	2.08E-06	7.12E-07	1.94E-05	6.65E-06	3.67E-16	1.26E-16	1.71E-15	5.87E-16
21	1.14E-08	1.64E-09	5.31E-08	7.65E-09	2.85E-06	4.11E-07	2.66E-05	3.84E-06	5.03E-16	7.25E-17	2.35E-15	3.38E-16
22	7.98E-09	1.75E-09	3.72E-08	8.16E-09	0.000002	4.38E-07	1.87E-05	4.09E-06	3.53E-16	7.74E-17	1.65E-15	3.61E-16
23	1.17E-08	2.95E-09	5.46E-08	1.38E-08	2.93E-06	7.40E-07	2.74E-05	6.90E-06	5.17E-16	1.31E-16	2.41E-15	6.09E-16
24	1.13E-08	1.80E-09	5.25E-08	8.42E-09	2.82E-06	4.52E-07	2.63E-05	4.22E-06	4.98E-16	7.98E-17	2.32E-15	3.72E-16
25	1.02E-08	2.19E-09	4.77E-08	1.02E-08	2.56E-06	5.48E-07	2.39E-05	5.11E-06	4.52E-16	9.67E-17	2.11E-15	4.51E-16
26	8.42E-09	2.79E-09	3.93E-08	1.30E-08	2.11E-06	6.99E-07	1.97E-05	6.52E-06	3.72E-16	1.23E-16	1.74E-15	5.75E-16
27	7.16E-09	2.02E-09	3.34E-08	9.44E-09	1.79E-06	5.07E-07	1.67E-05	4.73E-06	3.17E-16	8.94E-17	1.48E-15	4.17E-16

Table 5
The average values of chronic daily intake (CDI), hazard quotient (HQ) and hazard index (HI) for non-carcinogenic risk in adults and children of the Al-Khafji sediments.

PTEs	**Adults**						
	CDI $_{Ing.}$	CDI $_{Dermal}$	CDI $_{Inhal.}$	HQ $_{Ing.}$	HQ $_{Demal}$	HQ $_{Inhal.}$	HI
Pb	2.46E-06	9.83E-09	4.35E-16	7.04E-04	2.81E-06	1.24E-13	7.07E-04
Cd	5.31E-07	2.12E-09	9.38E-17	5.31E-03	2.12E-05	9.38E-13	5.33E-03
PTEs	**Children**						
	CDI $_{Ing.}$	CDI $_{Dermal}$	CDI $_{Inhal.}$	HQ $_{Ing.}$	HQ $_{Demal}$	HQ $_{Inhal.}$	HI
Pb	2.30E-05	4.59E-08	2.03E-15	6.57E-03	1.31E-05	5.80E-13	6.58E-03
Cd	4.96E-06	9.90E-09	4.38E-16	4.96E-02	9.90E-05	4.38E-12	4.97E-02

ingestion, dermal and inhalation pathways in adults and children using CR and LCR, is summarized in Table 6. The maximum and minimum CR values for Pb in adults for the three pathways were 3.14E-0 -/6.29E-09, 1.25E-10 - 2.51E-11, and 5.55E-18 - 1.11E-18, respectively; and for Cd were 4.66E-06 - 1.55E-06, 1.86E-08 - 6.20E-09, and 8.22E-16 - 2.74E-16, respectively. Similarly, the maximum and minimum CR values for Pb in children were 2.93E-07 - 5.87E-08, 5.85E-10 - 1.17E-10, and 2.59E-17 - 5.18E-18, respectively; and for Cd were 4.35E-05 - 1.45E-05, 8.68E-08 - 2.89E-08, and 3.84E-15 - 1.28E-15, respectively. Average CR values of both Pb and Cd for children were higher than adults in the three pathways by 9.3 folds, 4.7 folds, and 4.7 folds, respectively.

The methodology for assessing average lifetime cancer risk (LCR) involves calculating the probability of developing cancer over a lifetime due to exposure to carcinogenic substances like Pb and Cd. This is done using risk assessment models that consider several key factors: contaminant concentration, frequency and duration of exposure, ingestion or inhalation rates, and the toxicity of the substances. The LCR is calculated by multiplying the contaminant's concentration by its cancer slope factor (CSF), which quantifies the risk per unit of exposure. Key assumptions in these models include average body weight, an exposure duration typically 70 years, and standard exposure scenarios (e.g., residential or occupational). The models assume a linear, no-threshold dose-response relationship for carcinogens, meaning any exposure level carries some cancer risk. The maximum and minimum LCR values for Pb in adults and children were 3.21E-08 - 6.43E-09 and 2.93E-07 - 5.87E-08; and for Cd were 4.77E-06 - 1.59E-06 and 4.35E-05 - 1.45E-05. Average LCR values for Pb and Cd exceeded in children by 9.3 and 9.4 folds those of adults. The highest and lowest LCR values were reported in samples 14 and 6 for Pb and samples 23 and 5 for Cd (Fig. 4). Regarding LCR values, a broad study concurs that the carcinogenic health hazards of the metal are considered acceptable and unlikely to cause cancer when its level is less than 1 × 10–6. [7,24,36,59], while when its values exceed 1 × 10–4 it is considered harmful and the possibility of it causing cancer becomes a reality [58,60]. In the study area, all detected ranges and average concentrations were very low, both for adults and children, to testifying as in general, the LCR

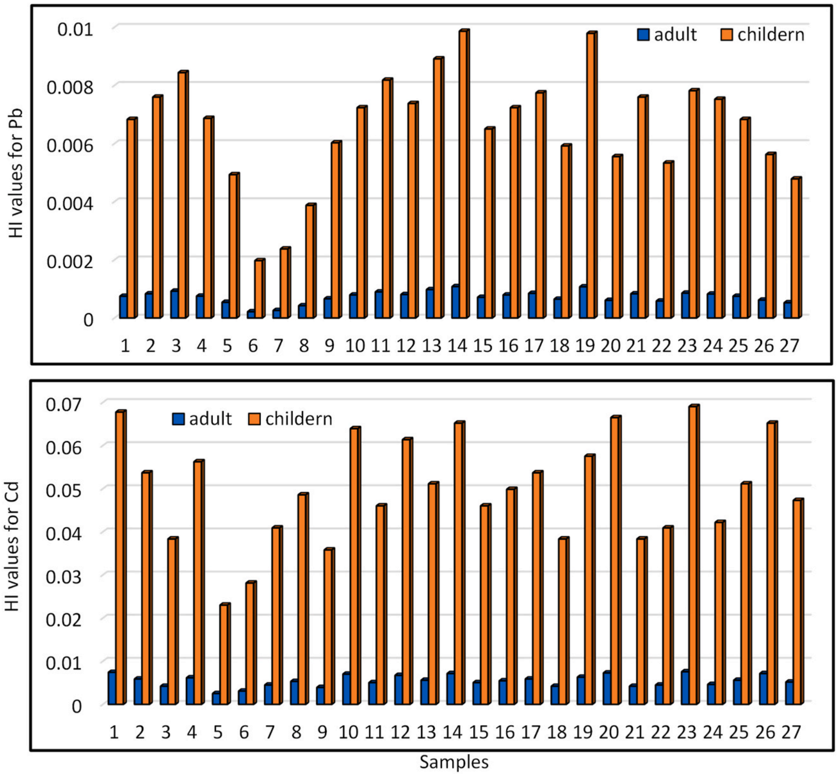

Fig. 3. Distribution of hazard index (HI) values for Pb and Cd in the investigated coastal sediment.

Table 6
The cancer risk (CR) and total cancer risk (LCR) for the whole study area.

HMs	Adults				Children			
	$CR_{Ing.}$	CR_{Dermal}	$CR_{Inhal.}$	LCR	$CR_{Ing.}$	CR_{Dermal}	$CR_{Inhal.}$	LCR
Pb	2.09E-08	8.35E-11	3.70E-18	2.10E-08	1.95E-07	3.90E-10	1.73E-17	1.95E-07
Cd	3.35E-06	1.34E-08	5.91E-16	3.36E-06	3.13E-05	6.23E-08	2.76E-15	3.14E-05

levels of both Pb and Cd in the Al-Khafji sandy beaches do not represent a potential carcinogenic health hazard.

A comparison of LCR values from the study area with those from the Al-Khobar coast (Saudi Arabia), the Gulf of Aqaba coast (Egypt), the Red Sea coast (Egypt), and the Hurghada coast (Egypt) (Fig. 5) reveals that the Pb and Cd LCR values at Khafji beach are higher than those at the Al-Khobar coast [24], the Gulf of Aqaba, and the Red Sea [25] for both adults and children. However, these LCR values are lower than those observed at Hurghada beach [10]. In general, studies on Pb and Cd contamination and associated health risks face uncertainties in measurement accuracy, exposure assumptions, reference doses, dose-response relationships, and individual risk factors. These issues underscore the need for better data and refined risk assessment models.

A regular monitoring program is essential for early detection and management of environmental health risks from Pb and Cd contamination. Such a program identifies trends, evaluates regulatory measures, and protects public health by keeping contaminant levels within safe limits. Monitoring should include Pb and Cd concentrations in soil, water, air, and food sources like crops and livestock. Additionally, tracking biological markers in humans, such as blood lead levels and urinary cadmium levels, provides direct evidence of exposure and potential health risks. The frequency of assessments should depend on exposure risks: high-risk areas might need quarterly or biannual monitoring, while lower-risk areas could be assessed annually. Increased monitoring is also necessary following contamination events or changes in industrial activities. Effective and consistent monitoring supports timely interventions, minimizes health risks, and ensures adherence to environmental standards.

To effectively mitigate Pb and Cd contamination in Al-Khafji and protect public health, several key interventions should be prioritized such as implementing strict emission controls, conducting regular monitoring of air, soil, water, and food sources, remediating contaminated sites, promote public awareness campaigns on Pb and Cd sources and health risks, encourage safe disposal of batteries and electronic waste, enforce environmental regulations robustly and collaborate with industries, communities, and governments to develop and implement strategies for minimizing exposure. Community awareness and education are crucial for addressing Pb and Cd contamination in Al-Khafji. Outreach programs should provide clear, accessible information on sources, health

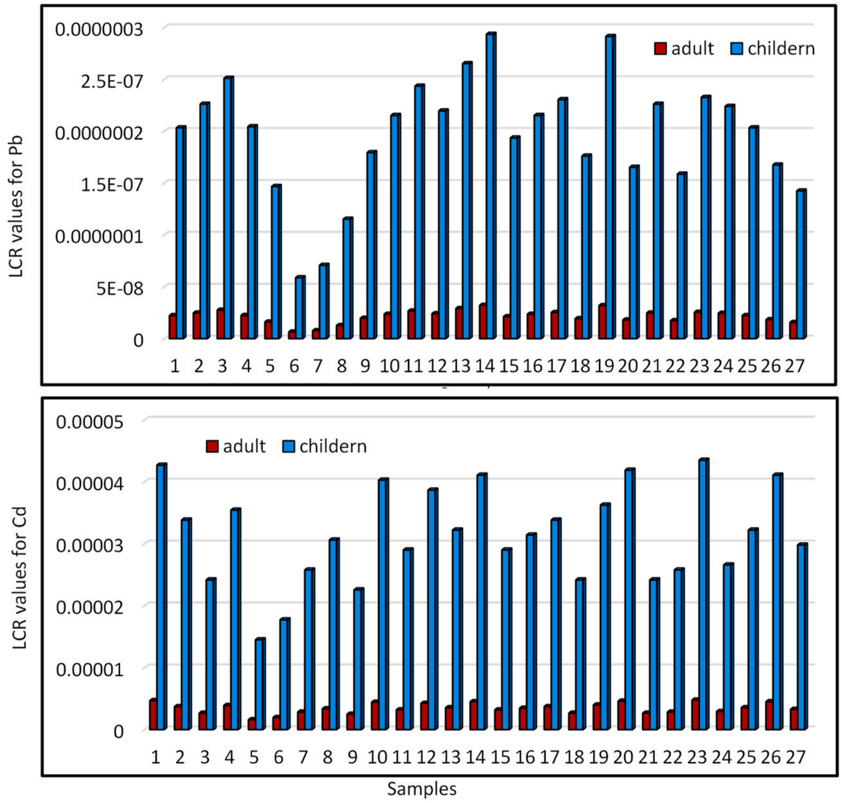

Fig. 4. LCR values of Pb and Cd for adults and children in the investigated coastal sediment.

risks, and preventive measures. Offering workshops and materials in local languages and engaging residents in citizen science initiatives can foster community involvement. These steps will help reduce contamination, track progress, and safeguard public health.

Future research on heavy metals contamination in coastal sediments should aim to deepen our understanding of how these metals are mobilized, transported, and transformed in marine environments. This involves studying the influence of sediment characteristics, such as organic matter content and grain size distribution, on metal sorption and release. Additionally, research should explore interactions between metals and other pollutants or natural ligands to uncover complex environmental dynamics and metal bioavailability. Advanced analytical techniques, like speciation analysis and isotopic tracing, can help identify contamination sources and metal uptake pathways in marine organisms. Incorporating modeling approaches to simulate metal transport and fate under various environmental conditions will also enhance predictive capabilities and inform effective management strategies for coastal sediment quality and ecosystem health.

4. Conclusions

This study aimed to highlight the levels of contamination of lead and cadmium in Al-Khafji coastal sediment and their adverse effects on marine organisms and human health. It indicated either low to no contamination levels and no adverse or low contamination levels, and no adverse for organisms due to the presence of these two metals, although the CDI average values for ingestion, dermal, and inhalation pathways were higher in children than adults. Similarly, despite LCR values for Pb and Cd exceeded in children by 9.3 and 9.4 folds than adults, a potential carcinogenic health hazard can be excluded. Also, the non-carcinogenic risk, showing values of HI below 1, testified that the conditions of the studied coastal area/sediments are acceptable and safe. Such results, although reassuring for public health and comforting about the current state of a popular stretch of coast, underline the need for a regular monitoring program, aimed at early detect signals of environmental healthiness depletion. Overall, the results indicate that the non-carcinogenic and potentially carcinogenic effects of lead and cadmium are most significant when transmitted to humans via ingestion, followed by dermal contact, with inhalation posing the least risk to human health.

Ethical approval

The present study did not use or harm any animals and followed all the scientific ethics.

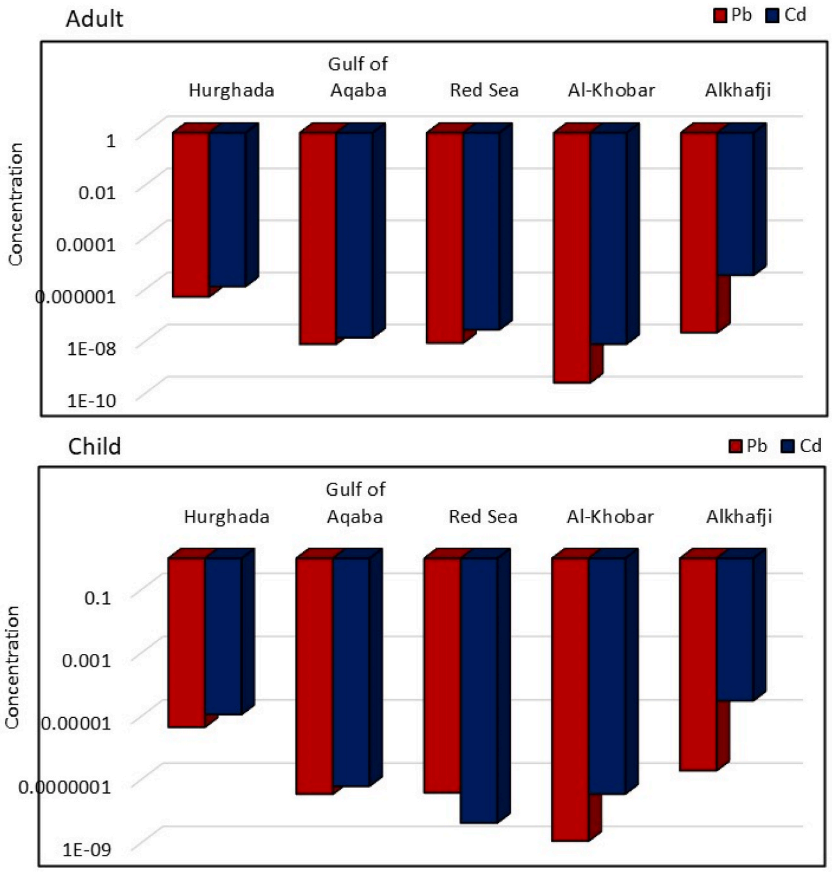

Fig. 5. The comparison of LCR values between the study area and other world sites.

Data availability statement

All data generated or analyzed during this study are included in this published article.

CRediT authorship contribution statement

Talal Alharbi: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Hamdy E. Nour:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Khaled Al-Kahtany:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Taisser Zumlot:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Abdelbaset S. El-Sorogy:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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