

Research Article

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Spatial distribution and potential ecological risk assessment of some trace elements in sediments and grey mangrove (*Avicennia marina*) along the Arabian Gulf coast, Saudi Arabia

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Abstract: To assess trace element concentrations (Zn, Cu, Pb, Cr, Cd and Ni) in the mangrove swamps along the Saudi coast of the Arabian Gulf, thirteen samples of surface sediment and leaves of grey mangrove, *Avicennia marina* were collected and analyzed. The detected trace element contents ($\mu\text{g g}^{-1}$) in surface sediments were in the following descending order according to their mean values; Cr (49.18) > Zn (48.48) > Cu (43.06) > Pb (26.61) > Ni (22.88) > Cd (3.21). The results showed that the average concentrations of Cd and Pb exceeded their world average concentration of shale. The geo-accumulation, potential ecological risk and toxicity response indices demonstrated that trace elements have posed a considerable ecological risk, especially Cd. The inter-relationships between physico-chemical characters and trace elements suggests that grained particles of mud represent a noteworthy character in the distribution of trace elements compared to organic materials. Moreover, the results revealed that Zn was clearly bioaccumulated in leaf tissues *A. marina*. Dredging, landfilling, sewage effluents and oil pollution can be the paramount sources of pollution in the area under investigation.

Keywords: Sediments; mangrove; trace elements; contamination indices; Arabian Gulf.

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1 Introduction

Mangrove ecosystem is the main intertidal wetlands along the coastlines of tropical and subtropical ecosystems between 30°N and 30°S latitude, covering an area between 160,000 and 200,000 km² [1]. It has unique ecological benefits in balance of the marine ecosystems [2]. It acts as a natural barrier against global warming, coastal erosion and storm surge besides storing huge quantities of carbon in sediments [3,4]. Moreover, mangrove ecosystem is one of the most productive ecosystems in the world, with a net primary production of about 149 mg C m⁻² y⁻¹ [3], and it is considered as habitat for many wild animals and provides nursery areas for many fish and invertebrate species [5]. They play a major role in steadying sediments and striking shoreline erosion by binding and deposition of soil particles [6]. Furthermore, mangroves can be recognized as potential accumulators for soil-borne contaminants, including trace elements [7].

Trace elements contamination is a major ecological crisis in marine environments because they are potentially destructive, non-degradable, and bio-accumulative in tissues of organisms through the food web [8]. Marine sediments involve complexes of different particles with cohesive properties such as clays and muds and non-cohesive properties such as sands. Hence, they act as a sink and transporter for trace elements in the marine ecosystems [8,9]. Therefore, the movement and accumulation of trace elements are influenced by complicated issues like sediment composition and structure [10], reduction/oxidation processes, grain-size distribution, contents of organic carbon, and hydrodynamic conditions [11]. Sediment contamination has been recognized as a major source of diminishing the quality of the aquatic environment, and various methods have been developed for their monitoring and management. Hence, sediment quality guidelines (SQGs) have been used to describe the levels of different contaminants in sediments along with

various categories of adverse effects and are often used to understand the chemical properties of sediments [12,13].

Nowadays, the mangrove ecosystem has been increasingly threatened as a result of human interference, including manufacturing and agro-based industries, huge urbanization, oil spills, domestic wastes and human pressure of dredging and land reclamation that led to serious pollutants [e.g. 14-18]. Unfortunately, because of a serious threat due to the contamination of trace elements, some areas of mangroves are being devastated all over the world [19]. However, characterizing the distribution of trace elements in the mangrove sediment could provide a better understanding of the mechanisms controlling the dispersal, accumulation, and fate of the metals in the mangrove surroundings. The shorelines of the Arabian Gulf are shallow with low sea level and frequent curves, creating many morphological features such as creeks and bays. Mangroves along the western Arabian Gulf of the Saudi Arabia cover an area of about 10.36 km² constituting about 6% of the total area in the Indian Ocean [20]. The coastal waters along Saudi Arabian coasts on the Arabian Gulf were subjected to anthropogenic activities and pollutants such as landfilling and reclamation, sewage effluents, desalination discharge, oil leakages and solid wastes [e.g. 20,21-23]. For example, mangrove in Tarut Bay has declined significantly by 55.93% between 1972 and 2011 [20]. Several studies investigated the concentration of trace elements in sediments of coastal areas along the central Arabian Gulf shoreline of Saudi Arabia, including some mangrove stands [24]. More recently, Al-Kahtany et al. [15] and Almahasheer [25] assessed the concentrations of trace elements in the mangrove swamps of Tarut Island. Results obtained from previous studies were significantly different. Therefore, the current study aimed to clarify the ambiguous situation in Tarut Island as well as other mangrove stands along the Saudi Arabian coast of the gulf. It also aimed to study the spatial distribution of trace elements in sediments and mangrove leaves and to assess toxicity by trace elements using sediment quality guidelines (SQGs).

2 Materials and methods

2.1 Study area

The study area is located mostly within Tarut bay, which is situated on the Saudi Arabian coast of the Arabian Gulf. Its area is about 440 km² and is characterized by its shallowness (average depth of 5m) and sandy texture at

the bottom. This bay is located in an arid-hot environment with high air temperature more than 50°C in summer and very little rainfall rate [26]. Surface water temperatures in the Saudi Arabian coastal waters fluctuate between 10 and 35°C in winter and summer, respectively [27]. Sediments and leaves of the grey mangrove *Avicennia marina* were collected from thirteen mangrove stands along the Saudi coast of the Arabian Gulf (Figure 1) that extends to about 175 km. These sites are settled from south to north as follows: Dammam (one site), Saihat (two sites), Tarut Island (three sites), Safwa (three sites), Ras Tanura (three sites) and Abu Ali Island (one site). Dammam is represented by one site that is characterized by the presence of obliterated mangrove trees due to continuous dredging. Saihat has two sites; one is isolated from the open water by a sand bank and is subjected to sewage effluents, and the other site is located north to the previous stand and is not subjected to any type of discharge. Three sites were selected in Tarut Island; the first and third sites receive sewage effluents from Tarut treatment plant. Whereas the second was located away from this discharge. Finally, Ras Tanura region includes three sites and Abu Ali Island to the north was represented by one site. All of these sites are adjacent to Aramco refinery plants and harbors.

2.2 Sampling

From each sampling site, triplicate surface sediment samples (top 10cm) were collected during March-April 2017 using an acid-washed PVC core. These samples were transferred to the laboratory in plastic bottles where sediment samples were air-dried at approximately 25°C and stored for further analyses. For trace metal analyses, the dried samples were homogenized with a grinder, sieved through 63µm nylon mesh sieve and were kept in a desiccator until further analyses. Meanwhile, non-sieved samples were used for other physico-chemical analyses. Mangrove leaves were collected and kept in clean plastic zip lock pouches. In the laboratory, the leaves were gently cleaned, washed with deionized water to remove any sticking dust particles, oven-dried at 70°C until constant weight and homogenized with a clean grinder.

2.3 Sediment characteristics

The particle size distributions for sediment samples were performed using the pipette method [28]. The pH was measured in deionized water (at ~27°C) with 1:2.5 sediment to solution ratio using a pH meter supported

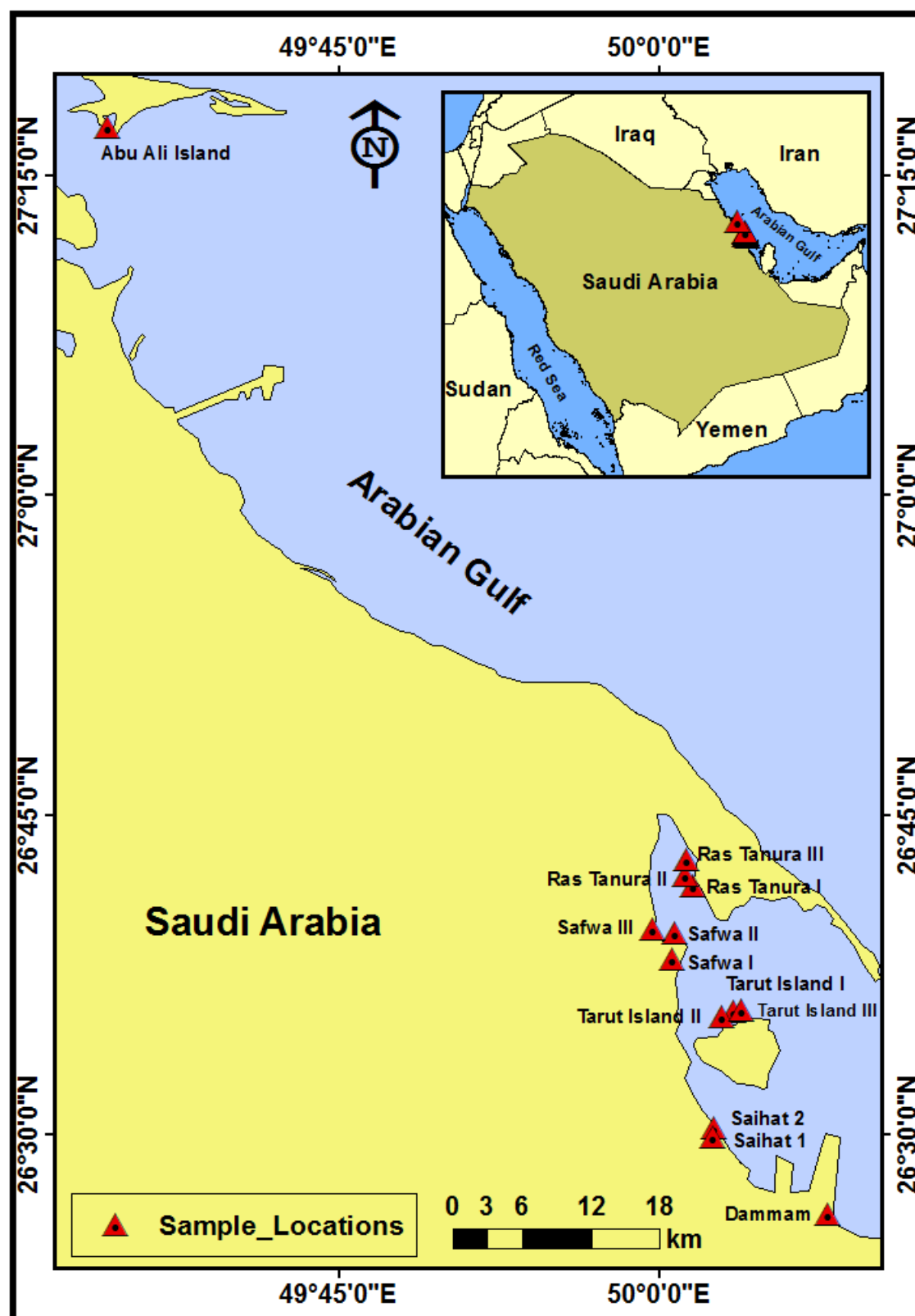


Figure 1: Sampling sites along the Saudi Arabian coast of the Arabian Gulf.

with a Beckman glass electrode and the electrical conductivity (EC) was measured in saturated soil paste extract, while the total carbonates was determined using Collins Calcimeter according to Hesse [29]. In addition, the percentage of organic matter was also determined through the oxidation method using $K_2Cr_2O_7$ as described by Walkley and Black [30]. All analyses were performed in triplicates and the three values were averaged.

2.4 Trace elements digestion and analysis

From each site, 200 mg of sieved sediment samples ($<63\mu m$) was digested with 10 ml of HNO_3 and 4 ml of HCl for approximately 3 hours until a clear solution was obtained to ensure appropriate digestion according to EPA method 3052 [31]. Then, the digested sediment samples were cooled to room temperature, diluted to a total volume of 50 ml after being filtered through Whatman No.1 filter paper and then kept at $4^\circ C$ until analysis. Similarly, 0.5g of dried and homogenized leaf samples was digested with 5ml concentrated HNO_3 and 2ml of H_2O_2 in polyethylene tubes at digestion systems for 2h at $100^\circ C$ and finally made to a total volume of 50ml [32]. The concentrations of trace elements (Zn, Cu, Pb, Cr, Cd and Ni) in sediments and leaves were analyzed using inductively coupled plasma-atomic emission spectrometry (Optima 5300 DV Perkin Elmer, with an auto-sampler Model AS 93 Plus/S10). A standard sediment reference material (BCSS-1) was processed at the same time along with the samples. The average recoveries of the measures trace elements were $103\pm 2.7\%$, $95\pm 1.0\%$, $105\pm 1.1\%$, $104\pm 4.7\%$, $88\pm 0.02\%$ and $108\pm 3.7\%$ for Zn, Cu, Pb, Cr, Cd and Ni, respectively.

2.5 Ecological risk assessment indices

Different risk or contamination indices, namely geo-accumulation index (I_{geo}), contamination factor (C_f), potential ecological risk index (E_r^i) and potential toxicity response index (RI) have been utilized to assess the trace elements pollution in the current study. The geo-accumulation index (I_{geo}) was adopted by Müller [33] and is calculated using the following equation:

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5 \cdot B_n} \right] \quad (1)$$

where, C_n is the concentration of metal (n) in sediment and B_n is the geochemical background value in the shale [34]. The constant 1.5 was used to account for potential variability in reference value due to the lithogenic inputs.

Then, seven criteria were applied as proposed by Müller [33]: uncontaminated (UC), uncontaminated to moderately contaminated (UMC), moderately contaminated (MC), moderately to heavily contaminated (MHC), heavily contaminated (HC), heavily to extremely contaminated (HEC) and an extremely contaminated (EC) at I_{geo} of <0 , 1, 1-2, 2-3, 3-4, 4-5 and >5 , respectively. The contamination factor (C_f) is the ratio obtained by dividing the concentration of each metal in the sediment background and considered as a major tool for identifying the pollution and the contamination level in the environmental matrix. It is calculated as follows:

$$C_f = \frac{M_x}{M_b} \quad (2)$$

where M_x is metal concentration in sediment and M_b is the background value, which refers to the concentration of metal in the sediments when there is no anthropogenic input [34]. The protocols of Håkanson [35] categorized the levels of contamination in terms of the following factors: $C_f < 1$ represents low levels of contamination; $1 \leq C_f < 3$ indicates moderate levels of contamination; $3 \leq C_f < 6$ is a category, which can be considered as below the higher-level contamination; and $C_f \geq 6$ indicates higher levels of contamination. The degrees of contamination (Cd) are normally a reflection of the sum of total contamination factors and are calculated according to the following method: $Cd \leq 7$ can be considered a low degree of contamination; $7 \leq Cd < 14$ moderate degree of contamination; $14 \leq Cd < 28$ considerable degree of contamination and $Cd \geq 28$ very high degree of contamination. The overall degree of contamination is given by the following equation:

$$Cd = \sum_{i=1}^n C_f^i \quad (3)$$

The potential ecological risk coefficient (E_r^i) was estimated using the formula mentioned by Håkanson [35] as follows:

$$E_r^i = T_r^i \times \frac{C_i}{C_o} \quad (4)$$

where T_r^i is the metals toxic response factors (Pb=5, Cd=30, Cr=2, Cu=5, Zn=5 and Ni=5), C_i is trace elements concentration in the sediment, and C_o is the background value for trace elements. Moreover, the potential toxicity response index (RI) was used to determine the trace metal toxicity in sediments and the subsequent environmental response. The potential ecological risk index (RI) was calculated as follows:

$$RI = \sum_{i=1}^n E_r^i \quad (5)$$

Then, the classification criteria for RI classes by trace elements are according to the calculations of Håkanson [35], and it is as follows: $E_r^i < 40$ falls in low risk (LR), $40 \leq E_r^i < 80$ in moderate risk (MR), $80 \leq E_r^i < 160$ as considerable risk (CR), $160 \leq E_r^i < 320$: high risk (HR) and $320 \leq E_r^i$ very high risk (VHR). While, RI was classified into four levels: $RI < 150$: low risk (LR), $150 \leq RI < 300$: moderate risk (MR), $300 \leq RI < 600$: considerable risk (CR) and $600 \leq RI$: very high risk (VHR).

2.6 Sediment quality guidelines (SQGs)

To describe the potential negative effects of contaminated sediments on the biological systems, the sediment quality guidelines (SQGs) were used [36]. Generally, these effects are termed as threshold effect levels (TEL), probable effect levels (PEL) according to the Canadian Council of Ministers of the Environment [37]. Meanwhile, effect range low (ERL) and effect range median (ERM) were used based on Long et al. [36]. In order to find out the possible and realistic measure of predicted toxicity, the mean quotient of ERM or PEL were calculated according to Long et al. [36].

2.7 Toxic units (ΣTU_s)

The potential acute toxicity of contaminants in sediment samples was estimated as the sum of the toxic units (ΣTU_s), where a toxic unit (TU) is defined as the ratio of each determined trace metal concentration to its PEL value according to Pederson et al. [38].

$$\Sigma TU_s = \sum_{i=1}^n (C_i / PEL_i) \quad (6)$$

2.8 Biological concentration factor (BCF)

The plant's ability to accumulate different trace elements from surrounding sediment was estimated using bioconcentration factor (BCF) calculated using the following formula:

$$BCF = C_{leaves} / C_{sediments} \quad (7)$$

where, C_{leaves} and $C_{sediments}$ represent the concentrations of trace elements in leaves and sediments, respectively.

2.9 Statistical Analysis

Descriptive statistical analysis of the studied characteristics was performed using SPSS software (version 23.0). In addition, Pearson's correlation coefficient was calculated to determine the interrelationships among the physico-chemical properties of sediments and the observed trace elements concentration in sediment and leaf samples. Principal Component Analysis (PCA) was performed as an explorative data analysis to figure out the systematic variation in the data and to identify the patterns hidden in the results.

Ethical approval: The conducted research is not related to either human or animal use.

3 Results and Discussion

3.1 Sediment characteristics

The particle size distribution in sediments normally considered as an effective tool to study the parental origin and lithogenic pathways in its deposition [39]. In the current study, sediments mainly composed of sand (80.26%) and varied between 64.10 and 94.60% at sites 7 and 13, respectively (Table 1). While the mud fraction fluctuated from 5.40% at site 13 to 35.90% at sites 7 (average: $19.74 \pm 9.21\%$). The obtained sand fractions were also classified based on their nature to *siliceous*, *hyperthermic*, to *aquic Torripsammments*. The occurrence of fine sediments in almost all the sediment samples is probably due to many reasons such as lithogenic origin, nature of the parent material, resultant of urban encroachment and degradation of coastal shorelines along the study area. Additionally, many aspects can affect the sediment grain size difference in the marine environment, such as sediment transportation and sedimentary process [35]. There are many studies that showed that the mangrove ecosystems can increase the suspension solid deposited by reducing the water dynamics and thereby releasing maximum time for fine-grained sediments, which are a main sink for trace elements [40]. Moreover, continuous remobilizing of trace elements ascended in water bodies as a result of the physical, chemical and biological operations in the sediments [41]. The pH values, which was in the majority of the studied sediment samples were alkaline, fluctuated between 7.49 and 8.51 at sites 6 and 13, respectively (average: 8.02 ± 0.27). Salinity values showed a variation between 5.27 dSm^{-1} at site 13 to 14.55 dSm^{-1} at site 3 with an average of $7.37 \text{ dSm}^{-1} \pm 2.57$ (Table 1). The differences in salinity can be

Table 1: Descriptive statistics of physico-geochemical properties of sediments along the west coast of Arabian Gulf, Saudi Arabia.

Site no.	Location	Particle size distribution (%)		Sediment Texture	Sediment Taxonomy	pH	EC (dSm ⁻¹)	OM (%)	CaCO ₃ (%)
		Sand	Mud						
1	DAMMAM	81.00	19.00	S L	<i>Torripsamments</i>	8.25	8.50	3.20	34.65
	SAIHAT								
2	Saihat I	79.30	20.70	S C L	<i>Fluvaquents</i>	8.16	6.38	2.86	31.20
3	Saihat II	66.80	33.20	S C L	<i>Fluvaquents</i>	7.65	14.55	4.55	31.20
	TARUT ISLAND								
4	Tarut I	79.60	20.40	S C L	<i>Fluvaquents</i>	7.99	6.70	3.90	31.20
5	Tarut II	83.80	16.20	S L	<i>Torripsamments</i>	8.35	6.49	2.69	25.90
6	Tarut III	84.10	15.90	S L	<i>Torripsamments</i>	7.49	6.42	3.76	40.02
	SAFWA								
7	Safwa I	64.10	35.90	S C.	<i>Fluvaquents</i>	8.10	7.22	2.51	37.90
8	Safwa II	86.00	14.00	S L	<i>Torripsamments</i>	7.95	6.21	3.15	37.90
9	Safwa III	65.90	34.10	S C	<i>Fluvaquents</i>	7.98	10.46	4.08	38.40
	RAS TANOURA								
10	Ras Tanura I	85.10	14.90	L S	<i>Torripsamments</i>	7.88	6.85	3.58	29.00
11	Ras Tanura II	86.60	13.40	L S	<i>Torripsamments</i>	8.00	5.36	1.61	40.00
12	Ras Tanura III	86.50	13.50	L S	<i>Torripsamments</i>	7.89	5.45	2.86	35.70
13	ABU ALI ISLAND	94.60	5.40	S	<i>Quartzipsamments</i>	8.51	5.27	1.43	22.30
	Minimum	64.10	5.40			7.49	5.27	1.43	22.33
	Maximum	94.60	35.90			8.51	14.55	4.55	40.02
	Average	80.26	19.74			8.02	7.37	3.09	33.49
	Standard deviation	9.21	9.21			0.27	2.57	0.91	5.58

Sediment textures: Sand S; Loam L; Sandy Loam SL; Coarse Loam CL; Fine Loam FL; Sandy Clay Loam SCL; Coarse Silt CS; Silty Clay Loam SLCL; Fine Silt FS; Silty Clay SC; Clay C; Fine clay FC

explained by variations in grain size and mineralogical composition of sediments [42]. The most important salinity controlled minerals are carbonate-bearing (calcite and aragonite) and evaporite minerals (halite).

The organic matter (OM) of mangrove sediments may be derived from terrigenous materials and/or decay of animals and plants as well as its assimilation pathways [43]. The percent of organic matter content in the collected sediments fluctuated from 1.43 to 4.55% at sites 13 and 3, respectively (average: 3.09±0.91%, Table 1). Interestingly, the OM content in the current study followed the same trend as the salinity values at sites 3 and 9. Furthermore, spatial distribution of OM with finer sediments in the present study showed that hydrodynamic processes could play a vital role in the accumulation of organic matter within the surface sediments [44]. It is worth mentioning that OM values obtained from the surface sediments of

mangrove areas of Arabian Gulf were low in comparison with the global mean of 7.9% of the estuarine tropical mangrove systems [45]. Rapid tidal export that may eventually export the locally formed organic materials to the coastal zone might be a possible reason for the lower values [45]. In addition, the limited absorption of the organic substances due to the presence of negatively charged coarse grains that originate from terrigenous sediments can also result in lower values of organic matter [46]. In the present study, carbonate contents of sediments showed its minimum of 22.30% at site 13 and a maximum of 40.02% at site 6 (average: 33.49%). This carbonate content originated mainly from land-derived terrigenous materials as well as biogenic sources. It is documented that it plays a key-role in controlling the availability of potentially toxic elements [47].

3.2 Spatial distribution of trace elements in sediments and sediment quality guidelines (SQGs)

The concentrations of the analyzed trace elements in sediments were in the ranges of 34.98-64.28, 12.51-67.09, 20.90-40.54, 21.77-77.18, 1.09-7.30 and 13.87-32.00 $\mu\text{g g}^{-1}$, for Zn, Cu, Pb, Cr, Cd and Ni, respectively (Table 2). The mean concentrations of various trace elements were in the following descending order: 49.18 ± 18.22 for Cr > 48.48 ± 7.96 for Zn > 43.06 ± 17.48 for Cu > 26.61 ± 6.29 for Pb > 22.88 ± 6.39 for Ni > 3.21 ± 1.71 for Cd. It is clear that most of the measured trace elements showed higher values at Tarut Island sites (Figure 2). For example, maximum concentrations of both Cu ($67.09 \mu\text{g g}^{-1}$) and Cr ($77.18 \mu\text{g g}^{-1}$) were observed at site 5. Similarly, site 6 exhibited the maximum concentrations of Pb ($40.54 \mu\text{g g}^{-1}$) and Cd ($7.30 \mu\text{g g}^{-1}$). Relatively higher concentration of Ni ($32.00 \mu\text{g g}^{-1}$) was detected at site 4. Whereas, the highest concentration of Zn ($64.28 \mu\text{g g}^{-1}$) was observed at site 13. These high concentrations can be related to human activities in Tarut Island. These anthropogenic contributions include sewage effluents, landfilling, urban encroachment and ports activity. This conclusion is similar to the findings obtained by Youssef et al. [22] and Almasoud et al. [23] in the same area. Almasoud et al. [23] stated that sediments around Tarut Bay were enriched with Zn, Cu, Cr and Pb from anthropogenic sources, while Ni originated from the soil parent materials and natural process. Moreover, higher concentration of trace elements observed in the study can be considered as a result of the presence of fine-grained sediments. For example, sites 3, 7 and 9 had the highest percent of mud (33.20, 35.90 and 34.10%, respectively) and accounted for the raised trace element concentrations. In comparison with the mean continental shale [34], it is assumed that the averages of Pb and Cd exhibited higher values than the shale background, while Cu, Pb, Cr, Cd and Ni display greater values with reference to upper continental crust values (UCC) [48] (Table 3). The obtained trace element concentrations were also compared with other mangrove sediments from all over the world. The average concentration of Cu ($43.06 \mu\text{g g}^{-1}$) was higher in comparison to the most studies carried in coastal areas of the Arabian Gulf and the Red Sea. Similarly, the average concentrations of Cr, Cd and Ni were also found to be greater than the previous studies in the Arabian Gulf [49,50]. In addition, the average concentration of Pb ($26.61 \mu\text{g g}^{-1}$) was higher than those recorded in some areas reported in the previous studies except for Shriadah [49] and Usama et al. [51] in Abu-Dhabi and Farasan Island, respectively. The average concentration of Zn ($48.48 \mu\text{g g}^{-1}$) was higher than those recorded in the coastal areas of the Arabian Gulf and the Red Sea except for Tubli, Bahrain [15], Hara

Biosphere Reserve, Iran [50] and Farasan Island [51] (Table 3). Recently, trace elements were studied in the same area and it was found that data obtained through the current study could be comparable with previous studies [15,22,23]. However, results of Almahasheer [25] were incredibly higher than that recorded in mangrove sediments in the current study as well as previous studies all over the world. Reasons of the hundred-fold concentrations of trace elements reported by Almahasheer [25] were not given. In comparison to some mangrove sediments worldwide, the current study revealed that the average concentrations of most trace elements were higher (Table 3). This is mainly due to huge discharges of both domestic and municipal wastewaters as well as effluents from different industrial activities in the study area [22-24]. Appropriate assessment of organisms that live in the mangrove-sediment ecosystem can deliver comprehensive baseline on the impact of such high concentrations of Cd on their health and can be useful in drawing future strategies to restrict the contamination [52].

Concerning sediment quality guidelines, numerous studies have been carried out in order to evaluate the potential toxicity of sediment and its adverse effect on the ecosystem [37]. Based on Canadian council of ministers of the environment, there are mainly two categories of sediment quality guidelines (SQGs) established (TEL-PEL). The concentration below which has less adverse biological effects and termed as TEL; while the concentration above which has adverse biological effects frequently occur and termed as PEL. With respect to threshold effect concentration (TEC), it is evident from Table (2) that the maximum concentrations of Cu, Pb, Cr, Cd and Ni (67.09 , 40.45 , 77.18 , 7.30 and $32.00 \mu\text{g g}^{-1}$, respectively) exceeded the TEL limit, while that of Zn ($64.28 \mu\text{g g}^{-1}$) was below TEL. The comparison between TEL-PEL SQGs and Zn, Cu, Pb, Cr, Cd and Ni contents in sediment samples exhibited percentages below TEL values with 100, 15.38, 69.23, 46.15, 69.23 and 92.23%, respectively. Meanwhile, the concentrations of Zn, Cu, Pb, Cr, Cd and Ni in the sediments have values between TEL and PEL (0.0, 84.62, 30.77, 53.85, 30.77 and 7.69%, respectively). The maximum concentrations of Cu, Cd and Ni were higher than those of the ERL SQGs values (Table 2). The abundances of Zn, Cu, Pb, Cr, Cd and Ni in sediment samples with those of ERL-ERM SQGs showed percentages below the ERL levels of 100, 23.08, 100, 100, 7.69 and 38.46%, respectively. On the other hand, Cu (76.92%), Cd (92.31%) and Ni (61.54%) fall-in between ERL-ERM SQGs ranges. From the obtained results, there is scarce or no adverse biological impact on biological pathways due to trace element contents in the mangrove-sediment ecosystem.

Table 2: Spatial distribution of trace elements ($\mu\text{g g}^{-1}$) in surface sediments and sediment quality guidelines along the west coast of the Arabian Gulf, Saudi Arabia.

Site no.	Location	Concentrations of trace elements in sediments ($\mu\text{g g}^{-1}$)					
		Zn	Cu	Pb	Cr	Cd	Ni
1	DAMMAM	48.89	60.98	27.30	56.10	2.87	31.90
	SAIHAT						
2	Saihat I	51.04	46.90	32.78	53.06	2.53	27.30
3	Saihat II	52.80	58.75	20.90	21.77	1.97	15.78
	TARUT ISLAND						
4	Tarut I	44.36	49.78	23.30	67.90	2.30	32.00
5	Tarut II	50.64	67.09	26.00	77.18	4.20	21.50
6	Tarut III	40.00	38.45	40.54	41.85	7.30	28.98
	SAFWA						
7	Safwa I	55.56	23.89	21.36	23.89	1.09	17.89
8	Safwa II	34.98	12.51	34.10	34.02	4.50	16.00
9	Safwa III	40.00	14.51	21.40	29.25	1.90	23.97
	RAS TANURA						
10	Ras Tanura I	43.20	34.00	23.90	43.80	2.77	24.89
11	Ras Tanura II	48.34	57.00	21.70	69.29	2.89	13.87
12	Ras Tanura III	56.21	47.88	21.10	63.83	1.96	26.89
13	ABU ALI ISLAND	64.28	48.00	31.60	57.46	5.40	16.46
	Minimum	34.98	12.51	20.90	21.77	1.09	13.87
	Maximum	64.28	67.09	40.54	77.18	7.30	32.00
	Average	48.48	43.06	26.61	49.18	3.21	22.88
	Standard deviation	7.96	17.48	6.29	18.22	1.70	6.39
Sediment quality guidelines (SQGs)							
	Threshold effect level (TEL) ^a	124	18.70	30.20	52.30	3.65	32.00
	Probable effect level (PEL) ^a	271	108.0	112.0	160.4	4.20	43.00
	Effect range low (ERL) ^b	150	34.00	46.70	81.00	1.20	20.90
	Effect range median (ERM) ^b	410	270	218	370	9.60	51.60

^a Canadian Council of Ministers of Environment [37]; ^b Long et al. [36].

3.3 Trace elements accumulation in mangrove leaves

The obtained results revealed that the average concentrations of detected trace elements were in the following descending order; $27.96 > 14.45 > 9.25 > 5.06 > 2.83 > 1.28$ for Zn, Pb, Cr, Ni, Cu and Cd, respectively (Table 4). The concentration of Zn in leaf tissues ranged from 18.19 at site 13 to $36.30 \mu\text{g g}^{-1}$ at site 3 (Figure 2). The concentration

of Cu fluctuated between 1.30 and $6.00 \mu\text{g g}^{-1}$ at sites 2 and 3, respectively. While, the concentration of Pb ranged from 7.20 at site 2 to $17.40 \mu\text{g g}^{-1}$ at site 4. Moreover, Cr concentrations fluctuated between 5.30 at site 12 to $18.20 \mu\text{g g}^{-1}$ at site 1. Both Cd and Ni concentrations in the leaves varied between minimum of 0.45 and 1.60 at site 7 to maximum of 2.98 and $15.26 \mu\text{g g}^{-1}$ at site 6, respectively (Figure 2).

Table 3: Comparison of trace elements concentrations ($\mu\text{g g}^{-1}$) in marine sediments with regional and worldwide studies.

Location	Zn	Cu	Pb	Cr	Cd	Ni	References
Minimum	34.98	12.51	20.90	21.77	1.09	13.87	Current study
Maximum	64.28	67.09	40.54	77.18	7.30	32.00	
Average	48.48	43.06	26.61	49.18	3.21	22.88	
Standard deviation	7.96	17.48	6.29	18.22	1.70	6.39	
Mean Continental Shale	95	45	20	90	0.30	68	[34]
UCC	71	25	20	35	0.098	20	[46]
Arabian Gulf							
Saudi Arabia							
Tarut Bay and Gurmah Island	7.28	1.83	11.78	6.68	1.06	8.21	[54]
Tarut Bay	26.9	6.9	144.82	26.2	1.45	-	[22]
Tarut Bay	789	4503	4207	1486	1686	2459	[25]
Tarut Island	28.35	209.8	4.39	50.65	1.67	81.05	[15]
Bahrain							
Tubli Bay	49.00	18.46	-	2.45	-	6.55	[15]
Tubli Bay	891.0	3782.0	4113.0	1549.0	4150	2677	[25]
Abu-Dhabi, UAE	9.05	6.33	37.3	8.28	5.17	14.00	[49]
Hara Biosphere Reserve, Iran	49.39	20.98	7.94	194.29	2.63	101.48	[50]
Coastal areas of the Red Sea							
Saudi Arabia coastal area	-	22.87	3.82	46.11	0.75	21.11	[70]
Farasan Island	57.0	112.0	45.2	9.6	1.23	8.50	[51]
Egypt	35.67	13.54	11.12	-	0.75	11.03	[60]
Worldwide							
Muthupet, India	27.96	13.49	13.49	-	0.29	-	[71]
Sunarban, Bangladesh	58.59	31.73	17.88	38.69	0.07	167.29	[46]
Punta Piuta, Costa Rica	11.40	9.80	25.60	19.80	6.00	99.00	[72]
Punta Mala Bay, Panama	105.0	56.3	78.20	23.3	<10	27.3	[73]
Port Klang, Malaysia	51.05	17.43	59.45	46.4	0.83	11.44	[74]
Guanabara Bay, Brazil	483.0	98.6	160.8	42.4	1.32	-	[75]
Hainan Island, China	57.0	18.0	19.00	40.0	0.11	-	[76]
Hong Kong	96.00	43.00	2.60	2.90	1.08	31.20	[7]
Hong Kong	293.0	46.00	199.0	14.00	0.60	66.00	[77]

*Only data of mangrove sediments

Even though the concentrations of most of the elements in leaf tissues of mangrove plants were lower than that those in the surrounding sediments (Figure 2), Zinc exhibited comparatively higher values indicating its importance as an essential micronutrient that mediate

several enzyme pathways such as respiration and hormone synthesis [53]. According to the excessive levels mentioned by Kabata-Pendias and Pendias [54], Cr in the mangrove leaves is categorized between the level of 5-30 $\mu\text{g g}^{-1}$ DW at site 13. While, Ni concentrations fall in between

Table 4: Comparison of trace element contents ($\mu\text{g g}^{-1}$ DW) in mangrove leaves with regional and around the world.

Location	Trace elements concentration ($\mu\text{g g}^{-1}$ DW)						References
	Zn	Cu	Pb	Cr	Cd	Ni	
Minimum	18.19	1.30	7.2	5.30	0.45	1.60	
Maximum	36.60	6.00	17.40	18.20	2.98	15.26	
Average	27.96	2.83	14.45	9.25	1.28	5.06	
Standard deviation	5.14	1.43	2.88	3.72	0.70	4.27	
Excessive Levels	100-400	20-100	30-300	5-30	5-30	10-100	[54]
Coastal areas of Arabian Gulf							
Tarut Bay, Saudi Arabia	196.0	370.0	1075.0	540.0	839.0	706.0	[25]
Tubli Bay, Bahrain	189.0	323.0	1120.0	567.0	894.0	699.0	[25]
United Arab Emirates	2.46	0.01	0.06	0.01	-	-	[59]
Coastal areas of the Red Sea							
Coastal area, Red Sea	-	13.24	3.79	14.96	0.18	7.56	[70]
Farasan Island, Red Sea	29.5	356.6	-	9.30	1.04	2.30	[51]
Egypt	79.74	12.60	21.63	-	0.83	6.21	[60]
Worldwide							
FAO	-	40.00	5.00	5.00	0.20	1.50	[1]
Peninsular, Malaysia	5.90	26.80	35.50	9.50	1.0	-	[18]
China	143.00	15.50	2500	-	0.48	3.32	[58]

the excessive level of 10 and 100 $\mu\text{g g}^{-1}$ at sites 6 and 8, respectively. The non-essential trace elements such as Pb, Cd and Ni exhibited higher values in leaves at site 6 might be a result of huge discharge of untreated or semi-treated domestic and municipal wastes along with the additions from different industries [25,55]. Moreover, higher concentrations of Zn in the leaf tissues analyzed within the studied mangrove-sediment indicates the inability of mangroves to intake this particular micronutrient owing to the resistance of mangrove leaves to trace elements [56]. In the current study, the higher concentrations of trace elements in the mangrove tissues further explain the capability of mangrove plants to uptake and accumulate many metal ions such as Pb and Cd in their tissues [57]. This is very important in order to avoid the trace metal pollution in coastal areas, and thereby, preserving the biodiversity in the Arabian Gulf coast. The obtained results revealed that the elevated concentrations of Cr at site 13, Cd and Ni at site 6 within the mangrove tissues were higher than that in the leaves of *A. marina* from various mangroves grown on the other areas worldwide (Table 4). However, the Pb concentration (17.40 $\mu\text{g g}^{-1}$) was lower than that in the leaves of mangrove in Peninsular, Malaysia [18], China

[58] and Egypt [60]. Furthermore, the concentration of Cu in the mangrove tissues in this study was higher than that in mangrove leaves (6.00 $\mu\text{g g}^{-1}$) measured in United Arab Emirates [59]. Only the highest concentration of Zn in the mangrove tissues at site 3 (36.30 $\mu\text{g g}^{-1}$) was lower than that in the leaves of *A. marina* in China [58] and Egypt [60]. Thus, the regions and level of trace metal pollutions significantly influence the process of trace metal bioaccumulation in the mangrove ecosystem.

3.4 Biological Concentration Factor (BCF)

In the current study, the descending mean values of BCF for all mangrove samples followed the sequence of Zn (0.59) > Pb (0.57) > Cd (0.41) > Ni (0.24) > Cr (0.22) > Cu (0.09). The greatest value of BCF among the various study sites for Zn was 0.84 at site 8 indicating that Zn is clearly bioaccumulated in leaf tissues of *A. marina*. On the other hand, the lowest value of BCF was recorded for Cu (0.02) at site 11 (Figure 3). This can be attributed to the low minimal mobility of this particular metal (Cu) in the respective sediments.

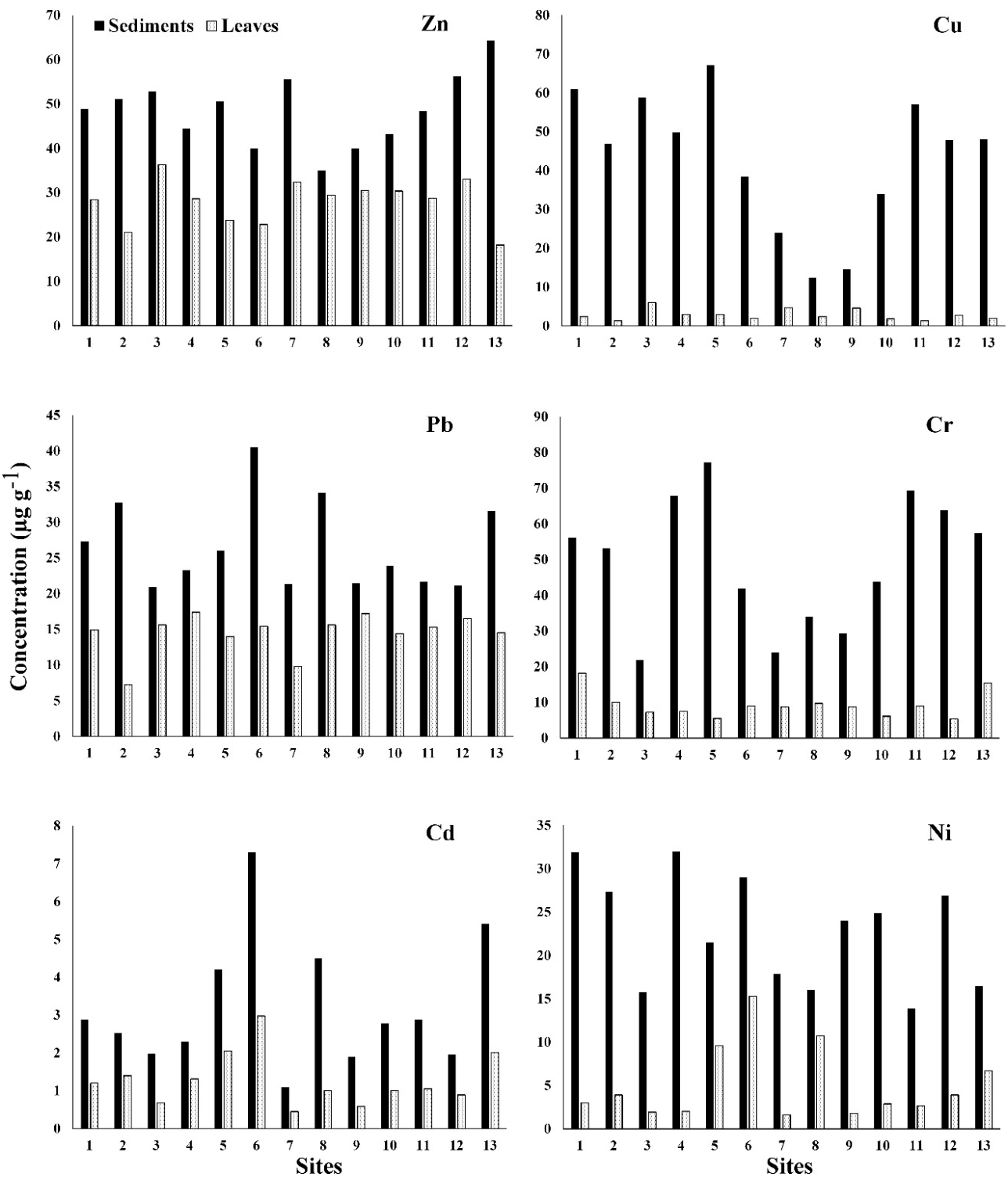


Figure 2: Spatial distribution of different trace elements ($\mu\text{g g}^{-1}$) in sediments and mangrove leaves along the Arabian Gulf coastal area.

Table 5: Averages of geo-accumulation (I_{geo}) of the studied trace elements at studied sites.

Site no.	Sampling sites	Averages of I_{geo} of the detected trace elements						I_{geo} class					
		Zn	Cu	Pb	Cr	Cd	Ni	Zn	Cu	Pb	Cr	Cd	Ni
1	DAMMAM	-1.54UC	-0.15UC	-0.14UC	-1.27/ UC	2.67MHC	-1.68UC	0	0	0	0	3	0
	SAIHAT												
2	Saihat I	-1.48UC	-0.53UC	0.13UMC	-1.35/ UC	2.49MHC	-1.90UC	0	0	1	0	3	0
3	Saihat II	-1.43UC	-0.20UC	-0.52UC	-2.63UC	2.13MHC	-2.69UC	0	0	0	0	3	0
4	TARUT ISLAND												
	Tarut I	-1.68UC	-0.44UC	-0.36UC	-0.99UC	2.35MHC	-1.67UC	0	0	0	0	3	0
	Tarut II	-1.49UC	-0.01UC	-0.21UC	-0.81UC	3.22HC	-2.25UC	0	0	0	0	4	0
6	Tarut III	-1.83UC	-0.81UC	0.43UMC	-1.69UC	4.02HEC	-1.82UC	0	0	1	0	5	0
7	SAFWA												
	Safwa I	-1.36UC	-1.50UC	-0.49UC	-2.50UC	1.28MC	-2.51UC	0	0	0	0	2	0
	Safwa II	-2.03UC	-2.43UC	0.18UMC	-1.99UC	3.32HC	-2.67UC	0	0	1	0	4	0
9	Safwa III	-1.83UC	-2.22UC	-0.49UC	-2.21UC	2.08MHC	-2.09UC	0	0	0	0	3	0
10	RAS TANURA												
	Ras Tanura I	-1.72UC	-0.99UC	-0.33UC	-1.62UC	2.62MHC	-2.03UC	0	0	0	0	3	0
	Ras Tanura II	-1.56UC	-0.24UC	-0.47UC	-0.96/ UC	2.68MHC	-2.88UC	0	0	0	0	3	0
12	Ras Tanura III	-1.34UC	-0.50UC	-0.51UC	-1.08/ UC	2.12MHC	-1.92UC	0	0	0	0	3	0
13	ABU ALI ISLAND	-1.15UC	-0.49UC	0.07UMC	-1.23/ UC	3.58HC	-2.63UC	0	0	1	0	4	0

The concentrations of Zn, Cu, Cr, Pb and Ni were higher in the respective sediments, but the BCF values did not clearly indicate the bioavailability of these trace elements in sediments or in the subsequent metal uptake by mangroves. This might be due to the restriction of trace elements through complexation or the fixation process with organic particles that are subjected to reduction pathway [61,62]. Therefore, speciation experiments of trace elements in sediments should be increased progressively in order to describe the toxicity and bioavailability of such elements [17,63].

3.5 Contamination status based on the geo-accumulation Index (I_{geo})

The average of the I_{geo} value for Zn, Cu, Cr and Ni at all investigated sites can be classified as uncontaminated ($I_{geo} \leq 0$) (Table 5). While, only four sites 2, 6, 8 and 13 showed levels that can be considered as uncontaminated to moderately contaminated sediments by Pb ($0 < I_{geo} < 1$).

Regarding Cd, only site 7 (7.69% of sediment samples) was categorized as moderately contaminated (MC), with

a value of 1.28 with respect to I_{geo} index ($1 < I_{geo} < 2$), while 61.54% of the sediment samples exhibited moderately to heavily contaminated (MHC) with a range between 2.08 at site 9 and 2.68 at site 11 compared to I_{geo} index ($2 < I_{geo} < 3$). Furthermore, 23.08% (sites 5, 8 and 13) of studied samples were classified as the heavily contaminated (HC) according to I_{geo} index ($3 < I_{geo} < 4$). Finally, only one site (6) was defined as heavily to extremely contaminated (HEC) when compared with the I_{geo} index ($4 < I_{geo} < 5$). The higher contamination of Cd may be a resultant of wastewater drainage from the Qateef Oasis, which is supposed to bring agricultural wastes from Tarut Island [55]. The steady spatial distribution of selected trace elements in all study regions (except site 6) indicates the occurrence of non-point sources such as aquaculture and agricultural run-off.

3.6 Contamination factor (C_f)

Results showed that the C_f values for Zn, Cr, and Ni ($C_f < 1$); which is considered to be a low contamination level at all study sites (Table 6). Except site 3, almost all the remaining

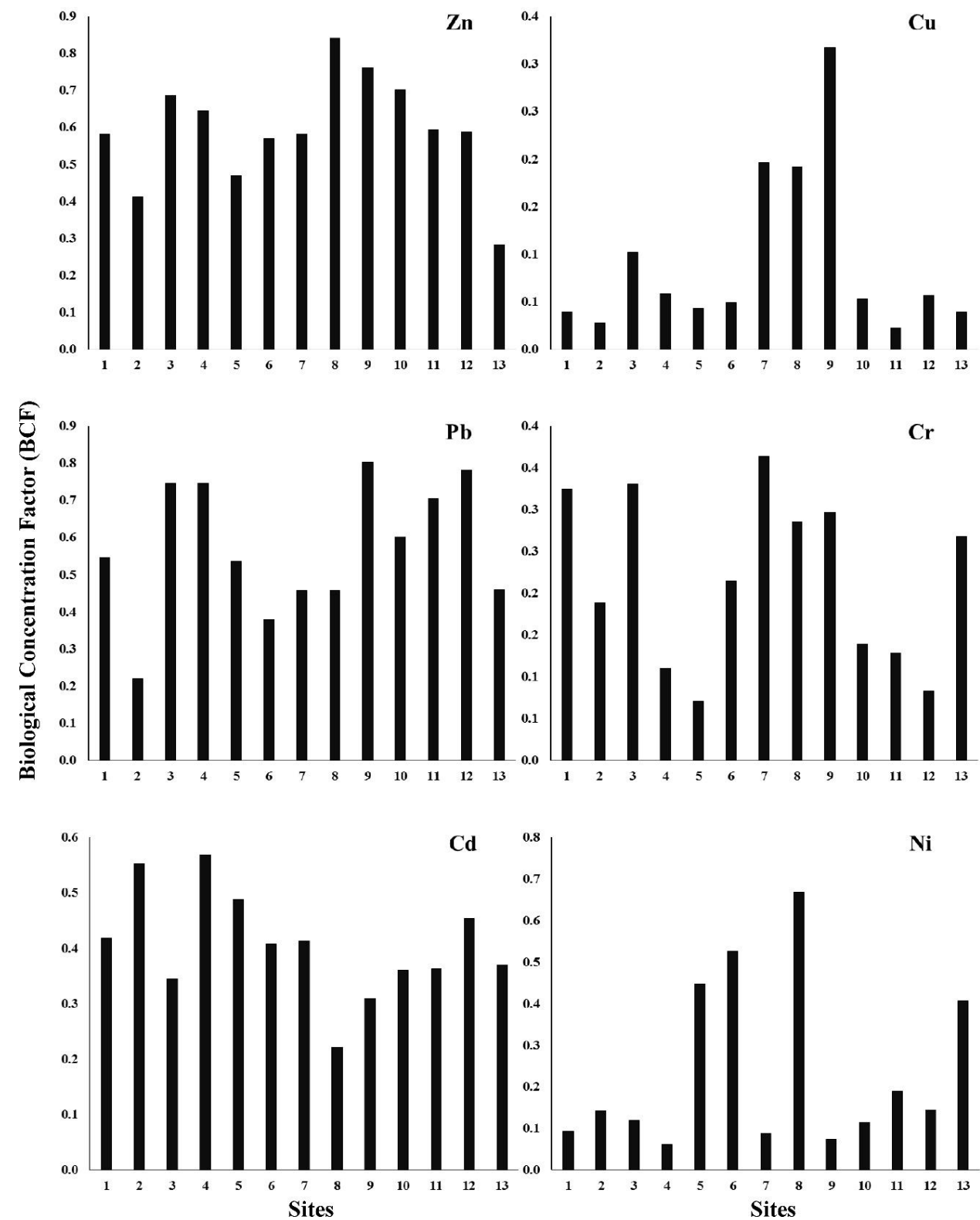


Figure 3: Biological concentration factor of trace elements at different sites along the Arabian Gulf coastal area.

Table 6: Contamination factor of trace elements and Mean ERM in surface sediments in the study area.

Site no.	Sampling Sites	Contamination factor (C_f)						C_d Degree	Mean		ΣTUs
		Zn	Cu	Pb	Cr	Cd	Ni		ERM-Q	PEL-Q	
1	DAMMAM	0.51	1.36	1.37	0.62	9.57	0.47	13.89	0.32	0.51	3.09
	SAIHAT										
2	Saihat I	0.54	1.04	1.64	0.59	8.43	0.40	12.64	0.30	0.47	2.82
3	Saihat II	0.56	1.31	1.05	0.24	6.57	0.23	9.95	0.20	0.32	1.93
	TARUT ISLAND										
4	Tarut I	0.47	1.11	1.17	0.75	7.67	0.47	11.63	0.31	0.49	2.94
5	Tarut II	0.53	1.49	1.30	0.86	14.00	0.32	18.50	0.34	0.57	3.43
6	Tarut III	0.42	0.85	2.03	0.47	24.33	0.43	28.53	0.38	0.68	4.10
	SAFWA										
7	Safwa I	0.58	0.53	1.07	0.27	3.63	0.26	6.35	0.18	0.27	1.60
8	Safwa II	0.37	0.28	1.71	0.38	15.00	0.24	17.96	0.25	0.44	2.65
9	Safwa III	0.42	0.32	1.07	0.33	6.33	0.35	8.82	0.21	0.33	1.96
	RAS TANURA										
10	Ras Tanura I	0.45	0.76	1.20	0.49	9.24	0.37	12.50	0.26	0.42	2.53
11	Ras Tanura II	0.51	1.27	1.09	0.77	9.63	0.20	13.47	0.27	0.44	2.65
12	Ras Tanura III	0.59	1.06	1.06	0.71	6.53	0.40	10.34	0.29	0.44	2.66
13	ABU ALI ISLAND	0.68	1.07	1.58	0.64	18.00	0.24	22.20	0.33	0.57	3.42
	Descriptive statistics										
	Minimum	0.37	0.28	1.05	0.24	3.63	0.20	6.35			
	Maximum	0.68	1.49	2.03	0.86	24.33	0.47	28.53			
	Average	0.51	0.96	1.33	0.55	10.69	0.33	14.37			
	Standard deviation	0.08	0.39	0.31	0.20	5.05	0.09	6.04			

sites were categorized as moderate contamination of sediments for Pb ($1 \leq C_f < 3$). While, Cu ranged from low to moderate contamination with values of 38.46% to 61.54%, respectively. On the other hand, the contamination by Cd in most of the sites varied from considerably high (7.69% of total sites) to very high contamination (92.31% of total sites). The high C_f for Cd in all studied sites could result from the urban effluents that collect wastewater discharges from treatment plants. The degree of contamination (C_d) values for the current study indicates that 7.69% of total sites were in the lower level of contamination (< 7) and 61.54% of total sites were in a moderate degree of contamination ($7 \leq C_d < 14$). Furthermore, sites 5, 6, 8 and 13 (representing 30.77% of the total sites) fall under the category of considerably contaminated ($14 \leq C_d < 28$) (Table 6).

3.7 Mean ERM or PEL quotients

Generally, all the study sites had the potential toxic level of 21% based on the $m\text{-ERM-Q}$; 0.11-0.51 [36]. The lowest values of $ERM\text{-Q}$ or $PEL\text{-Q}$ were registered at site 7, demonstrating the minimum hazard levels of those regions. Based on the calculation of $m\text{-PEL-Q}$, all sites are defined as moderately impacted ($m\text{-PEL-Q}$; 0.1-1.0). This result coincided with those obtained from Bohai Bay and the coastal regions of Shandong Peninsula, Yellow Sea [64]. In terms of placing such features in ΣTUs category, the selected sites for the current study revealed that the toxicity was in following order: site 6 > site 5 > site 13 > site 1 > site 4 > site 2 > site 12 > site 8 > site 11 > site 10 > site 9 > site 3 > site 7 (Table 6).

Table 7: Potential ecological risk indices (E_r^i) and potential toxicity response index (RI) of trace elements.

Site no.	Sampling Sites	Ecological risk categories of single trace metal (E_r^i)						Potential Toxicity Response Index (RI)
		Zn	Cu	Pb	Cr	Cd	Ni	
1	DAMMAM	0.51LR	6.78LR	6.83LR	1.25LR	287.00/HR	2.35/LR	304.71/CR
	SAIHAT							
2	Saihat I	0.54LR	5.21LR	8.20LR	1.18LR	253.00/HR	2.01/LR	270.13/MR
3	Saihat II	0.56LR	6.53LR	5.23LR	0.48LR	197.00/HR	1.16/LR	210.95/MR
	TARUT ISLAND							
4	Tarut I	0.47LR	5.53LR	5.83LR	1.51LR	230.00/HR	2.35/LR	245.68/MR
5	Tarut II	0.53LR	7.45LR	6.50LR	1.72LR	420.00/VHR	1.58/LR	437.78/CR
6	Tarut III	0.42LR	4.27LR	10.14LR	0.93LR	730.00/VHR	2.13/LR	747.89/VHR
	SAFWA							
7	Safwa I	0.58LR	2.65LR	5.34LR	0.53LR	109.00/CR	1.32/LR	119.43/LR
8	Safwa II	0.37LR	1.39LR	8.53LR	0.76LR	450.00/VHR	1.18/LR	462.22/CR
9	Safwa III	0.42LR	1.61LR	5.35LR	0.65LR	190.00/HR	1.76/LR	199.80/LR
	RAS TANURA							
10	Ras Tanura I	0.45LR	3.78LR	5.98LR	0.97LR	277.20/HR	1.83/LR	290.11/MR
11	Ras Tanura II	0.51LR	6.33LR	5.43LR	1.54LR	289.00/HR	1.02/LR	303.62/CR
12	Ras Tanura III	0.59LR	5.32LR	5.28LR	1.42LR	195.75/HR	1.98/LR	210.33/MR
13	ABU ALI ISLAND	0.68LR	5.33LR	7.90LR	1.28LR	540.00/VHR	1.21/LR	556.40/CR
Descriptive statistics								
	Minimum	0.37/LR	1.39/LR	5.23/LR	0.48/LR	109.00/CR	1.02/LR	119.43/LR
	Maximum	0.68/LR	7.45/LR	10.14/LR	1.72/LR	730.00/VHR	2.35/LR	747.89/CR
	Average	0.51/LR	4.78/LR	6.66/LR	1.09/LR	320.61/HR	1.68/LR	335.34/CR
	Standard deviation	0.08	1.94	1.57	0.41	107.27	0.47	107.24

3.8 Potential Ecological Risk Indices (E_r^i) and Potential Toxicity Response Index (RI)

From the results in (Table 7), it can be concluded that there is a parallel relation between the ecological risk assessment index (E_r^i) and I_{geo} index. In all sediments, Zn, Cr, Cu, Ni and Pb revealed a low ecological risk ($E_r^i < 40$). On the other hand, Cd exhibited considerable risk ($80 \leq E_r^i < 160$) at site 7, whereas it revealed a high risk ($160 \leq E_r^i < 320$) at sites of sites 1-4, and 9-12. Furthermore, a very high ecological risk (VHR) ($E_r^i > 320$) was observed at sites 5, 6, 8 and 13, respectively. These results could be an outcome of the huge anthropogenic wastes resultant of refining and untreated sewage effluents [55]. The highest RI value of 747.89 was recorded at site 6, while the lowest (119.43) was observed at site 7 with an average of 335.34. Considering the RI ranges, 76.9% of total studied sites categorized

in low ecological risk ($RI \leq 150$); 46.15% categorized as moderate risk ($150 \leq RI < 300$) and 38.64% to a category of considerable risk ($300 \leq RI < 600$). On the other hand, one site classified as very high risk ($RI > 600$).

3.9 Pearson's correlation analysis

Pearson's correlation was calculated in order to study the inter-relationship between the contaminants and physico-chemical properties of the mangrove-sediments (Table 8). Significant negative correlation was observed between sand fraction and trace elements in the sediments: Cr ($r = -0.67$, $p < 0.05$) and Cd ($r = -0.62$, $p < 0.05$), as well as in the leaves: Zn ($r = -0.58$, $p < 0.05$), Cu ($r = -0.83$, $p < 0.05$) and Cd ($r = -0.57$, $p < 0.05$). These values indicate the lowest level of trace element absorption in the coarse-grained sediment

Table 8: Pearson's correlation coefficients among soil properties and trace elements concentration in the study area.

	Sand	Mud	pH	EC	OM	CaCO ₃	Concentrations in sediments					Concentrations in leaves					
							Zn	Cu	Pb	Cr	Cd	Ni	Zn	Cu	Pb	Cr	Cd
Mud	0.97**																
pH	0.28	-0.15															
EC	0.72**	0.73**	-0.36														
OM	-0.55	0.45	-0.66*	0.70**													
CaCO ₃	-0.34	0.20	-0.58*	0.04	0.19												
Concentrations in sediments																	
Zn	0.11	0.05	0.52	-0.08	-0.55	-0.53											
Cu	0.29	-0.29	0.24	0.03	-0.19	-0.45	0.50										
Pb	0.46	-0.44	-0.07	-0.36	-0.08	-0.02	-0.26	-0.14									
Cr	-0.67*	0.70**	0.46	-0.62*	-0.48	-0.35	0.23	0.65*	0.03								
Cd	-0.62*	0.57*	-0.08	-0.37	-0.17	-0.11	-0.18	0.04	0.85**	0.18							
Ni	0.03	-0.12	-0.11	-0.11	0.42	0.03	-0.23	0.14	0.17	0.28	0.01						
Concentrations in mangrove leaves																	
Zn	-0.58*	0.48	-0.49	0.56*	0.53*	0.43	-0.15	-0.18	-0.71**	-0.45	-0.68*	-0.14					
Cu	-0.83**	0.86**	-0.24	0.82**	0.53	0.09	0.08	-0.16	-0.53	-.63*	-0.49	-0.23	0.66*				
Pb	0.17	-0.18	-0.31	0.17	0.32	0.13	-0.33	0.00	-0.20	0.12	0.15	0.07	0.32	0.17			
Cr	0.21	-0.09	0.48	-0.05	-0.31	-0.10	0.21	0.10	0.35	0.01	0.24	0.09	-0.41	-0.24	-0.11		
Cd	-0.57*	-0.54	0.01	-0.40	-0.15	-0.24	-0.02	0.32	0.77**	0.42	0.89**	0.29	-0.78**	-0.35	0.01	0.18	
Ni	0.48	-0.49	-0.18	-0.36	-0.06	0.05	-0.31	-0.08	0.83**	0.10	0.91**	0.01	-0.46	-0.37	0.08	0.01	0.80**

** . Correlation is significant at the 0.01 level (2-tailed). * . Correlation is significant at the 0.05 level (2-tailed).

due to many factors such as weathering, hydrodynamic transport, and deposition mechanism of fine-grained sediment. On the other hand, significant positive correlations were recorded between the mud fraction and trace elements in the sediments: Cr ($r = 0.70$, $p < 0.05$), Cd ($r = 0.85$, $p < 0.05$) and Cu in mangrove leaves ($r = 0.86$, $p < 0.05$). It is identified that Cr and Cd exhibited homeostasis to accumulate within the fine-grained sediments, which may in turn act as a major transporter of these trace elements. This may be a resultant of high surface area, cation exchangeable capacity and deposition of inorganic or organic complexation [46]. Moreover, there is a positive correlation between the salinity and OM ($r = 0.70$, $p < 0.05$). This could be attributed to the higher salinity levels with low osmotic potential that might reduce the microbial activity and then decomposition of organic matter [65]. In the current study, no significant correlations were detected between OM and measured trace elements in sediments and mangrove leaf tissues, except for Zn in mangrove leaves ($r = 0.53$, $p < 0.05$) (Table 8). Therefore, OM content in the current study cannot provide a clear picture about the source of trace elements. However, a

high relation has been observed between organic matter and trace elements through adsorption and complexation action in an aquatic environment, which in turn influences the geochemical behavior of trace elements in the marine environment [66].

For sediments, a significant positive correlation was observed between pairs of detected trace elements such as Cu-Cr ($r = 0.65$, $p < 0.05$) and Pb-Cd ($r = 0.85$, $p < 0.05$). Meanwhile, a negative correlation was observed between Zn in mangrove leaves and both Pb ($r = -0.71$, $p < 0.05$) and Cd ($r = -0.68$, $p < 0.05$) in sediments. On the other hand, a positive correlation was registered between Pb in sediment and Cd ($r = 0.77$, $p < 0.05$) and Ni ($r = 0.83$, $p < 0.05$) in mangrove leaves, respectively. Furthermore, a strong positive correlation was observed between Cd in the sediment and concentration of Cd ($r = 0.89$, $p < 0.05$) and Ni ($r = 0.91$, $p < 0.05$) in mangrove leaves. With respect to mangrove leaves, there are positive correlations between pairs of trace elements such as Zn-Cu ($r = 0.66$, $p < 0.05$) and Cd -Ni ($r = 0.80$, $p < 0.05$). While, a negative correlation was registered for Zn-Cd ($r = -0.78$, $p < 0.05$). According to Suresh et al. [67], if the correlation coefficient between

Table 9: Principal component analysis (PCA) with varimax for various sediment categories.

Parameters	PC1	PC2	PC3	PC4
EC (dSm ⁻¹)	-0.92		-0.19	0.10
Mud % (Silt + Clay)	-0.79	-0.12	-0.47	-0.18
Cr (μg g ⁻¹)	0.78	0.45		0.33
Sand %	0.76	0.24	0.52	
OM (%)	-0.72	-0.26		0.60
CaCO ₃ (%)		-0.86	-0.17	
Cu (μg g ⁻¹)	0.17	0.78		0.35
Zn (μg g ⁻¹)	0.10	0.74	-0.24	-0.39
pH	0.42	0.56	-0.17	-0.38
Cd (μg g ⁻¹)	0.21		0.94	
Pb (μg g ⁻¹)	0.14	-0.13	0.90	
Ni (μg g ⁻¹)	0.10			0.85
Eigen value	4.64	2.72	1.54	1.15
Variance %	38.65	22.63	12.87	9.62
Cumulative %	38.65	61.28	74.15	83.76

A marked bold is referred to the loadings having a greater than 0.60 and bold loadings are statistically significant

the metals is high, metals have common sources, mutual dependence and identical behavior during the transport. The absence of correlation among the other metals suggests that the concentrations of these metals are not controlled by a single factor. In the present study, Cu, Zn, Ni, Cd and Cr had a common source, whereas others metals may have diverse sources. While, higher elemental pair correlation is representing the influence of primary anthropogenic source such as urbanization and human progress [68].

3.10 Principal component analysis (PCA)

The principal component analysis with varimax for various trace elements and the loadings recording more than 0.60 in the current study (Table 9). The first principal component (PC1), accounting for 38.65% of the total variance with an eigenvalue of 4.64, displayed significant weight components of Cr = 0.78 and sand = 0.76, explaining the role of weathering and anthropogenic sources [69]. On the other hand, the PC2 was accounted for 22.63% of the total variance of with an eigenvalue of 2.72 that dominated with Cu (0.78) and Zn (0.76). Moreover, the PC3 has loadings for the following trace elements Cd: 0.94

and Pb: 0.90 with total variance of 12.87% (eigenvalue = 1.54) which are commonly originated from anthropogenic inputs such as sewage treatment plant at Tarut Island (sites 4-6), the Aramco refinery at Abu Ali Island (site 13), commercial harbors and Industrial waste disposal at Dammam city (site 1) [51,55,70]. Eventually, PC4 amounted to 9.62% of the total variance with an eigenvalue of 1.15, which overloaded with Ni (0.85) OM (0.60). Obviously, these results may be a subsequent of the human activities as a result of the continuous inputs from various sewage discharge and Aramco refinery [55].

4 Conclusion

The detected trace elements (μg g⁻¹) in surface sediments of the investigated sites from Saudi Arabia's Gulf coastline are in the following descending order according to their mean values; Cr>Zn>Cu>Pb>Ni>Cd. The elevated concentrations of the measured trace elements were recorded at sites that are subjected to different anthropogenic activities and pollutants. The I_{geo} and E_r^i results indicated that site 6 classified as heavily to extremely contaminated with Cd. Furthermore, contamination factor revealed the most sites varied from considerable to very highly contaminated with Cd but low contamination from Zn, Cr, Pb, and Ni. The interrelationships between physico-chemical characters of the sediments and trace elements suggests grained particles of mud represent a noteworthy character in the distribution of trace elements compared to organic materials. Moreover, the results revealed that Zn was clearly bioaccumulated in leaves of *A. marina*. Owing to environmental management, these results could be used as contribution to the information and rational management of the Arabian Gulf.

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this work.

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