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ORIGINAL RESEARCH ARTICLE

Ecological assessment of heavy metals in the grey mangrove (*Avicennia marina*) and associated sediments along the Red Sea coast of Saudi Arabia

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Summary Mangroves play an integral role as a metal accumulator in tropical and subtropical marine ecosystems. Twenty-one sets of sediment samples and portions of mangroves were collected along the Saudi Arabian coast of the Red Sea to assess the accumulation and ecological risks of heavy metals. Results showed that the following mean concentrations of heavy metals in sediments: Cr (46.14 $\mu g\ g^{-1}$ $\pm$ 18.48) > Cu (22.87 $\mu g\ g^{-1}$ $\pm$ 13.60) > Ni (21.11 $\mu g\ g^{-1}$ $\pm$ 3.2) > Pb (3.82 $\mu g\ g^{-1}$ $\pm$ 2.46) > Cd (0.75 $\mu g\ g^{-1}$ $\pm$ 0.87). The maximum concentrations of the studied metals were above the threshold effect level, indicating a limited impact on the respective ecosystems. The maximum concentration of Cd exceeded its toxic effect threshold, revealing a harmful risk to biota in the sediments. Based on metallo-phytoremedation, biological concentration factors were >1, suggesting that *Avicennia marina* can accumulate heavy metals, especially Cr and Pb. The translocation factor was above the known worldwide average. The geo-accumulation index revealed that sediments in mangrove areas ranged from moderately to heavily contaminated with Cd at Al-Haridhah and moderately contaminated at South Jeddah, Rabigh, Duba, and the wastewater treatment station near Jazan. The ecological risk index revealed that Cd could pose a relatively very high risk to the mangrove ecosystem. The present study emphasized the possibility of establishing a framework for the management of the coastal aquatic ecosystems along the Red Sea coast of Saudi Arabia.

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1. Introduction

Human activities such as transportation, construction and manufacturing not only diminish natural resources but also create large quantities of waste materials that cause soil, water and air pollution. These waste further results in global warming, acid rain and ocean contamination (Saenger et al., 1983). Mangrove ecosystems are highly influenced by anthropogenic activities including urbanization, pollutants from urban runoff, oil spills, industrial wastes, harmful waste disposal and wastewater treatment plants and are highly susceptible to the accumulation of heavy metals from all of these sources (Bodin et al., 2013; Marchand et al., 2006). Throughout tropical and subtropical tidal marshes, mangrove ecosystems are located mainly in intertidal and subtidal estuarine wetlands (Lee et al., 2014; Qiu et al., 2011; Wang et al., 2013). These regions are further characterized by mangrove plants, including shrubs and trees (monocots and dicots), that provide unique ecological benefits (Fernández-Cadena et al., 2014; Lewis et al., 2011). Mangrove plants act as a large source of organic carbon for the associated sediments and have a direct impact on the food web of the marine ecosystem (Alongi, 2002; Asaeda and Kalibbala, 2009; Wang and Sousa, 2009). In addition, they provide nursery shelter for many marine organisms (MacFarlane et al., 2007; Walters et al., 2008) and are used by human beings in many ways, such as food, fodder for animals, house construction, fishing boat construction and warming/cooking of food (FAO, 2007; PERSGA, 2004). Mangrove plants further represent a refuge for many migratory birds (Abohassan et al., 2012; Kumar et al., 2010).

Generally, mangroves are known to adapt well to different environmental conditions such as low oxygenated sediments, intermittent flooding, sustaining osmotic balance and metal pollutants (Buajan and Pumijumnong, 2010; Greger, 2004; Li et al., 2016; MacFarlane et al., 2007). Several studies have been carried out on heavy metal pollution within mangrove environments worldwide (e.g., Bodin et al., 2013; Defew et al., 2005; Fernandes et al., 2012; Fernández-Cadena et al., 2014; Li et al., 2016; Usman et al., 2013). These studies have proven the capability of mangroves to eliminate or control the absorption of various heavy metals next to the root media and transport them to the shoot (MacFarlane et al., 2003). Heavy metals are considered to be hazardous pollutants when they have a specific density greater than 5 g cm^{-3}, and they may change the structure of the environment and living organisms (Järup, 2003; Yan et al., 2017). High concentrations of heavy metals in sediments can also result in reduced density and diversity of organisms by affecting the balance of the food chain. They can also alter survival, metabolism, growth and reproduction of organisms (Wright and Welbourn, 2002). Numerous studies have pointed out that metal pollutants (Pb, Mn, Cu, Zn, Fe and Cd) accumulate mainly in the root tissue as compared to the shoots in various mangrove taxa such as *Rhizophora* spp., *Avicennia* spp. and *Kandelia* spp. (Chiu et al., 1995; MacFarlane and Burchett, 2002; Peters et al., 1997; Tam and Wong, 2000; Thomas and Fernandez, 1997). Globally, many indices can be used to assess the status of heavy metals in the surrounding environment and their potential risks. These indices include contamination factor (CF), pollution load index (PLI), potential ecological risk, ecological risk index (E_r^i) and geo-accumulation index (I_{geo}) (Li et al., 2016; Nath et al., 2014; Sakan et al., 2015; Sekabira et al., 2010; Udechukwu et al., 2015).

As a part of urbanization, the Red Sea coast is continuously subjected to changes that result in the loss of many intertidal and near shore subtidal habitats (Chiffings, 1989). Petrochemical industries and the associated ship traffic can also cause pollution in coastal water bodies of the Red Sea (Badr et al., 2009; Fahmy and Saad, 1996). However, it has also been reported that mangrove plants in the Red Sea environment of Saudi Arabia are exposed to severe growth conditions such as extreme salinity, low soil fertility and poor textures (Mandura et al., 1988) as well as anthropogenic activities that contribute various pollutants, particularly trace elements (Badr et al., 2009). Current information about the interactions between heavy metals in the sediments and mangrove plants is inadequate, especially as pertains to the Red Sea coastal area of Saudi Arabia (Badr et al., 2009; Usman et al., 2013). Accordingly, this work was designed to assess the status of heavy metals and their potential risk to the grey mangrove, *Avicennia marina* (Forsk.) Vierh, and associated sediments along the Red Sea coast of Saudi Arabia.

2. Material and methods

2.1. Study area

The length of the Saudi Arabian coastline is approximately 1840 km, which comprises 79% of the eastern Red Sea coastline (MEPA/IUCN, 1987). The present study area extended along the entire Saudi Arabian coast of the Red Sea (between 36°10′—42°20′E, 16°30′—25°30′N). The study was conducted during February—March 2014. Sediment and mangrove samples (aerial roots and leaves) were collected from twenty-one mangrove stands distributed along the coastlines of several cities (Fig. 1 and Table 1). These stations, arranged from south to north, are as follows: Jazan (5 stations), Sabya (1 station), Wadi Baish (1 station), Al-Haridhah (1 station), Al-Qahma (1 station), Al-Birk (1 station), Al-Shaqqah (1 station), Al-Lith (2 stations), Jeddah (3 stations), Rabigh (3 stations), Al-Wajh (1 station) and Duba (1 station). The Jazan region comprised a total of 5 stations in which JI was characterized by the presence of dead mangrove trees, JII lies near a fish farm effluent, JIII was located in front of a sewage water treatment plant, JIV was 2 km away from a sewage treatment plant, and JV was situated near a shelter area for fishing boats. Stations such as Sabya (VI), Wadi Baish (VII), Al-Haridhah (VIII), Al-Qahma (IX), Al-Birk (X), Al-Shaqqah (XI) and Al-Lith (XII) represented the typical type of mangrove stands (back reef) located at the end of wadis. The Al-Haridhah station (VIII) was located near a fish farm effluent. Of the three stations studied in the Jeddah region, one station (XV) was located near the effluent of a municipal sewage treatment plant. The Rabigh area contained two stations (one located at the end of the Al-Kharrar lagoon and the other in the central part of the lagoon), while Al-Wajh and Duba consisted of one station each that can be considered as unaffected by human interference.

2.2. Physico-chemical properties and heavy metals determination in sediments

Composite surface sediment (0—10 cm) samples were randomly collected from all the studied stations from

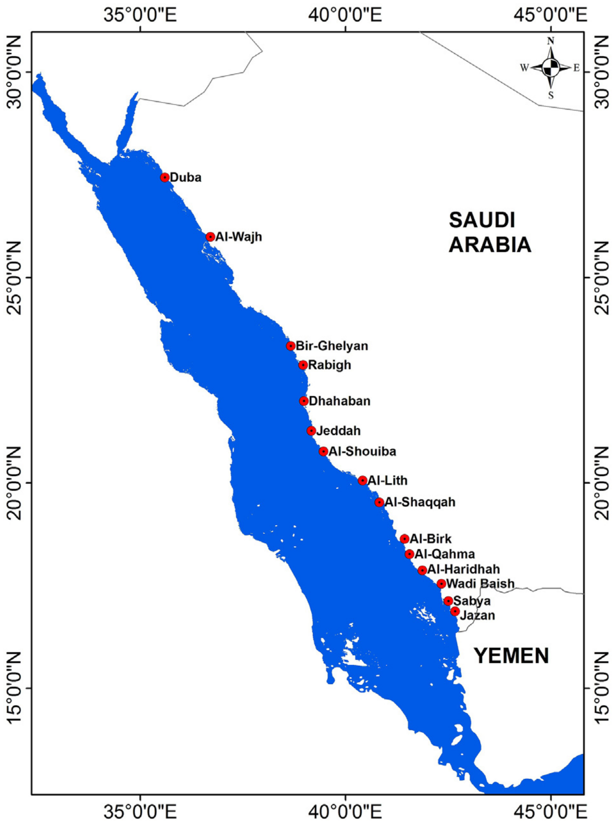

Figure 1 Sampling stations along the Saudi Arabian coast of the Red Sea.

underneath/or adjacent to the mangrove trees. All the sediment samples were dried at 50 ± 5°C, sieved through a 63 μm stainless steel sieve and stored for subsequent analysis. To determine the physico-chemical properties of the sediments, particle size distributions were examined using the pipette method as described by Dewis and Fertias (1970). Total carbonates were estimated gasometrically using a Collins calcimeter and calculated following Hesse (1971). Total soluble salts were determined by measuring electrical conductivity (dS m^{-1}) in 1:3 soil:water extract and soil pH (in saturated soil paste), while total organic matter (TOM) was measured according to Walkley and Black (1934). The concentrations of Cr, Cu, Ni, Pb and Cd were measured according to the direct aqua regia method. A total of 1000 mg of normalized sediment sample was weighed and digested using a 4:1 mix of nitric acid (HNO_3 AnalaR grade, BDH 69%) and perchloric acid ($HClO_4$, AnalaR grade 60%) (Yap et al., 2002). The digested samples were then filtered and diluted with deionized water to a total volume of 50 ml and kept for further analysis. The total content of Cr, Cu, Ni, Pb and Cd in the sediment samples were analysed using ICP-OES.

2.3. Sediment quality guidelines

In this study, sediment quality guidelines (SQGs) were applied as described by Bakan and Özkoç (2007), Luo et al. (2010) and MacDonald et al. (2000). These guidelines include the lowest effect level (LEL), threshold effect level (TEL), probable effect level (PEL), effect range low (ERL), probable effect

Table 1 Coordinates of the studied mangrove stations along the Saudi Arabian coast of the Red Sea.

Station name	Station no.	Latitude	Longitude
Jazan	JI	16°41′38.18″N	42°43′3.57″E
	JII	16°43′50.49″N	42°42′22.91″E
	JIII	16°47′5.84″N	42°40′22.43″E
	JIV	16°46′32.57″N	42°40′24.37″E
	JV	16°49′39.37″N	42°36′36.09″E
Sabya	VI	17°3′3.74″N	42°27′8.99″E
Wadi Baish	VII	17°10′43.76″N	42°21′57.12″E
Al-Haridhah	VIII	17°48′4.32″N	41°53′21.38″E
Al-Qahma	IX	17°57′13.99″N	41°41′2.28″E
Al-Birk	X	18°7′11.99″N	41°34′51.97″E
Al-Shaqqah	XI	19°47′32.84″N	40°37′50.29″E
Al-Lith			
Al-Lith 1	XII	20°3′11.06″N	40°25′0.06″E
Al-Lith 2	XIII	20°32′49.87″N	39°36′40.36″E
Jeddah			
Al-Shouiba	XIV	20°45′46.94″N	39°27′59.26″E
South Jeddah	XV	21°16′8.27″N	39°7′33.13″E
Dhahaban	XVI	21°59′24.84″N	38°59′15.84″E
Rabigh			
Rabigh I	XVII	22°51′50.75″N	38°58′12.43″E
Rabigh II	XVIII	22°54′7.61″N	38°55′13.38″E
Bir-Ghelyan	XIX	23°19′45.49″N	38°41′15.70″E
Al-Wajh	XX	25°59′27.67″N	36°42′39.29″E
Duba	XXI	27°25′52.30″N	35°36′9.54″E

level (PEL), effect range median (ERM), severe effect level (SEL), and toxic effect threshold (TET).

2.4. Heavy metals determination in leaves and pneumatophores (aerial roots) of mangroves

Leaves of *A. marina* were collected from 5 to 10 trees of similar health status (>3 m in height and >20 cm in diameter at breast height) from the studied stations. Three leaves of the second whorl from each tree were collected from each of three facing branches at 1 m in height. In addition, aerial roots were sampled from what were considered to be nutritive roots for absorption; larger anchoring roots were avoided. The samples (leaves and aerial roots) were washed several times with distilled water to remove the adhering fine sediments and homogenized after drying at 60°C. One gram (with three replicates) of the ground leaf material was placed into 125 ml digestion tubes. Five ml of concentrated perchlorate acid was added to each tube in a block digester, then heated for 3 h at 120°C, and finally diluted to a final volume of 50 ml upon analysis (Cottenie et al., 1982). Heavy metal (Cr, Cu, Ni, Pb and Cd) concentrations, as $\mu g\ g^{-1}$, were determined using an Inductively Coupled Plasma Optical Emission Spectrometer (Optima 5300 DV with an autosampler Model AS 93 Plus/S10, Perkin Elmer, USA). Standards were prepared to detect the concentrations of the digested samples. To ensure the accuracy of the analysis, a certified reference material from the National Institute of Standards and Technology Standard (CRM 1570) was used. The certified reference material was analysed (in triplicate) with the measured samples for quality control of the analytical procedures. The results showed that all of the heavy metals were analysed with a 99.5% recovery rate.

2.5. Biological concentration (BCF) and translocation factors (TFs)

In the present study, three relative measures of metal uptake were used to differentiate the uptake of each heavy metal. The biological concentration factor (BCF) of aerial roots and leaves was calculated to evaluate the sensitivity of different tissue types under varying environmental loadings. In addition, the translocation factor (TF) was calculated as the ratio between the concentrations of heavy metals in the leaves and the aerial roots. This parameter indicates the ability to transport heavy metals from the roots to the leaves. BCF and TF values for aerial roots and leaves were expressed as original data averages. For the heavy metals (Cr, Cu, Ni, Pb and Cd), the bio-concentration factors were calculated based on the equation described by Cui et al. (2007) and Yoon et al. (2006):

$$\mathrm{BCF}_{\mathrm{leaf}} = \frac{C_{\mathrm{leaf}}}{C_{\mathrm{sediment}}}, \quad \mathrm{BCF}_{\mathrm{root}} = \frac{C_{\mathrm{root}}}{C_{\mathrm{sediment}}}, \tag{1}$$

where C_{leaf} and C_{root} are the heavy metal concentrations in the leaf and aerial root, respectively, and C_{sediment} is the heavy metal concentration in the sediment. The translocation factor (TF) was calculated using the following equation:

$$\mathrm{TF}_{\mathrm{leaf}} = \frac{C_{\mathrm{leaf}}}{C_{\mathrm{root}}}, \tag{2}$$

where C_{leaf} and C_{root} are the heavy metal concentrations in the leaves and roots, respectively.

2.6. Risk assessment model

For environmental pollution assessment, the geochemical and physiochemical characteristics of sediments are very crucial to identify the contamination sources. Geo-accumulation index (I_{geo}) was calculated to assess the changes of heavy metal concentrations by associating the heavy metal concentrations in aquatic sediments with the geochemical background. It is calculated according to Müller (1969) based on the following equation:

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right), \tag{3}$$

where C_n is the concentration of metal measured in mangrove sedimentary and B_n is the geochemical background value in the earth's crust (Taylor and McLennan, 1985). A constant of 1.5 was applied to account for the potential variability in the reference value due to the influence of lithogenic processes. In this regard, seven classes of I_{geo} were categorized as follows: uncontaminated (UC) when $I_{geo} \leq 0$; uncontaminated to moderately contaminated (UMC) when $0 < I_{geo} < 1$; moderately contaminated (MC) when $1 < I_{geo} < 2$; moderately to heavily contaminated (MHC) when $2 < I_{geo} < 3$; heavily contaminated (HC) when $3 < I_{geo} < 4$; heavily to extremely contaminated (HEC) when $4 < I_{geo} < 5$; and extremely contaminated (EC) when $5 < I_{geo}$. The probable ecological risk coefficient (E_r^i) was calculated using the formula by Hakanson (1980) as follows:

$$E_r^i = T_r^i * C_r^i = T_r^i * \frac{C_s^i}{C_n^i}, \tag{4}$$

where T_r^i values for measured heavy metals are as follows: Cr = 2, Cu = 5, Ni = 5, Pb = 5 and Cd = 30; C_r^i is the contamination factor; C_s^i is the concentration of heavy metals in the sediment; C_n^i a background value for heavy metals and T_r^i is the metal toxic response factor. The degree of E_r^i can be categorized as follows: if $E_r^i < 40$: low risk (LR), $40 \leq E_r^i < 80$: moderate risk (MR), $80 \leq E_r^i < 160$, considerable risk (CR), $160 \leq E_r^i < 320$: high-risk (HR) and $E_r^i \leq 320$: very high risk (VHR).

2.7. Statistical analysis

Descriptive statistics for each of the studied heavy metals in sediments were obtained using the Statistical Package for the Social Sciences (SPSS) (version 23.0). The possible relationship between measured heavy metals and the other physico-chemical properties was determined by calculating Pearson's correlation coefficient (r). A principal component analysis (PCA) was performed on the logarithmic transformed data using factor extraction. The Eigenvalue remained greater than 1 after varimax rotation.

Table 2 Physico-chemical properties of the investigated mangrove sediments along the Saudi Arabian coast of the Red Sea (EC = electrical conductivity, $\%CaCO_3$ = percent of calcium carbonate, %OM = percent of organic matter).

Characters	Range	Mean	Std. error	Std. deviation	Variance	Skewness	Kurtosis
Sand%	90.0—99.8	96.56	0.60	2.75	7.55	−1.07	0.28
Mud%	0.2—10.0	3.45	0.56	2.74	7.56	1.06	0.26
Soil pH	4.3—8.1	7.45	0.18	0.84	0.71	−2.94	10.27
EC [dS m^{-1}]	2.3—37.5	12.47	2.01	9.20	84.58	1.50	1.62
$\%CaCO_3$	1.3—71.4	14.83	3.99	18.26	333.48	1.89	3.67
%OM	0.3—5.0	2.54	0.31	1.44	2.08	0.21	−0.96

3. Results and discussions

3.1. Sediment characteristics and quality

The properties of the studied sediment samples (conductivity, acidity and organic matter content) are presented in Table 2. Based on the grain size analysis, the results revealed that sand is the highly dominant fraction at all of the study stations (90% to 99.8%). According to the soil texture of the studied stations, which was predominantly sandy, the soils were then classified as "sandy, siliceous, hyperthermic, and *aquic Torripsamments*". Soil pH values fluctuated within a wide range, from 4.28 at JII and 8.08 at Al-Wajh area (XX), with a mean value of 7.45. The lower pH values were observed at the same stations that displayed higher concentrations of organic matter. Electrical conductivity (EC) ranged from 2.31 to 37.50 dS m^{-1} at Rabigh 1 (XVII) and JI, respectively (average: 12.47 dS m^{-1}). This high variation can be explained by the fact that Red Sea mangroves usually grow in coastal areas that receive seasonal floods, which in turn reduce the salinity of those regions (Usman et al., 2013). The higher salt concentrations observed at station JI can also be due to the construction of a road, which eventually separated the mangrove swamp from the sea. This unexpected increase in salt concentration can adversely affect the growth of mangrove trees, which further leads to their death and decay (Lambs et al., 2015). Calcium carbonate concentration in sediment samples varied from 1.30% to 71.40%, with a mean value of 14.83%. Organic matter content was relatively low and ranged from 0.27% to 5.00% (average: 2.54%). The highest values of 5.00%, 4.46%, 4.46% and 4.94% were observed at stations JI, JII, JIV and XIX, respectively. This can be mainly due to the accumulation of mangrove litter in the associated sediments at these stations. This phenomenon can be further connected to the higher salinities observed at these stations, which, as mentioned above, will reduce the growth of the mangrove trees and have an inhibitory effect on the decomposition of organic substances in sediments within the mangrove ecosystem (Van de Broek et al., 2016).

The concentrations of the different heavy metals in the sediment samples varied from 10.19 to 76.79 $\mu g\ g^{-1}$ for Cr, from 3.27 to 51.46 $\mu g\ g^{-1}$ for Cu, from 7.00 to 59.19 $\mu g\ g^{-1}$ for Ni, from 0.80 to 10.07 $\mu g\ g^{-1}$ for Pb and from 0.10 to 3.10 $\mu g\ g^{-1}$ for Cd (Table 3). These heavy metals are arranged as following order according to their mean value and standard deviation: Cr (46.14 $\mu g\ g^{-1} \pm 18.48$) > Cu (22.87 $\mu g\ g^{-1} \pm 13.60$) > Ni (21.11 $\mu g\ g^{-1} \pm 3.2$) > Pb (3.82 $\mu g\ g^{-1} \pm 2.46$) > Cd (0.75 $\mu g\ g^{-1} \pm 0.86$). The highest value of Cr (76.79 $\mu g\ g^{-1}$) was observed at station XVI. The highest concentrations of Cu and Ni were detected at stations JII, XVI and XVII, and the highest value of Pb (10.07 $\mu g\ g^{-1}$) was recorded at station XIX. The concentrations of Cd were relatively high at stations III, IV, XIV, XVI and XVII, with the maximum value (3.10 $\mu g\ g^{-1}$) observed at station IV. Interestingly, the highest concentrations of most of the heavy metals were observed at stations that were positioned near various anthropogenic influences, such as sewage effluents, refineries, aquaculture facilities and commercial ports. These findings are in agreement with those reported by Badr et al. (2009), who emphasized that the upper 15 cm of sediments contained higher concentrations of pollutants (Cr, Ni, Mn and Zn) along the Red Sea coastal areas of Saudi Arabia. The average concentration of Cu was 22.87 $\mu g\ g^{-1}$ and is lower than the values obtained from previous studies in the Red Sea area, except for the Farasan Island region (Table 3). We assume that the major reason for this difference is the presence of many fishing boats that use antifouling paints containing $CuSO_4$ as a major ingredient, as proposed by Usman et al. (2013). The mean concentration of Ni (21.11 $\mu g\ g^{-1}$) was lower than its value in previous studies in the Red Sea except for Farasan Island (Saudi Arabia) and the Yemeni coast (Table 3). Moreover, the mean concentration of Pb was higher than recorded by Abohassan (2013) at both the Al-Shouiba and Yanbou sites (Table 3). Except for Jeddah and Rabigh, the mean concentration of Cd was typically higher in the current study than values recorded in previous studies carried out along the Red Sea (Table 3). From a global perspective, many investigators have discussed the possibility of anthropogenic influences being responsible for the increase of heavy metals in mangrove sediments (e.g., Cuong et al., 2005; Defew et al., 2005; El-Said and Youssef, 2013; Harikumar and Jisha, 2010; Li et al., 2016; Qiu et al., 2011; Tam and Wong, 2000). Both the maximum (3.10 $\mu g\ g^{-1}$) and the average (0.75 $\mu g\ g^{-1}$) concentrations of Cd in the investigated area surpassed the averages in shale around the world (Turekian and Wedepohl, 1961). The maximum concentration observed for Cu (51.46 $\mu g\ g^{-1}$) was also above the world average concentration in shale (45 $\mu g\ g^{-1}$) and is comparable to the findings of Lindsay (1979). The results of this study revealed that the maximum concentrations of Cu, Ni, Pb and Cd exceeded the minimum and average of the common ranges (30, 40, 10 and 0.10 $\mu g\ g^{-1}$ respectively). This indicates the possible lithogenic origin of all of these heavy metals (Cu, Ni, Pb and Cd). It is known that heavy metals can be introduced into coastal environments from different sources, including natural weathering processes and anthropogenic activities (Badr

Table 3 Comparison of total heavy metals [$\mu g\ g^{-1}$] in mangrove sediment at different stations along the coastal areas from Saudi Arabia and around the world.

Locations	Cr	Cu	Ni	Pb	Cd	References
Minimum (Min.)	10.19	3.27	7.00	0.80	0.10	Current study
Maximum (Max.)	76.79	51.46	59.19	10.07	3.10	
Average	46.11	22.87	21.11	3.82	0.75	
Std. deviation (SD)	18.48	13.60	13.85	2.46	0.86	
Average shale	90	45	68	20	0.30	Turekian and Wedepohl (1961)
Common range						
Max.	1000	100	500	200	0.70	Lindsay (1979)
Min.	1	2	5	2	0.01	
Av.	100	30	40	10	0.06	
The coastal areas of Red Sea						
Saudi Arabia						
Farasan Island	9.6	112.0	8.50	45.2	1.23	Usman et al. (2013)
Al-Shouiba	8.8	4.10	27.40	0.5	0.02	Abohassan (2013)
Yanbou	11.5	13.90	—	3.8	0.20	Abohassan (2013)
Jeddah	17.9	20.60	76.60	89.5	4.84	Badr et al. (2009)
Rabigh	19.4	21.30	80.10	87.2	3.51	Badr et al. (2009)
Egypt	ND	108	22	25	1.8	El-Said and Youssef (2013)
Yemen	20.2	32.10	12.00	6.90	—	Hassan and Nadia (2000)
Around the world						
Kottuli, India	ND—0.71	0.8—224	0.03—1.9	2.3—23.6	ND—0.08	Harikumar and Jisha (2010)
Punta Portete, Costa Rica	22.60	8.40	102.00	34.50	7.30	Guzmán and Jiménez (1992)
Queensland, Australia	72.00	1—12	9.00	36.0	0.60	Preda and Cox (2002)
Mai Po, Hong Kong	39.20	78.50	—	79.2	2.62	Tam and Wong (2000)
Guanabara Bay, Brazil	42.40	98.60	—	160.8	1.32	Kehrig et al. (2003)
Punta Mala Bay, Panama	23.30	56.30	27.3	78.2	<10	Defew et al. (2005)
Shenzhen Bay, China	75.70	79.72	40.40	—	0.83	Li et al. (2016)
South Port Klang, Malaysia	60.19	24.89	13.9	96.02	1.46	Udechukwu et al. (2015)
Threshold effect concentration (TEC) SQGs						
Threshold effect level (TEL)	26	16	16	31	0.596	MacDonald et al. (2000)
Lowest effect level (LEL)	37.3	35.7	18	35	0.6	
Effect range low (ERL)	80	70	30	35	5	
Canadian sediment quality guidelines (TEL)	—	18.7	—	30.2	0.7	Canadian Council of Ministers of Environment (2002)
Probable effect concentration (PEC) SQGs						
Probable effect level (PEL)	90	149	36	91.3	3.53	MacDonald et al. (2000)
Severe effect level (SEL)	110	110	75	250	10	
Toxic effect threshold (TET)	100	86	61	170	3	
Effective range median (ERM)	145	390	50	110	9	
Canadian sediment quality guidelines (PEL)	—	108	—	112	112	Canadian Council of Ministers of Environment (2002)

et al., 2009; Sadiq and Zaidi, 1994). Several previous studies have recorded high concentrations of heavy metals in mangrove sediments and have concluded that anthropogenic activities are a long-term pollution source (e.g., Defew et al., 2005; Tam and Wong, 2000). This study revealed that the measured concentrations of Cd, Cr, Cu, Ni and Pb were above the optimum levels in some of the mangrove sediments from the Red Sea as well as other mangrove ecosystems worldwide (Table 3). The average concentration of Cr was also higher than the average concentrations within the Red Sea coastal area but was lower than other studies, especially in China and Australia (Li et al., 2016; Udechukwu et al., 2015).

3.2. Sediment quality guidelines (SQGs)

In terms of TEC, the results obtained here revealed that the maximum concentrations of Cr and Cu were 76.79 and 51.46 $\mu g\ g^{-1}$, respectively. These values were higher than the LEL, but below the TEL and the ERL, as illustrated in Table 3. The maximum concentration of Ni (59.19 $\mu g\ g^{-1}$) was above the TEC, EL, TEL and ERL. On the other hand, the maximum concentration of Pb (10.07 $\mu g\ g^{-1}$) was below the LEL, TEL and ERL. The maximum concentration of Cd (3.10 $\mu g\ g^{-1}$) exceeded its LEL and TEL limits, revealing its extreme impact on different biological processes (MacDonald et al., 2000). Regarding the PEL, the maximum

Table 4 Average concentrations of measured heavy metals [$\mu g\ g^{-1}$ dw] in mangrove tissue along Saudi Arabian coast of the Red Sea and around the world.

Locations	Tissue type	Cr	Cu	Ni	Pb	Cd	References
Saudi Arabian coastal areas, Red Sea	Leaves	14.96	13.24	7.56	3.79	0.18	Current study
	Pneumatophores	17.46	9.82	7.58	3.67	0.07	
Excessive or toxic levels		5–30	20–100	10–100	30–300	5–30	Kabata-Pendias and Pendias (1992)
Farasan Island, Saudi Arabia	Leaves	9.30	356.6	2.30	–	1.04	Usman et al. (2013)
	Pneumatophores	14.9	270.5	4.02	–	NC	
Al-Shouiba, Saudi Arabia	Leaves	4.53	4.17	6.70	0.57	0.01	Abohassan (2013)
	Pneumatophores	4.35	3.37	4.07	–	0.33	
Yanbou, Saudi Arabia	Leaves	2.37	6.38	21.10	–	–	Abohassan (2013)
	Pneumatophores	11.94	6.79	3.64	0.46	0.32	
Around the world							
Shenzhen, China	Leaves	–	5.20	–	1.90	–	Li et al. (2016)
	Pneumatophores	–	13.00	–	3.50	–	
Punta Mala Bay, Panama	Leaves	–	3.70	–	6.20	–	Guzmán and Jiménez (1992)
	Pneumatophores	–	–	–	–	–	
FAO (2007)	Leaves	5.00	40.00	1.50	5.00	0.20	FAO (2007)
	Pneumatophores	–	–	–	–	–	
Sydney Estuary, Australia	Leaves	–	–	–	–	–	Nath et al. (2014)
	Pneumatophores	1.40	20.00	2.00	5.80	0.60	
Port Jackson, Australia	Leaves	–	3.2	–	1.7	–	MacFarlane and Burchett (2002)
	Pneumatophores	–	–	–	–	–	

concentration of Ni (59.19 $\mu g\ g^{-1}$) was above the PEL and ERM levels, but it was below the SEL and TEL. This can be considered as an occasional threat to benthic organisms (MacDonald et al., 2000). In the case of Cr, Cu and Pb, their maximum concentrations were lower than the PEL, ERM, SEL and TET, which in turn reveals an adverse biological impact. The maximum concentration of Cd also exceeded its TET and can be considered as harmful to benthic organisms (MacDonald et al., 2000; Vane et al., 2009). By comparing the mean concentrations of Cu, Cd, and Pb with those of Canadian sediment quality guidelines, it was observed that the concentrations of Cu and Cd were above the TEL. This indicates that adverse biological effects may occur frequently (Canadian Council of Ministers of the Environment, 2002). On the other hand, the concentrations of Cu, Pb and Cd were below the PEL, which shows that these metals are not known to have any negative impact on living organisms.

3.3. Accumulation of heavy metals in mangrove compartments

The results obtained here indicated wide variations in the content of heavy metals within the leaves and aerial roots of *A. marina*. The concentrations of heavy metals were in the following order: Cr > Cu > Ni > Pb > Cd and are shown in Table 4. The levels of measured heavy metals, especially Cr, in mangrove tissues were considered to be relatively high when compared with respective global concentrations. This may be due to the presence of those metals in higher concentrations in the surrounding sediments. This study showed that the concentrations of Cr in the root tissues of mangrove plants were relatively higher than the concentrations in the leaves. Chromium can be highly toxic to plants, seriously affecting their growth; however, the exact mechanism of Cr translocation in plants remains uncertain (Hajar et al., 2014; Shanker et al., 2005). In the current study, the concentrations of Ni and Pb observed in the leaves were comparable with those observed in the aerial roots of the same mangroves. Generally, most of the absorbed trace elements are restricted to the outer cortex of the root (MacFarlane et al., 2003; Peng et al., 1997). The present study clearly showed that the concentrations of most accumulated heavy metals in mangrove tissues were higher than their respective concentrations in mangroves worldwide (Guzmán and Jiménez, 1992; Li et al., 2016; MacFarlane and Burchett, 2002; MacFarlane et al., 2003; Peng et al., 1997; Qiu et al., 2011; Usman et al., 2013) (Table 4). One of the most important findings of the current study was the higher concentrations of Cr in both the leaves and aerial roots of *A. marina*, which were considerably above toxic levels (Kabata-Pendias and Pendias, 1992). Moreover, it was also clear from the present study that the accumulation of Cr in the sediments was higher than that in the aerial roots and leaves (Fig. 2), which further indicates the passive absorption of Cr by *A. marina* compared to the other heavy metals. Except for Pb and Cd, the present study found much

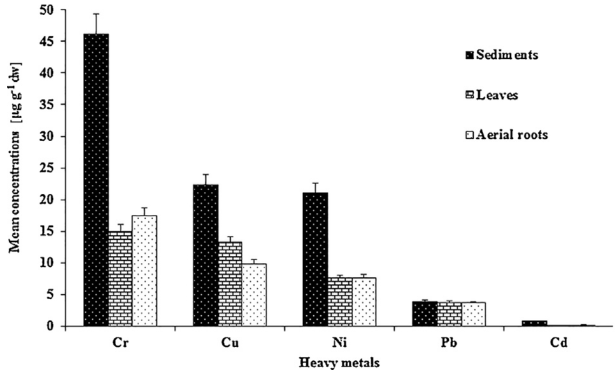

Figure 2 Average concentrations (± standard error) of heavy metals in sediment, mangrove leaves and aerial roots.

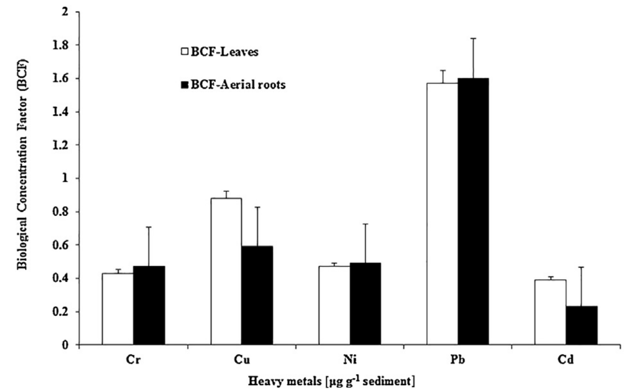

Figure 3 Average of biological concentration factors (± standard error) of heavy metals in mangrove leaves and aerial roots.

higher values for the other heavy metal concentrations in the sediments than in the aerial roots and leaves of *A. marina*.

3.4. Biological concentration factors (BCFs) and translocation factors (TFs)

The mean BCFs values obtained for Cr, Cu, Ni, Pb and Cd in the mangrove leaves were 0.43, 0.88, 0.47, 1.57 and 0.39, respectively (Table 5). Moreover, the mean BCFs values in aerial roots were 0.47 for Cr, 0.59 for Cu, 0.49 for Ni, 1.60 for Pb and 0.23 for Cd. In general, the highest BCF average among the different investigated stations was obtained for Pb in both the leaves and aerial roots. This is a clear reflection of the bioavailability of Pb in the sediments as compared to other heavy metals (Fig. 3). The lowest BCF values in the highly contaminated sediments (station XIII) can be due to the low bioavailability of these heavy metals in the respective sediments. This can be explained by the binding of heavy metals to form immovable compounds as a result of chelation with organic molecules (Li et al., 2016; MacFarlane et al., 2003; Nath et al., 2014). Future studies regarding the bioavailable fractions and toxicity of heavy metals should take speciation into consideration (Li et al., 2016; Luo et al., 2017; MacFarlane et al., 2007). Generally, plants with TF values greater than 1 are classified as having a greater potential for metal accumulation in polluted sites (Usman et al., 2012). These plants can effectively translocate metals

Table 5 Comparison between the biological concentrations factors (BCFs), translocation factors (TFs) of heavy metals in the Red Sea coastal areas and around the world.

Locations	Tissue type		Cr	Cu	Ni	Pb	Cd	Reference
Red Sea coastal areas, Saudi Arabia	BCF	Leaves	0.43	0.88	0.47	1.57	0.39	Current study
		Pneumatophores	0.47	0.59	0.49	1.60	0.23	
		TF	0.90	1.74	1.29	1.42	2.72	
Farasan Island, Saudi Arabia	BCF	Leaves	0.23	1.25	1.06	—	1.50	Usman et al. (2013)
		Pneumatophores	4.23	9.08	3.01	0.01	0.03	
		TF	0.42	1.30	0.35	0.00	00	
Al-Shouiba, Saudi Arabia	BCF	Leaves	0.34	1.00	0.46	1.07	0.50	Abohassan (2013)
		Pneumatophores	3.43	9.23	1.21	9.45	16.50	
		TF	0.25	0.10	0.20	0.11	0.03	
Futian Mangrove, South China Sea	BCF	Leaves	—	—	—	—	—	Li et al. (2016)
		Pneumatophores	0.36	0.10	0.27	—	0.06	
		TF	0.22	2.27	0.38	—	0.58	
Shenzen, China	BCF	Leaves	—	0.15	—	0.06	—	Peng et al. (1997)
		Pneumatophores	—	0.37	—	0.10	—	
		TF	—		—	0.54		
Ting Kok, Hong Kong	BCF	Leaves	—	1.26	—	0.24	—	Chen et al. (2003)
		Pneumatophores	—	1.02	—	0.44	—	
		TF	—	1.23	—	0.53		
SE, Australia	BCF	Leaves	—	0.15	—	0.05	—	MacFarlane et al. (2003)
		Pneumatophores	—	1.66	—	1.64	—	
		TF	—	0.09	—	0.03	—	

Table 6 Averages of geo-accumulation index (I_{geo}) and potential ecological risk index (E_r^i) of the measured heavy metals in mangrove sediments for all studied stations.

Stations	Geo-accumulation index (I_{geo})					Potential ecological risk index (E_r^i)				
	Cr	Cu	Ni	Pb	Cd	Cr	Cu	Ni	Pb	Cd
J I	−1.87UC	−1.95UC	−2.68UC	−3.22UC	−0.49UC	0.89/LR	1.94/LR	1.81/LR	0.80/LR	42.67/MR
J II	−1.02UC	−0.46UC	−1.55UC	−1.92UC	0.83UMC	1.48/LR	5.45/LR	3.97/LR	1.98/LR	106.67/CR
J III	−1.04UC	−2.20UC	−2.73UC	−2.58UC	2.55MHC	1.46/LR	1.63/LR	1.74/LR	1.26/LR	352.00/VHR
J IV	−1.77UC	−1.41UC	−2.59UC	−2.16UC	2.78MHC	0.88/LR	2.82/LR	1.93/LR	1.68/LR	413.33/VHR
J V	−2.40UC	−2.98UC	−3.58UC	−3.75UC	−1.17UC	0.57/LR	0.95/LR	0.97/LR	0.56/LR	26.67/LR
Sabya	−1.10UC	−1.34UC	−2.13UC	−2.49UC	−2.17UC	1.40/LR	2.96/LR	2.65/LR	1.34/LR	13.33/LR
Wadi Baish	−2.32UC	−3.07UC	−3.34UC	−3.67UC	−1.79UC	0.60/LR	0.89/LR	1.14/LR	0.59/LR	17.33/LR
Al-Haridhah	−2.30UC	−2.13UC	−3.04UC	−3.91UC	−1.79UC	0.61/LR	1.71/LR	1.41/LR	0.50/LR	17.33/LR
Al-Qahma	−1.12UC	−1.29UC	−2.22UC	−2.78UC	0.00UC	1.38/LR	3.07/LR	2.49/LR	1.09/LR	60.00/MR
Al-Birk	−1.60UC	−1.77UC	−2.08UC	−4.69UC	0.49UMC	0.99/LR	2.20/LR	2.74/LR	0.29/LR	84.00/CR
Al-Shaqqah	−1.23UC	−1.42UC	−2.16UC	−2.33UC	−1.91UC	1.28/LR	2.80/LR	2.59/LR	1.49/LR	16.00/LR
Al-Lith 1	−1.36UC	−1.24UC	−2.19UC	−1.58UC	−2.17UC	1.17/LR	3.18/LR	2.54/LR	2.51/LR	13.33/LR
Al-Lith 2	−2.55UC	−2.77UC	−3.43UC	−4.99UC	0.53UMC	0.51/LR	1.10/LR	1.08/LR	0.24/LR	86.67/CR
Al-Shouiba	−2.01UC	−1.59UC	−2.52UC	−3.20UC	−1.91UC	0.75/LR	2.48/LR	2.02/LR	0.81/LR	16.00/LR
South Jeddah	−1.43UC	−2.68UC	−3.87UC	−4.09UC	1.45MC	1.11/LR	1.17/LR	0.80/LR	0.44/LR	164.00/HR
Dhahaban	−0.81UC	−0.50UC	−0.87UC	−2.43UC	1.64MC	1.71/LR	5.29/LR	6.35/LR	1.39/LR	186.67/HR
Rabigh I	−3.73UC	−4.37UC	−3.59UC	−4.67UC	2.15MHC	0.23/LR	0.36/LR	0.96/LR	0.29/LR	266.67/HR
Rabigh II	−0.86UC	−0.39UC	−0.79UC	−2.64UC	0.32UMC	1.65/LR	5.72/LR	6.73/LR	1.20/LR	74.67/MR
Bir-Ghelyan	−1.94UC	−2.28UC	−2.62UC	−1.34UC	−0.58UC	0.78/LR	1.54/LR	1.89/LR	2.96/LR	40.00/MR
Al-Wajh	−1.21UC	−0.99UC	−2.30UC	−2.88UC	0.83UMC	1.30/LR	3.78/LR	2.36/LR	1.02/LR	40.00/MR
Duba	−1.80UC	−1.70UC	−2.39UC	−2.69UC	−0.49UC	0.86/LR	2.30/LR	2.21/LR	1.16/LR	74.67/MR

from roots to other tissues. The mean values of TF for the studied metals in aerial roots displayed the following order: Cd (2.72) > Cu (1.74) > Ni (1.42) > Pb (1.29) > Cr (0.90) (Table 5). These results indicate that all of the TF means were greater than 1, except in the case of Cr, and further reveal that the mangrove plants can accumulate Cu, Ni, Pb and Cd in considerable amounts. This finding is also supported by the higher concentrations obtained for Cu, Ni, Pb and Cd in the leaves (13.24, 7.56, 3.79 and 0.18 $\mu g\ g^{-1}$ dw, respectively), which are in accordance with TF values >1 (1.74, 1.42, 1.29 and 2.72, respectively). In addition, as shown in Table 5, it can be seen that the leaf BCF of Pb observed here was higher than those reported by many previous studies (i.e., Abohassan, 2013; Chen et al., 2003; MacFarlane et al., 2003; Usman et al., 2013). To the contrary, the root BCF of Cu, Pb and Ni were higher than that reported by Li et al. (2016).

3.5. Risk assessment indices

Müller classification (Müller, 1981) was used for assessing pollution levels among the studied mangrove sediments (Table 6). The I_{geo} index revealed that Cd exhibited moderate to heavy contamination in the sediments (MHC), with values ranging from 2.15 at station XVII (Rabigh I) and 2.78 at station JIV, compared to the I_{geo} range in that class ($2 < I_{geo} < 3$). Stations XV ($I_{geo} = 1.45$) and XVI ($I_{geo} = 1.64$) showed moderately contaminated (MC) sediments ($1 < I_{geo} < 2$). Furthermore, only five stations (JII, X, XIII, XVII and XX) showed uncontaminated to moderately polluted sediments ($0 < I_{geo} < 1$). Generally, all stations revealed uncontaminated sediment types with respect to Cr, Cu, Ni and Pb, with moderate to heavy contamination of Cd. The ecological risk assessment index, E_r^i, revealed that the studied heavy metals in mangrove sediments showed almost the same pattern as the I_{geo} index. The concentration of Cr, Cu, Ni and Pb in sediments of the studied stations showed low ecological risk (E_r^i values lower than 40). On the other hand, Cd showed a moderate risk (E_r^i values of $40 \leq E_r^i < 80$) at stations JI, IX, XVII, XIX and XX. In addition, Cd exhibited considerable risk (E_r^i values of $80 \leq E_r^i < 160$) at stations JII, X, XIII, XVIII and XXI, while it showed high risk (E_r^i values of $160 \leq E_r^i < 320$) at stations XV, XVI and XVII. Moreover, a very high ecological risk (HVR) (E_r^i values ≥ 320) was observed at stations JIII and JIV. These results could be attributed to the huge inputs of wastes coming from anthropogenic sources at these stations, including discharge of refining wastes and untreated sewage effluents (Usman et al., 2013). Further, this finding is in agreement with those of Badr et al. (2009) who reported that urbanization activities (electrical power and desalination plants, the Aramco refinery plant and commercial harbours) may be responsible for augmenting trace metals concentrations in mangrove sediments near the city of Rabigh, in the central Red Sea.

3.6. Correlation analyses

Pearson's correlation coefficient (r) was performed to study the relation between heavy metals and physico-chemical properties (Garcia and Millan, 1998). The results, presented in Table 7, show that the EC values were positively correlated with organic matter (OM) content ($r = 0.56$, $P < 0.01$). It is noteworthy that microbiological decomposition of soil organic matter is mainly initiated by the enzymatic hydro-

Table 7 Pearson's correlation coefficient (*r*) between physico-chemical properties and total concentration of heavy metals in sediment of the study area (values in bold indicate the statistically significant ones).

	%Sand	%Mud	pH	EC	%OM	%$CaCO_3$	Cr	Cu	Ni	Pb
%Mud	**−1.000****									
	0.000									
pH	0.124	−0.133								
	0.591	0.566								
EC	−0.279	0.291	**0.647****							
	0.221	0.201	**0.002**							
%OC	−0.371	0.383	**−0.577****	**0.560****						
	0.098	0.086	**0.006**	**0.008**						
%$CaCO_3$	0.143	−0.143	0.051	0.129	−0.280					
	0.536	0.537	0.825	0.577	0.219					
Cr	−0.348	0.343	−0.305	0.076	0.184	0.052				
	0.122	0.127	0.179	0.744	0.425	0.822				
Cu	−0.330	0.327	**−0.449***	0.178	0.272	−0.294	**0.818****			
	0.144	0.148	**0.041**	0.441	0.234	0.196	**0.000**			
Ni	−0.332	0.330	−0.234	0.092	0.167	−0.330	**0.754****	**0.907****		
	0.142	0.144	0.306	0.691	0.470	0.144	**0.000**	**0.000**		
Pb	−0.077	0.092	**−0.480***	0.316	**0.605****	−0.063	0.415	0.431	0.323	
	0.739	0.693	**0.027**	0.162	**0.004**	0.786	0.062	0.051	0.153	
Cd	−0.188	0.193	−0.074	−0.135	−0.047	0.262	0.054	−0.051	−0.016	−0.008
	0.415	0.402	0.749	0.560	0.839	0.252	0.815	0.827	0.944	0.973

* Correlation is significant at the 0.05 level ($P < 0.05$).
** Correlation is significant at the 0.01 level ($P < 0.01$).

Table 8 Varimax rotated principal component analysis (PCA) of measured heavy metals in sediment samples (bold loadings are statistically significant).

Studied variables	Factor 1	Factor 2	Factor 3	Factor 4
Cu [μ g^{-1}]	**0.922**			
Ni [μ g^{-1}]	**0.909**			
Cr [μ g^{-1}]	**0.896**			
pH		−0.829		
EC [dS m^{-1}]		**0.826**		
OM%		**0.803**	0.307	
Pb [μ g^{-1}]	0.407	**0.666**		
%Sand			−0.962	
%Mud			**0.960**	
%$CaCO_3$				**0.848**
Cd [μ g^{-1}]				**0.713**
Eigenvalue	4.11	1.83	1.69	1.31
Variance %	37.32	16.66	15.36	11.92
Cumulative %	37.32	53.97	69.34	81.25

lysis of miscellaneous extracellular macromolecules and plant debris converted to monomeric and oligomeric molecules (Shi, 2011). This leads to the recycling of organic materials and the return of nutrient content to sediments and plants in tidal wetlands (Morrissey et al., 2014). However, elevated salinity reduces the activity of microorganisms (Wichern et al., 2006) by inhibiting amino acid capture and protein synthesis (Gennari et al., 2007) and altering the C N^{-1} ratio in the soil (Wichern et al., 2006). Soil pH showed negative correlations with EC ($r = -0.647$, $P < 0.01$), OM ($r = -0.577$, $P < 0.01$), Cu ($r = -0.449$, $P < 0.01$) and Pb ($r = -0.480$, $P < 0.01$) (Table 8). Lower pH values were associated with the highest levels of organic decomposition in the studied area, which is in accordance with Matsui et al. (2015). Based on the negative relationship between soil pH and both Cu and Pb under the alkaline conditions, the solubility and availability of Cu and Pb to plants were decreased (Fijałkowski et al., 2012). A significant positive correlation was observed between Pb and organic matter in sediments ($r = 0.605$, $P < 0.01$), implying that anaerobic conditions and enrichment of sediments with organic matter result in greater retention of heavy metals (Li et al., 2016;

Tam and Wong, 2000). Significant correlations were also observed between Cr and both Cu and Ni ($r = 0.818$, 0.754, $P < 0.01$, respectively). In addition, Cu had a significant positive correlation with Ni ($r = 0.907$, $P < 0.01$). These correlations among heavy metals in sediments might be due to the changes in physico-chemical properties, biological processes and discharging of contaminants into the aquatic ecosystem (Kumar et al., 2010; MacFarlane et al., 2007).

3.7. Principal component analysis (PCA)

In this study, principal component analysis (PCA) and computed Eigenvalues had a substantial role in identifying and understanding the associations of heavy metals with metallo-organic compounds (chelation) and the conditions of sediment change. Furthermore, the Varimax method was carried out to perform the rotation of the PCA. Loadings greater than 0.60 are statistically significant and are marked in bold in Table 8. The factor analysis included four factors that described 81.25% of total data variability in the mangrove sediments. The first dominant factor accounted for 37.32% of the total variance with an Eigenvalue of 4.11. This describes the accumulation of heavy metals such as Cu, Ni and Cr. These results are in agreement with those of Badr et al. (2009) and Usman et al. (2013), based on work conducted along the coast of the Red Sea. These studies reported that Cu, Pb, Zn, Ni and Cr were primarily introduced as a result of human activities (sewage treatment plant at JIII, the Aramco refinery, commercial harbours and sewage discharge at Jeddah and Rabigh areas). Similar results were reported by Mao et al. (2013), who identified the source of heavy metals in the upper layers of sediments. This study found that Co, Cr, Cu, Cd and Pb originated from human activities, but Ni came from lithogenic origin. The second factor (16.66% of the total variance with Eigenvalue = 1.83) revealed significant loading on the sediment properties, such as EC and organic matter, as well as Pb. This finding could be attributed to anthropogenic activities, such as bridge construction, which separated most of the mangrove areas from the open sea. The third component amounted to 15.36% of the total variance (Eigenvalue = 1.69). This factor gave significant load to only the mud fraction. Finally, the fourth factor accounted for only 10.97% of total variance, with an Eigenvalue of 1.21 and gave load to $CaCO_3$ content and Cd. This suggests that $CaCO_3$ content and Cd that originate due to weathering of lithogenous sources have a greater contribution than water and urban development, including industrial activities found in some areas. In conclusion, our results imply that activities associated with urbanization have significant influences on the contamination of the biotic community in the mangrove ecosystem along the coastal areas of the Red Sea, Saudi Arabia.

4. Conclusions

The concentrations of various heavy metals in the areas along the Saudi Arabian coast of the Red Sea were higher than their respective world average shale concentrations. These concentrations were above the threshold effect level, indicating a very limited biological impact on the marine environment. The concentration of Cd was higher than its toxic effect threshold level, which revealed a harmful risk to marine ecosystems. The higher concentrations of heavy metals in both the leaves and aerial roots of mangroves indicated that *A. marina* accumulates heavy metals, particularly Cr and Pb. Based on the I_{geo} index, sediments ranged between moderately and heavily contaminated with Cd, in Al-Haridhah (station VIII), but were moderately contaminated in South Jeddah, Rabigh, Duba and the wastewater treatment station in Jazan. The translocation factor was above the known worldwide average. The ecological risk index also revealed that Cd could have a considerable potential risk to the mangrove ecosystem. Principal component analysis indicated that industrial activities represent the main sources of heavy metal contamination at the studied locations. In terms of future investigations, the bioavailability fractions and toxicity of heavy metals should take molecular speciation into account. Finally, the results obtained from this study can contribute to establishing a decision-making framework for the future management of natural aquatic ecosystems of the Red Sea in Saudi Arabia.

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