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RESEARCH ARTICLE

Phytomanagement of trace metals in mangrove sediments of Hormozgan, Iran, using gray mangrove (*Avicennia marina*)

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Abstract

Trace elements (Zn, Cu, Pb, and Cd) in root and leaf tissues of the gray mangrove (*Avicennia marina*) and in corresponding sediment samples were studied. Samples were taken from the inflow/outflow points in two distinct habitats, i.e., the Hara Protected Area and the Azini Bay, of Hormozgan Province in south Iran. Heavy metal concentrations ($\mu g\ g^{-1}$ of dry weight) in the sediments of the Hara Protected Area ranged from 16.0 to 68.0 for Pb, 15.0 to 52.0 for Zn, 9.0 to 27.0 for Cu, and 1.0 to 3.3 for Cd. In the Azini Bay, these concentrations ranged from 7.1 to 27.5 for Pb, 17.1 to 55.9 for Zn, 12.1 to 37.9 for Cu, and 0.2 to 2.3 for Cd. The accumulation trend of heavy metal concentrations in the roots of *A. marina* was in the order Pb (16.1) > Zn (15.8) > Cu (9.3) > Cd (1.3) $\mu g\ g^{-1}$ of dry weight in the Hara Protected Area and in the order Zn (13.7) > Cu (9.4) > Pb (5.5) > Cd (0.6) $\mu g\ g^{-1}$ of dry weight in the Azini Bay. The value of translocation factor (TLF) was smaller than 1 in both regions. It was estimated from 0.44 to 0.62 in the Hara Protected Area and from 0.51 to 1.01 in the Azini Bay. The enrichment coefficient for root (ECR) varied from 0.32 to 0.93 in the Hara Protected Area and from 0.32 to 0.51 in the Azini Bay. The ratio of heavy metals in leaves/sediments (ECL) also varied from 0.01 to 0.67 in the Hara Protected Area and from 0.01 to 0.47 in the Azini Bay. The enrichment coefficient for leaf (ECL) was always lower than ECR in both regions. Based on the above findings, *A. marina* can be regarded as an excluder for the heavy metals examined in this study, given its low efficiency in translocating and accumulating the heavy metals in the shoots. Apart from serving as a baseline for the study area, findings could be useful for mitigating heavy metal contamination in these sensitive ecosystems through possible phytomanagement using gray mangrove.

Keywords Coastal zone pollution · Enrichment coefficient · Mangrove forest · Translocation factor

Introduction

Heavy metals have posed numerous environmental problems in most coastal and aquatic ecosystems for a long time (Islam and Tanaka 2004; Rai 2008). Despite the fact that they are components of the earth's crust (Alloway 2013) and occur naturally in all ecosystems (Harborne 2014), their concentrations are considerably increased by human activities (Sharma et al. 2016). The main challenge with heavy metals is that, unlike organic pollutants, these inorganic pollutants are not decomposable (Achary et al. 2017). Therefore, they are considered major environmental pollutants (Sahu 2016) and have been in the center of attention in the recent years due to the adverse impacts on different ecosystems (Naji and Ismail 2012; Nath et al. 2014a; Willemsen et al. 2016). These elements find their way into the aquatic environments by natural factors, industrial and agricultural activities, as well as urban sewage and can impair the bioactivities and the quality of

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aquatic systems (Alloway 2013). They can accumulate in the bodies of marine organisms through the food chain (Cabrita et al. 2017), and the growing rate of their accumulation expose people who feed on these organisms to risks (Nachev and Sures 2016).

In Iran, mangrove ecosystems in the coastal areas of Hormozgan Province, widely known as the Hara forests, create a notorious coastal environment of major value (Masnavi et al. 2016). During the recent decades, these coastal areas have been subject to pollution by trace elements due to progressive industrialization and urbanization near these areas, which largely affect trace element accumulation and distribution, along with natural processes. Therefore, remedial measures are required to mitigate potential impacts of these hazardous trace elements (Mondal et al. 2018). Mangroves are known to play an effective role in alleviating metal pollutants through accumulating them in their own tissues (Zhou et al. 2010; Usman et al. 2013; Nath et al. 2014b) and have been reported to exhibit significant phytoremediation potential for certain heavy metals (Einollahipeer et al. 2013; Kaewtubtim et al. 2016; Kaewtubtim et al. 2018).

In Sydney, Australia, the root epidermis was the main barrier to the transport of Pb into *Avicennia marina* trees, while Cu and Zn had always higher concentrations in the cellular wall of the leaves than inside the cells (MacFarlane and Burchett 2000). Copper and Pb concentrations were higher in root and leaf tissues of *A. marina* than in sediments of mangrove forests in the same area, while a robust linear relationship between concentrations of those metals in sediments and root tissues was noted (MacFarlane et al. 2003). In Sirik Azini creek, Iran, the concentrations of heavy metals in leaves of *A. marina* were higher than those in sediments, resulting in bioconcentration factors higher than 1 for certain metals (Parvaresh et al. 2011). In Qeshm Island of Iran, the highest Pb and Cd concentrations in leaves of *A. marina* were 34.5 and 3.5 ppm, respectively, while the lowest concentrations in the stems were 2.0 and 0.05 ppm, respectively (Shirvani Mahdavi et al. 2012), with heavy metals accumulating more in the leaves than in the stems. The accumulation of heavy metals in the sediments and tissues of *A. marina* trees in Qeshm Island, Iran, followed different patterns, with Ni being the dominant metal in sediments and root tissues, whereas Cu was the dominant metal in stems and leaves (Einollahipeer et al. 2013). In Thailand, the bioconcentration factor (BCF) values for the roots of *A. marina* were 8.1 for Zn, 1.5 for Cu, 10.1 for Pb, and 10.6 for Cd, while for the leaves, the respective values were 4.7, 1.7, 4.1, and 12.2 (Kaewtubtim et al. 2016). Furthermore, *A. marina* was considered a heavy metal excluder species, since roots accumulated certain heavy metals in higher quantities than other plant parts (Kaewtubtim et al. 2018). Despite efforts undertaken to evaluate pollution levels in the Persian Gulf, continuous monitoring and additional research on accumulation of pollutants in local marine flora are essential for identifying gaps in our knowledge that could be used for better management of these sensitive ecosystems.

Because the sediments of mangrove forests in Hormozgan Province of the Persian Gulf can accumulate heavy metals, the objective of this study was to estimate the accumulation of heavy metals in the surface sediments, including the metals Zn, Cu, Pb, and Cd, and the distribution of those metals in gray mangrove, seeking an answer to the question whether local *A. marina* trees could be used for phytomanagement of heavy metals in this sensitive environment through exploitation for decorative purposes, timber used for building dwellings and boats, as well as fuel-wood for cooking and heating. To this end, ecological-biological indices, such as translocation factor (TLF), bioconcentration factor (BCF), and enrichment factors (EF) were also used.

Materials and methods

Study area

The study was conducted at two mangrove sites of Hormozgan Province, Iran (Fig. 1). The Hara Protected Area, between Qeshm Island and Bandar Khamir (26° 40′ to 26° 59′ N, 55° 21′ to 55° 52′ E), and the Azini Bay are located in the international wetland of the Gaz and Hara river deltas (26° 10′ to 26° 28′ N, 57° 01′ to 57° 14′ E). The former is a relatively virgin area that was officially registered in the Biosphere Reserve Directory of UNESCO’s Man and Biosphere Programme, and the latter is also virgin, but with a high commuting rate of fishing boats. The main factors threatening these wetlands include the cutting of mangrove trees for fuel or feed, petroleum pollutions, and the pollution caused by urban and rural sewage as well as the development of shrimp farming industry. It is estimated that about 2000 trips are daily made by boats in the Azini Bay.

Sampling and measurement of heavy metals

We used point count sampling method to randomly select five stations in each habitat, so as to cover the maximum part of the region and to meet the objectives of the study. This is a method where data are collected at points dispersed across an area where sampling needs to be done (Southwood and Henderson 2000). Samples were taken from the five inflow/outflow points in each habitat and in total, 10 points (Fig. 1). All points were sampled at full low tide on a daily basis from 10:00 to 15:00 in October to December of 2015. Plant and sediment samples were collected from the field. Taxonomic identification of *A. marina* was made in situ with the help of the experts of Jonoub Keifiat-Azma company and of an expert of the Environment Protection Organization of Hormozgan

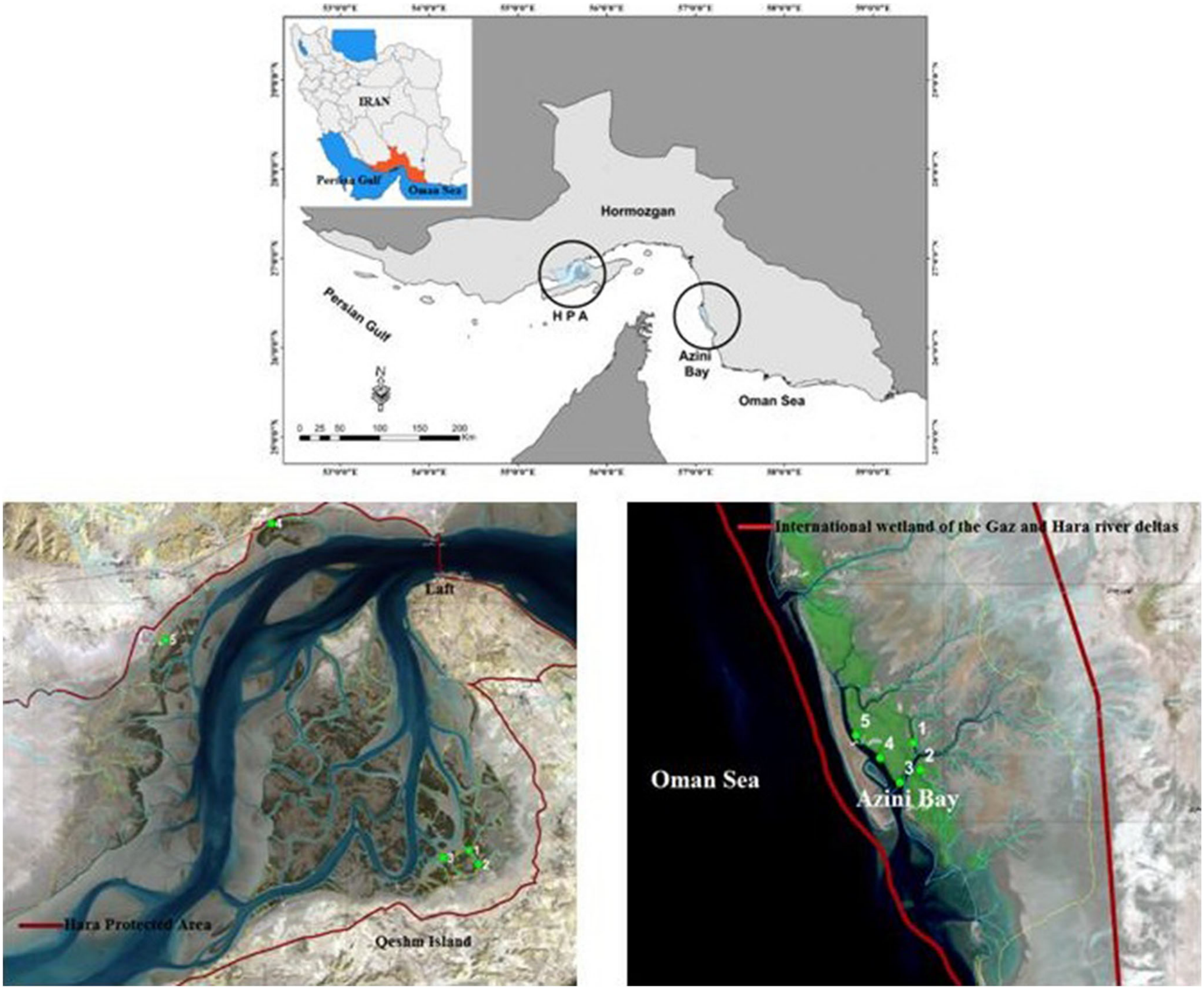

Fig. 1 Geographical location of the studied regions in the realm of the Persian Gulf and Oman Sea, along with the position of sampling stations in the Hara Protected Area and the Azini Bay

Province who contributed to the field phase of the research. In all individual sites, the leaves, roots, and sediment were sampled in three replications. In total, 15 samples of sediment, root, and leaf were collected from each habitat. For each sample, almost 15 leaves and parts of the roots of several trees were gathered. Then, they were washed with water right away (not allowing rinsates to reach the sediment) and packaged in plastic bags labeled with the site name and the sampling date.

The collected leaves and roots were also washed with distilled water in the laboratory. Then, the leaves were oven-dried at 60 °C and the roots at 101 °C for 24 h (Memmert Universal Oven UN55, Germany). The dried samples were ground in a mortar. Next, 1 g was digested with a hot plate for 1 h at 40 °C and for 3 h at 140 °C after adding concentrated nitric acid and hydrogen peroxide (1:5 ratio). During the leaf and root harvest, a certain amount of surrounding sediment was also collected with a plastic spatula and a steel-made shovel. Then, the samples were placed in acid-pickled polyethylene containers labeled with the station name and the sampling date and transported to laboratory in an icebox where they were cooled down to − 20 °C. The samples were kept at this temperature until analysis.

To measure the heavy metals, the sediment samples were oven-dried at 101 °C for 24 h. The dried samples were powdered in a mortar and screened through a 69-μm sieve to have an homogenous mixture. Then, 1 g of the sediments was digested by adding a mixture of nitric acid and concentrated perchloric acid (1:4) and placed at room temperature for 1 h and at 140 °C for 3 h. Next, the digested samples were infiltrated through a 42-μm Whatman filter and adjusted to a certain volume by adding twice-distilled water. The concentrations of the sample metals were measured by an atomic absorption spectrophotometer (UNICO - UV/Vis 4802, USA). The atomic absorption spectroscopy (AAS) technique is a

Table 1 Classification of *A. marina* according to enrichment factor

Enrichment level	EF
No enrichment to low enrichment	≤2
Moderate enrichment	2–5
High enrichment	5–20
Very high enrichment	20–40
Extreme enrichment	≥40

spectro-analytical procedure for the quantitative determination of chemical elements employing the absorption of optical radiation (light) by free atoms in the gaseous state. In this study, we followed the procedure described by El Nemr et al. (2016). Percentage recovery values were all above 95%.

Data analysis

The data of laboratory measurements are presented as mean ± standard error of the mean (SEM). The potential of the plants to uptake, accumulate, and translocate the heavy metal was estimated by calculating the translocation factor (TLF), the bioconcentration factor (BCF), and the enrichment factor (EF) as explicitly described below:

Translocation factor It specifies the rate of translocation of heavy metals from plant root to shoot. TLF values > 1 represent metal accumulator species and TLF values < 1 represent metal repellent species (Mattina et al. 2003). The TLF was calculated by Eq. (1) (Sasmaz and Sasmaz 2017):

$$TLF = \frac{\text{metal concentration in shoot}}{\text{metal concentration in root}} \qquad (1)$$

Bioconcentration factor It is determined as the ratio of the concentration of heavy metals in shoot to their concentration in exchangeable form in soil (Barla et al. 2017). The BCF can be calculated by Eq. (2) (Sasmaz and Sasmaz 2017):

$$BCF = \frac{\text{metal concentration in shoot or root}}{\text{metal concentration in sediment}} \qquad (2)$$

Enrichment factor The ratio of heavy metals in a leaf to sediment is called enrichment coefficient of leaf (ECL), and the ratio of heavy metals in a root to sediment is called enrichment coefficient of root (ECR). The EF is a good way to distinguish the natural and human-made sources of pollution (Abrahim and Parker 2008). The classification of *A. marina* according to values of EF is presented in Table 1.

Results

Concentration of heavy metals in sediments

Mean concentrations of Zn, Cu, Pb, and Cd were 35.7 ± 2.5, 15.1 ± 1.2, 49.8 ± 3.4, and 1.4 ± 0.1 μg g^{-1} dry matter (DM) in sediments of the Hara Protected Area and 31.8 ± 2.8, 23.9 ± 1.9, 17.3 ± 1.5, and 1.1 ± 0.2 μg g^{-1} DM in sediments of the Azini Bay, respectively (Table 2). Mean concentrations of the heavy metals were in the order of Pb > Zn > Cu > Cd in the Hara Protected Area and in the order of Zn > Cu > Pb > Cd in the Azini Bay.

Concentration of heavy metals in root and leaf tissues of gray mangrove

Total average concentrations of Zn in root tissue of *A. marina* in the Hara Protected Area and the Azini Bay were 15.8 ± 0.9 and 13.7 ± 1.0 μg g^{-1} DM, respectively (Table 3). The

Table 2 Mean concentrations (μg g^{-1} DM ± SEM, $n = 3$) of the metals in the sediments of the Hara Protected Area and the Azini Bay (different letters within each column in each site indicate significant differences at $P < 0.05$)

Habitats	Metal	Concentration (μg g^{-1} DM) in sediments					Average	Range
		1	2	3	4	5		
Hara Protected Area	Zn	36.0 ± 5.3 a	46.7 ± 2.9 a	35.7 ± 3.2 ab	37.0 ± 4.6 b	23.0 ± 4.0 b	35.7 ± 2.5 b	15.0–52.0
	Cu	12.7 ± 1.5 b	11.7 ± 1.8 b	16.3 ± 0.9 ab	19.7 ± 4.1 b	15.0 ± 2.1 b	15.1 ± 1.2 c	9.0–27.0
	Pb	40.7 ± 2.6 a	54.3 ± 5.4 a	46.0 ± 15.2 a	60.0 ± 4.6 a	48.0 ± 3.2 a	49.8 ± 3.4 a	16.0–68.0
	Cd	1.0 ± 0.1 c	1.8 ± 0.2 b	1.2 ± 0.3 b	1.7 ± 0.3 c	1.2 ± 0.4 c	1.4 ± 0.1 d	1.0–3.3
Azini Bay station	Zn	24.1 ± 2.8 a	32.2 ± 2.2 a	41.9 ± 2.3 a	27.9 ± 5.9 a	32.7 ± 11.6 a	31.8 ± 2.8 a	17.1–55.9
	Cu	25.6 ± 4.6 a	25.8 ± 6.6 a	22.5 ± 5.6 b	22.2 ± 4.8 a	23.4 ± 1.7 ab	23.9 ± 1.9 b	12.1–37.9
	Pb	14.1 ± 2.8 b	18.9 ± 1.4 a	21.8 ± 2.2 b	17.9 ± 5.9 a	13.7 ± 2.6 ab	17.3 ± 1.5 b	7.1–27.5
	Cd	1.3 ± 0.6 c	1.0 ± 0.4 b	0.9 ± 0.3 c	0.7 ± 0.5 a	1.4 ± 0.1 b	1.1 ± 0.2 c	0.2–2.3

DM dry matter, *SEM* standard error of the mean

Table 3 Mean concentrations (μg g^{-1} DM ± SEM, $n = 3$) of the metals in the roots of *A. marina* in the Hara Protected Area and the Azini Bay (different letters within each column in each site indicate significant differences at $P < 0.05$)

Habitats	Metal	Concentration (μg g^{-1} DM) in roots					Average	Range
		1	2	3	4	5		
Hara Protected Area	Zn	15.0 ± 1.1 a	18.3 ± 0.3 a	16.5 ± 1.1 a	17.8 ± 2.4 a	11.6 ± 1.8 b	15.8 ± 0.9 a	8.0–20.6
	Cu	8.2 ± 0.7 b	7.6 ± 0.7 b	9.8 ± 0.4 b	11.6 ± 2.1 a	9.3 ± 1.3 b	9.3 ± 0.6 b	6.5–15.5
	Pb	16.3 ± 1.3 a	17.1 ± 3.6 a	12.5 ± 1.7 ab	15.0 ± 0.2 a	19.4 ± 0.8 a	16.1 ± 1.0 a	9.1–22.8
	Cd	1.5 ± 0.7 c	1.3 ± 0.3 b	1.0 ± 0.2 c	1.3 ± 0.3 b	1.3 ± 0.6 c	1.3 ± 0.2 c	0.3–2.7
Azini Bay station	Zn	10.7 ± 0.7 a	14.2 ± 1.0 a	17.9 ± 1.2 a	13.8 ± 3.6 a	11.9 ± 2.6 a	13.7 ± 1.0 a	8.2–21.0
	Cu	9.0 ± 2.0 ab	10.2 ± 1.9 ab	9.7 ± 1.6 b	8.8 ± 1.1 a	9.3 ± 0.5 ab	9.4 ± 0.6 b	5.7–13.1
	Pb	5.7 ± 0.7 b	6.7 ± 0.5 b	6.8 ± 0.8 b	4.2 ± 0.8 ab	4.2 ± 0.6 bc	5.5 ± 0.4 c	2.7–8.1
	Cd	0.7 ± 0.2 b	0.4 ± 0.1 c	0.6 ± 0.1 c	0.4 ± 0.0 b	0.7 ± 0.1 c	0.6 ± 0.1 d	0.2–1.0

DM dry matter, *SEM* standard error of the mean

respective values were 9.3 ± 0.6 and 9.4 ± 0.6 μg g^{-1} DM for Cu, while these were 16.1 ± 1.0 and 5.5 ± 0.4 μg g^{-1} DM for Pb, respectively. Also, *A. marina* had 1.3 ± 0.2 μg g^{-1} DM Cd with a variation range of 0.3–2.7 in their roots in the Hara Protected Area and 0.6 ± 0.1 μg g^{-1} DM Cd with a variation range of 0.2–1.0 in the Azini Bay. Mean Zn concentrations in the leaves of *A. marina* were 7.0 ± 0.7 and 9.1 ± 0.5 μg g^{-1} DM in the Hara Protected Area and the Azini Bay, respectively (Table 4). The respective values were 5.7 ± 0.5 and 6.6 ± 0.4 μg g^{-1} DM for Cu, while these were 7.3 ± 0.8 and 2.8 ± 0.3 μg g^{-1} DM for Pb, respectively. Also, mean Cd concentration in the roots of *A. marina* was estimated at 0.6 ± 0.1 μg g^{-1} DM with a variation range of 0.2–1.6 in the Hara Protected Area and 0.6 ± 0.0 μg g^{-1} DM with a variation range of 0.3–0.8 in the Azini Bay. Mean concentrations of all metals were higher in the roots than in the leaves (Fig. 2). Moreover, mean concentrations followed a similar trend in the two sampled areas for all metals, except for Zn, which showed higher concentrations in the roots in the Hara Protected Area, but higher concentrations in the leaves in the Azini Bay (Fig. 2).

Mean comparison of the elements in the roots of *A. marina* between the two sampling sites by *t* test showed significant differences between mean concentrations of Pb and Cd ($P < 0.05$) (Table 5). Also, significant differences were observed between the two studied regions in Zn and Pb concentrations in the leaves ($P < 0.05$) (Table 6). The results of the *t* test for comparing mean concentrations of the elements between roots and leaves of *A. marina* in the Hara Protected Area and the Azini Bay showed significant higher concentrations of the four heavy metals in the former region ($P < 0.05$) (Table 7). The same trend was also observed in the Azini Bay, except for Cd, where the mean Cd concentrations in roots and leaves did not differ significantly ($P > 0.05$) (Table 8).

Biological indices of *A. marina* in the studied region

The values of ECR, ECL, and TLF of heavy metals in *A. marina* in the Hara Protected Area and the Azini Bay are summarized in Tables 9 and 10, respectively. Accordingly, heavy

Table 4 Mean concentrations (μg g^{-1} DM ± SEM, $n = 3$) of the metals in the leaves of *A. marina* in the Hara Protected Area and the Azini Bay (different letters within each column in each site indicate significant differences at $P < 0.05$)

Habitats	Metal	Concentration (μg g^{-1} DM) in leaves					Average	Range
		1	2	3	4	5		
Hara Protected Area	Zn	6.9 ± 2.6 a	8.9 ± 0.6 a	8.1 ± 0.5 a	6.7 ± 0.8 a	4.3 ± 1.2 ab	7.0 ± 0.7 a	1.8–10.6
	Cu	6.6 ± 1.6 a	4.4 ± 0.6 b	7.2 ± 0.9 a	4.5 ± 0.4 ab	6.0 ± 0.4 ab	5.7 ± 0.5 a	3.3–9.6
	Pb	6.9 ± 2.2 a	8.9 ± 1.1 a	4.2 ± 0.8 b	8.1 ± 1.8 a	8.5 ± 2.1 a	7.3 ± 0.8 a	2.6–12.6
	Cd	0.5 ± 0.1 a	0.6 ± 0.2 c	0.4 ± 0.1 c	0.9 ± 0.4 b	0.6 ± 0.2 b	0.6 ± 0.1 b	0.2–1.6
Azini Bay station	Zn	8.5 ± 1.3 a	9.1 ± 0.7 a	7.9 ± 0.8 a	9.2 ± 1.1 a	10.8 ± 0.8 a	9.1 ± 0.5 a	6.3–12.3
	Cu	6.4 ± 1.3 ab	7.1 ± 0.6 a	6.4 ± 0.7 a	5.7 ± 1.0 b	7.4 ± 1.1 b	6.6 ± 0.4 b	4.2–9.3
	Pb	3.7 ± 0.5 bc	2.0 ± 0.8 b	1.6 ± 0.2 b	3.0 ± 0.4 bc	3.9 ± 0.4 c	2.8 ± 0.3 c	0.8–4.7
	Cd	0.5 ± 0.1 c	0.5 ± 0.0 b	0.6 ± 0.1 b	0.6 ± 0.1 c	0.5 ± 0.2 d	0.6 ± 0.0 d	0.3–0.8

DM dry matter, *SEM* standard error of the mean

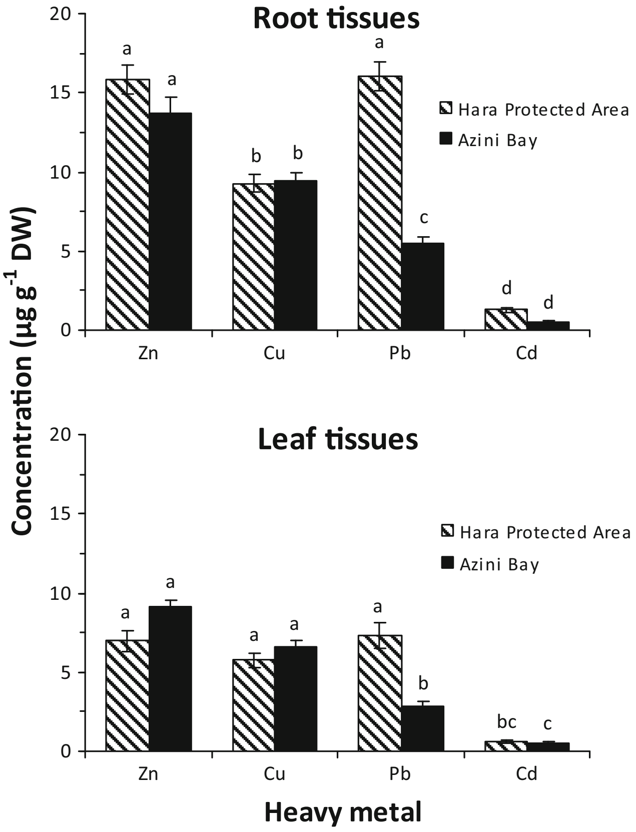

Fig. 2 Concentrations of heavy metals in the *A. marina* root and leaf tissues (different letters within each tissue indicate significant differences at $P < 0.05$)

metals TLF, i.e., the translocation rate of heavy metals from root to leaf tissues, varied from 0.44 to 0.62 in the Hara Protected Area and from 0.51 to 1.01 in the Azini Bay. In the Hara Protected Area, the highest TFL value of 0.62 was related to Cu and the lowest TLF value of 0.44 to Zn, while the highest value was related to Cd and the lowest to Pb in the Azini Bay. ECR, i.e., the ratio of heavy metals in roots/sediments, varied from 0.32 to 0.93 in the Hara Protected Area and from 0.32 to 0.51 in the Azini Bay. Total average ECR was smaller than 1 for all metals. In both habitats, the highest ECR value was related to Cd and the lowest one to Pb. ECL, i.e., the ratio of heavy metals in leaves/sediments, varied from 0.01 to 0.67 in the Hara Protected Area (Table 9) and from 0.01 to 0.47 in the Azini Bay (Table 10). Mean ECL was smaller than 1 for all metals. The highest ECL value in the Hara Protected Area was obtained for Cd and the lowest one for Pb, while Cd and Zn exhibited the highest and the lowest values of ECL in the Azini Bay. Averaged over studied areas, there was a steady amount in the TLF and ECR for Zn and Cu, while this amount was reduced for Pb and raised for Cd (Fig. 3). Moreover, there was a low amount in ECL in all metals, except from Cd, which showed a significant higher value than the other metals (Fig. 3).

Table 5 Mean comparison of the elements in the roots of *A. marina* in the two sampled regions

Metal	Levene's test		*t* test for equality of means					
	F	Sig.	t	Sig.	Difference	SED	95% CI	
							Lower	Upper
Zn	0.81	0.38	1.56	0.13	2.12	1.36	− 0.66	4.90
Cu	0.40	0.53	− 0.15	0.88	−0.13	0.83	− 1.82	1.57
Pb	7.81	0.01	10.22	0.00	10.53	1.03	8.38	12.69
Cd	12.10	0.00	4.19	0.00	0.74	0.18	0.37	1.12

SED standard error of difference, *CI* confidence intervals

Table 6 Means comparison of the elements in the leaves of *A. marina* in the two sampled regions

Metal	Levene's test		*t* test for equality of means					
	F	Sig.	t	Sig.	Difference	SED	95% CI	
							Lower	Upper
Zn	1.50	0.23	− 2.62	0.014	− 2.12	0.81	− 3.78	− 0.46
Cu	0.02	0.88	− 1.44	0.162	− 0.86	0.60	− 2.09	0.37
Pb	15.99	0.00	5.27	0.000	4.47	0.85	2.69	6.25
Cd	7.99	0.01	0.23	0.822	0.02	0.11	− 0.20	0.25

SED standard error of difference, *CI* confidence intervals

Discussion

In this study, Zn, Cu, Pb, and Cd concentrations were determined in the root and leaf tissues of gray mangrove (*A. marina*) in coastal environments of Hormozgan Province of Iran. Also, biological indices, such as the translocation factor (TLF), the bioconcentration factor (BCF), and the enrichment factor (EF) for characterizing the potential of gray mangrove to uptake, accumulate, and translocate the heavy metal were calculated. The phytoremediating role of gray mangroves,

Table 7 Mean comparison of the elements in the roots and leaves of *A. marina* at Hara Protected Area

Metal	Levene's test		*t* test for equality of means					
	F	Sig.	t	Sig.	Difference	SED	95% CI	
							Lower	Upper
Zn	1.76	0.20	8.06	0.000	8.86	1.10	6.61	11.11
Cu	0.36	0.56	4.77	0.000	3.54	0.74	2.02	5.06
Pb	0.19	0.67	7.08	0.000	8.74	1.23	6.21	11.27
Cd	3.58	0.07	3.62	0.001	0.71	0.20	0.31	1.11

SED standard error of difference, *CI* confidence intervals

Table 8 Means comparison of the elements in the roots and leaves of *A. marina* at Azini Bay

Metal	Levene's test		*t* test for equality of means					
	F	Sig.	t	Sig.	Difference	SED	95% CI	
							Lower	Upper
Zn	12.49	0.00	4.07	0.001	4.62	1.13	2.25	6.99
Cu	3.37	0.08	3.97	0.000	2.80	0.71	1.35	4.25
Pb	0.85	0.36	5.30	0.000	2.68	0.51	1.64	3.72
Cd	1.10	0.30	−0.10	0.921	−0.01	0.07	−0.14	0.13

SED standard error of difference, *CI* confidence intervals

especially in contaminated areas, has been described in earlier studies (Suresh and Ravishankar 2004; Mac Farlane et al. 2007), but despite efforts undertaken to evaluate pollution levels in the Persian Gulf, data on the response of *A. marina* to heavy metal contamination in the coastal zone of Hormozgan, Iran, remain limited. From this point of view, the present study adds novel evidence on the response of *A. marina* to accumulation and translocation of metal pollutants that could be useful for potential phytomanagement of trace metal contamination in these sensitive ecosystems.

The accumulation trend of heavy metals in the sediment was in the order of Pb > Zn > Cu > Cd of the Hara Protected Area and in the order of Zn > Pb > Cu > Cd in the Azini Bay. Similarly, the accumulation trend in the roots of *A. marina* was in the order of Pb > Zn > Cu > Cd in the Hara Protected Area, but in the order of Zn > Cu > Pb > Cd in the Azini Bay. The leaf exhibited the same accumulation trend as the sediment. According to the accumulation trends of heavy metals, we can say that since the roots are in direct contact with the sediment, the accumulation of metals in the sediment may influence their accumulation trend in roots; whereas, in other tissues, the accumulation trend may differ from that of the sediment. The trend of heavy metal accumulation (expressed in $\mu g\ g^{-1}$ DM) in different tissues of *A. marina* in the Hara Protected Area and the Azini Bay, as compared with other aquatic sites in the world, are shown in Table 11. It appears that the concentrations of heavy metals in the tissues of *A. marina* in the two studied areas are comparable or lower than those of other areas, probably reflecting the low contamination levels in both studied areas.

Translocation and bioaccumulation factors of the studied metals showed a variety of trends, indicating a different uptake capability of the heavy metals at the different tissues of *A. marina*. Previous studies noted the role of *A. marina* in purifying coastal sediments and reducing metallic pollutants by accumulation in plant tissues and immobilization in the medium (MacFarlane et al. 2003). The decreased level of translocation of the metals from the roots to the leaves of *A. marina* could be probably related to the use of the metals in physiological processes of plant growth, but this assumption was not tested in the current study. TLF represents the rate of translocation of heavy metals from root to shoot/leaf tissues (Sasmaz and Sasmaz 2017) and is used to estimate the potential of a plant to clean the environment from heavy metals (Sasmaz et al. 2008). The values of TLF were smaller than 1 in both Hara Protected Area and Azini Bay. Likewise, the ECR and ECL, which show the ratio of heavy metals in root and leaf to total heavy metals in sediment, respectively, were smaller than 1 for all metals in both regions. The values of ECR and ECL reflect the potential of a plant to accumulate and translocate the trace metals and the above findings mean that *A. marina* can be regarded as a repellent species for the heavy metals examined in this study, given its low efficiency in translocating and accumulating the heavy metals in the shoots. The roots of *A. marina* had higher EF than the leaves for all metals, implying higher potential of roots to accumulate the metals. This finding means that the roots of *A. marina* have a critical capacity to accumulate the heavy metals, as also mentioned in a previous study (MacFarlane and Burchett 2000). Moreover, the EF values were smaller than 2 in all cases, showing that *A. marina* lacked or had low enrichment in both study sites (Table 1). The lower BCF and TLF values indicate that gray mangrove adopted an exclusion strategy for the studied heavy metals.

The highest TLF from root to leaf tissues was related to Pb in the Hara Protected Area and to Cd in the Azini Bay. The

Table 9 Enrichment coefficients of leaf and root and translocation factor of *A. marina* across the sampling sites in the Hara Protected Area

Site	Zn			Cu			Pb			Cd		
	TLF	ECR	ECL	TLF	ECR	ECL	TLF	ECR	ECL	TLF	ECR	ECL
1	0.46	0.42	0.01	0.80	0.65	0.05	0.42	0.40	0.01	0.34	1.43	1.38
2	0.49	0.39	0.01	0.58	0.65	0.06	0.52	0.32	0.01	0.42	0.73	0.40
3	0.49	0.46	0.01	0.74	0.6	0.04	0.33	0.27	0.01	0.34	0.84	0.70
4	0.37	0.48	0.01	0.39	0.59	0.03	0.54	0.25	0.00	0.71	0.75	0.44
5	0.37	0.50	0.02	0.65	0.62	0.04	0.44	0.41	0.01	0.41	1.16	1.01
Mean	0.44	0.44	0.01	0.62	0.62	0.04	0.46	0.32	0.00	0.45	0.93	0.67

TLF translocation factor, root/leaf; *ECR* enrichment coefficient of root, sediment/root; *ECL* enrichment coefficient of leaf, sediment/leaf

Table 10 Enrichment coefficients of leaf and root and translocation factor of *A. marina* across the sampling sites in the Azini Bay

Site	Zn			Cu			Pb			Cd		
	TLF	ECR	ECL	TLF	ECR	ECL	TLF	ECR	ECL	TLF	ECR	ECL
1	0.80	0.45	0.02	0.71	0.35	0.01	0.65	0.41	0.03	0.75	0.52	0.40
2	0.64	0.44	0.01	0.70	0.40	0.02	0.29	0.36	0.02	1.46	0.36	0.34
3	0.44	0.43	0.01	0.66	0.43	0.02	0.24	0.31	0.01	1.00	0.62	0.68
4	0.66	0.46	0.02	0.65	0.40	0.02	0.72	0.23	0.01	1.46	0.62	0.88
5	0.91	0.37	0.01	0.79	0.40	0.02	0.92	0.31	0.02	0.76	0.49	0.34
Mean	0.66	0.43	0.01	0.70	0.39	0.02	0.51	0.32	0.02	1.01	0.51	0.47

TLF translocation factor, root/leaf; *ECR* enrichment coefficient of root, sediment/root; *ECL* enrichment coefficient of leaf, sediment/leaf

higher TLF for Pb or Cd and the lower one for Zn reflect the high potential of root in accumulating Zn and the high potential of leaf in accumulating Pb or Cd, including possible atmospheric heavy metal deposition. The higher translocation rates of Pb and Cd to the leaves can be a defensive mechanism against excessive accumulation, which reduces the concentrations of these harmful elements when the leaves are shed. Unnecessary heavy metals were accumulated in the leaves of the spotted mangrove tree (*Rhizophora stylosa*) and then repelled as the leaves were shed (Zheng et al. 1997). High bioavailability of Pb and Cd for plant uptake was probably the responsible factor for the increased concentrations of those metals in the leaf tissues as compared to the sediment (Yim and Tam 1999). Bioavailability depends largely on the concentrations and chemical forms (species) of the metals in the pore water, which are controlled by numerous complex interacting processes (Kim et al. 2015). Higher Cd concentration in the shoots than other elements is in line with previous reports (Nirmal Kumar et al. 2011) and could be probably associated with the high root-to-shoot translocation rates of Cd, as previously reported for other plant species (Sękara et al. 2005; Lu et al. 2008; Dong et al. 2017). Cd accumulation ability was weakened in roots of *A. marina* and the translocation factor increased in stems and leaves with increase of stress duration (Jian et al. 2017). Nonetheless, much lower Cd concentration in such tissues as roots and leaves as compared to other elements can be related with the lower demand of these tissues for Cd and with the fact that Cd is not lost with leaf shedding. In a study on the transfer of heavy metals from roots to leaves, Zn had the lowest concentration in the leaves and its weak translocation to the leaf tissues was related to the fact that the white mangrove trees (*Laguncularia racemosa*) tolerated Zn in the roots and did not require to repel this metal through leaf shedding (Machado et al. 2002). Low translocation rate of Zn from the sediment to the leaves was reported by a previous study (Zheng et al. 1997), which suggested that the lower Zn bioavailability in the sediment than other metals was the main reason for its lower concentration in the leaves.

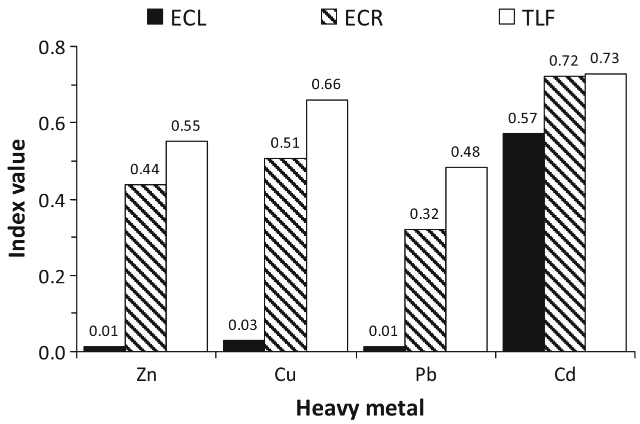

Fig. 3 Biological indices of *A. marina* for the trace elements Zn, Cu, Pb, and Cd averaged over studied regions

The EF is a good way to distinguish the natural source and the human-made pollution (Salem et al. 2017). The present study showed that the highest value of EF was related to Cd and the lowest to Pb. Moreover, the EF was higher for all metals in the roots of *A. marina* than in the leaves. Higher EF values in the roots than in the leaves reflect a higher potential of roots to accumulate metals (Sasmaz et al. 2008). This response may be due to the aerial roots of *A. marina*, which supply oxygen requirements for the oxidation at lower layers and substrate, resulting in high accumulation of metals in the roots. The exploration of EF revealed that all tissues were able to receive the studied heavy metals (Zn, Cu, Pb, and Cd) from the sediment. Previous research showed that the essentiality of some elements (like Zn and Cu) for plants and inessentiality of others were the main reason for their different accumulation rates during the metabolic process (Kaewtubtim et al. 2016; Willemsen et al. 2016). In an examination of the inflow rate of heavy metals from the sediment and their bioaccumulation in the leaves, Cu and Zn had lower bioaccumulation rates (MacFarlane and Burchett 2002). Similarly, the present study showed that the root of *A. marina* was an optimum transporter of heavy metals from the environment to the aboveground tissues. Sharifan and Davari (2010) studied Cu concentration in *A. marina* in Qeshm Island and estimated Cu translocation

Table 11 Comparison of heavy metals accumulation pattern in different tissues of *Avicennia marina* in the studied regions with other aquatic bodies of the world (μg g^{-1} DM)

Part	Species	Zn	Cu	Pb	Cd	Reference
Root	Pichavaram mangrove area, India	55.5	13.1		13.52	Subramanian and Vannucci (2004)
	Pattani Bay, Thailand, *A. marina*	19.1	9.7	75.7	0.40	Kaewtubtim et al. (2016)
	Yingluo Bay, China, *Rhizophora stylosa*	6.5	0.7		0.01	Zheng et al. (1997)
	Sevan (Armenia) and Carambolim (India) lake	307.8	25.7		0.17	Vardanyan and Ingole (2006)
	Natal of Brazil, *A. marina*	0.5	0.9		1.06	Ramos e Silva et al. (2006)
	Hara Protected Area, Iran, *A. marina*	15.8	9.3	16.1	1.29	Present study
	Azini Bay, Iran, *A. marina*	13.7	9.4	5.5	0.55	Present study
Leaf	Peninsular Malaysia, *Sonneratia caseolaris*	5.9	26.8		1.00	Nazli and Hashim (2010)
	Natal of Brazil, *A. marina*	0.2	0.1		0.01	Ramos e Silva et al. (2006)
	Yingluo Bay, China, *Rhizophora stylosa*	5.7	0.6		0.19	Zheng et al. (1997)
	Pattani Bay, Thailand, *A. marina*	11.1	10.8	30.3	0.40	Kaewtubtim et al. (2016)
	Hara Protected Area, Iran, *A. marina*	7.0	5.7	7.3	0.58	Present study
	Azini Bay, Iran, *A. marina*	9.1	6.6	2.8	0.55	Present study

rate from root to leaf at 0.89 and BCF at 0.84. They argued that since Cu is an essential element for the plant, its concentration is constant across the different parts of the plant. Copper and Zn have important roles to play in the processes of chloroplasts, the synthesis of proteins and enzymatic activities, growth hormones, and the metabolism of the carbohydrates (Hänsch and Mendel 2009; Mousavi 2011).

In this study, BCF was found to be 8.1 for Zn, 1.5 for Cu, 10.1 for Pb, and 10.6 for Cd in the root tissues of *A. marina* and 4.7 for Zn, 1.7 for Cu, 4.1 for Pb, and 12.2 for Cd in the leaf tissues. These findings indicate high accumulation of Zn and Pb in the roots compared with the shoots and almost equal accumulation of Cu in both tissues. Moreover, the ratio of the concentrations of heavy metals in leaf to root was 1:2.3 (Zn), 1:1.6 (Cu), 1:2.2 (Pb), and 1:2.2 (Cd) in the Hara Protected Area and 1:1.5 (Zn), 1:1.4 (Cu), 1:1.9 (Pb), and 1:1 (Cd) in the Azini Bay. Likewise, the ratio of heavy metal concentrations in leaf to sediment was found to be 1:5.11 (Zn), 1:2.6 (Cu), 1:6.8 (Pb), and 1:2.4 (Cd) in the Hara Protected Area and 1:3.5 (Zn), 1:3.6 (Cu), 1:6.1 (Pb), and 1:1.9 (Cd) in the Azini Bay. In total, it can be said that higher concentrations of metals in the sediment and roots as opposed to leaves can be associated with a lower demand of those metals by the leaves than by the roots. This requirement is remarkable especially for Cu. Mangrove plants are known to accumulate trace elements in their aboveground tissues at different concentrations because some metals are considered necessary for growth and survival (MacFarlane and Burchett 1999). Therefore, metal accumulation in these plants is driven by basic metabolic requirements of the plants. For example, Cu and Zn are essential growth elements and are more mobile than non-essential elements like Pb, a fact that leads in variable accumulation in plant tissues (MacFarlane et al. 2003, 2007). Moreover, gray mangrove may act as a heavy metal phytostabilizer close to contaminant sources (Singh 2012; Birch et al. 2013) by 'fixing' heavy metals in the rhizosphere at concentrations greater than underlying sediments. This reaction can be regarded as a physiological mechanism of translocation prevention of the metals to aboveground tissues, which limits toxicity to plants and exclusion of metals via leaf litter. Mangrove ecosystems along coastal areas play a crucial role in filtering sediments and material deposits in marine ecosystems. Thus, the ability of *Avicennia* spp. to fix heavy metals in their tissues is very important in phytoremediation, which focuses on ecological processes and functions for gentle remediation options of ecosystem services in contaminated areas, including production of usable biomass for the production of renewable energy or provide feedstock for the circular bioeconomy. In light of the above, local *A. marina* trees could be an option for phytomanagement of heavy metals in this sensitive environment, keeping contaminants of this group at low availability levels to the soil.

Conclusions

The role of gray mangrove as a biofilter of heavy metals in coastal environments of Hormozgan Province, Iran, was explored. The study provided actual heavy metal accumulations in the sediment-plant ecosystem of mangrove forest, being important in designing the long-term management and conservation policies for the managers of mangrove forest. Overall, accumulation of heavy metals in the sediment may determine their accumulation in the root, while the variation of heavy metal concentrations in other tissues may differ from that of the sediment. Despite heavy metal contamination levels in the coastal environments of Hormozgan Province, Iran, *A. marina* has successfully adapted itself to this stress condition with a mechanism for selective uptake of only necessary minerals. In light of the above, local *A. marina* trees could be used for potential phytomanagement of heavy metals in this sensitive environment through exploitation for decorative purposes, timber used for building dwellings and boats, as well as fuel wood for cooking and heating, as it could bear and accumulate (immobilize) common trace metals.

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