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Identifying toxic elements in water, sediments, and roots of mangrove forest (*Avicennia marina*) in Chabahar Bay, Sea of Oman

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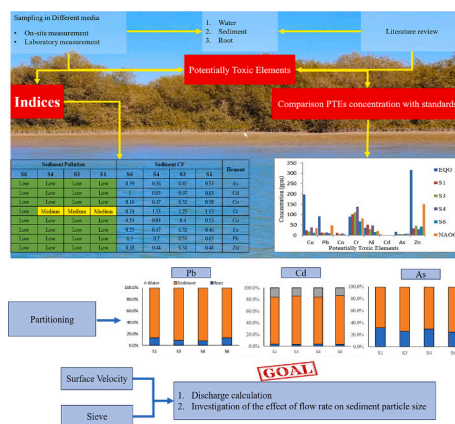
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HIGHLIGHTS

- The distribution of heavy metals in three mediums was investigated.
- The lowest and the highest concentrations of PTEs were detected.
- Except Zn, As, and Cd, other PTEs in sediment correlated with decreasing flow rate.
- As sediments become finer, the concentration of heavy metals increases.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangroves play a crucial role in filtering pollutants from water and sediments. However, excessive accumulation of potentially toxic elements (PTEs) has harmful effects on marine organisms. This article investigates the concentration and distribution of PTEs in water, sediment, and the roots of endangered mangrove species in Chabahar Bay, a subtropical coastal wetland. The relationship between PTE absorption and accumulation rates with flow rate, mangrove extent, and sedimentation was also explored. Water, sediments, and aerial roots samples were taken at four stations along the wetland from upstream fresh water toward outfall. According to the results, Cd had more distribution in sediment and water samples and plants did not play as adsorbent in the study area. The lowest and highest PTEs concentrations were detected in water and sediment media, respectively. The average concentrations of PTEs in the sediments in the Chabahar Bay were $Fe > Cr > Zn > Ni > Cu > Pb > Co >$

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As > Cd while in aerial roots of the mangroves were Fe > Zn > Ni > Cr > Cu > Co > As > Pb > Cd. Except Zn, As, and Cd, there was a good correlation between increasing PTEs content in the sediments with decreasing flow velocity and increasing vegetation density along stations 3 to 4. In addition, the amount of PTEs uptake by the mangroves was less than that of global wetlands. The results also demonstrated a greater uptake in aerial roots in saline water for Cr, Ni and Co. Since the absorption rate of PTEs by the aerial roots of pneumatophores is slower than that in sediments, elevated concentrations of PTEs in the sediment can disrupt the entire ecosystem, leading to a potential decline in biodiversity. These toxins can enter the food chain, affecting not only organisms directly interacting with the sediment but also higher trophic levels, such as fish and birds.

1. Introduction

The accumulation of potentially toxic elements (PTEs) in natural aqua systems like wetlands threatens human health and biodiversity due to their persistence and toxicity (Aradpour et al., 2020; Azhar et al., 2024; Calmuc et al., 2021; Dias and Nayak, 2016; Ji et al., 2018; Liu et al., 2020; Torabi Kachoosangi et al., 2020; Yüksel et al., 2021). PTEs originating from municipal wastewater, agricultural and industrial activities, mining, energy production, and transportation have highly affected wetland, coastal areas, and marine ecosystems (Boehnert et al., 2020; Fernandez-Maestre et al., 2018; Kang et al., 2017; Kobdang et al., 2024; Rashid et al., 2023; Xinyu et al., 2024; Yüksel et al., 2024). While PTEs such as Cu, Ni, and Zn are essential for aquatic life, they can be harmful at a certain concentration and pose a risk to aquatic biodiversity. Moderate to high Cd and Zn leaching poses a high ecological risk primarily attributable to human activities (Moushmi et al., 2022).

When PTEs from sewage and industrial effluents are discharged into rivers and coastal area without adequate treatment, they accumulate and form contaminated bed load that causes toxic effects on aquatic fauna and flora (Sun et al., 2015; Lim et al., 2022; Nour and El-Sorogy, 2020; Siegel, 2002). Such anthropogenic PTEs tend to interact with clay and organic matter in sediments through processes such as ion exchange, complexation, and chemical adsorption (Adikaram et al., 2024; Kumar et al., 2022; Li et al., 2015a, 2015b; Wang et al., 2018; Zhang et al., 2014). In addition, organometallic compounds are formed in sediment from various oxides and humic substances that finally result in accumulation of heavy metals in surface sediments (Nasrabadi et al., 2022; Ranjan et al., 2018; Violante et al., 2010). These procedures result in higher bioavailability and exposes more serious risks to aquatic ecosystems than metal pollution from natural sources (Li et al., 2015a, 2015b; Marchand et al., 2016; Partani et al., 2024a; Palma et al., 2015; Yaşar Korkanç et al., 2024). Thus, when examining the anthropogenic impacts on wetlands and coastlines, it is recommended to concentrate not only on the total concentration of PTEs but also on the chemical fraction of metals in surface sediments. Chemical partitioning and sequential extraction methods are commonly used to detect pollutions and identify the bonds of sediments with trace metals (Karbassi et al., 2006; Xu et al., 2016; Zhou et al., 2024b). These processes provide valuable information on the origin, physicochemical availability, mobilization, and transport of trace metals in nature (Bourgeois et al., 2019; Nemati et al., 2011; Rao et al., 2010; Santos et al., 2024).

Mangrove forests act as the natural buffer to remove nutrients, pollutants, and sediments (Wang et al., 2022; Zhao et al., 2022). They also protect coastal zones against erosion and play an essential role in the ecosystem conservation and coastline stability (Bai et al., 2012; Feng et al., 2017; Lee et al., 2014). Studies have demonstrated that mangrove roots can effectively trap PTEs, and their tissues can absorb metal released into the nearby marine environment (Alongi et al., 2004; Qiu et al., 2011; Ray et al., 2021; Lacerda et al., 2024; Mohamad Pazi et al., 2021; Nagelkerken et al., 2008; Partani et al., 2015; Yang et al., 2008). Despite their high advantages as phytoremediators (Rai, 2008; Yap and Al-Mutairi, 2023), mangroves are threatened species under ongoing decrease due to both natural climate variability and anthropogenic impacts (Bakshi et al., 2018; Hossain Bhuiyan et al., 2022; Lewis et al., 2011; Ram et al., 2018). They are disappearing at an annual rate of 1 %

to 2 % due to over-exploitation and pollution (Duke et al., 2007; Wilkie and Fortuna, 2003).

Air and water quality, freshwater availability, and health of aquatic resources are threatened by climate change, population increases, industrialization, urbanization, and land use change (Osintseva and Ishutin, 2023; Ding et al., 2024; Shen et al., 2024). Wetlands have been seriously threatened due to anthropogenic pollution such as the releases of industrial effluent, pesticides, metals and metalloid particles, polluted urban runoff, and contaminated solids (Banerjee et al., 2012; Gamón et al., 2003; Johnson and Harrison, 2015). These threats have led to global environmental challenges resulting from the destruction of this valuable environment across the world. According to Alongi (2002), >30 % of the world's mangrove has been disappeared in the recent five decades. Such a situation was also reported in Iranian mangrove ecosystems that mostly seen in northern part of the Persian Gulf and Oman Sea (Zahed et al., 2010).

It has been well-documented that the distribution of heavy metals in biota and sediment is significantly affected by the properties of the sediment, including pH, redox potential and particle size (Maghrebi et al., 2018; Otero et al., 2009; Shin and Lam, 2001; Tam and Wong, 1996; Zhang et al., 2014). These characteristics effect the spatial distribution of different tree/mangrove species (Marchand et al., 2004), which in turn influences on metal accumulation and sediment toxication (Agah et al., 2016; Chakraborty et al., 2016; Almahasheer, 2019). Therefore, recognizing the degree of toxicity and metallic pollution in shallow coastlines is an important task in marine environmental protection studies. Our review on the associated literature has shown that most of earlier studies have focused on the geochemical process of absorption of heavy metals and trace elements in sediment and water, while flow velocity, plant density, aerial roots, and their physiological features may significantly affect the pollutant concentration. To fill the gap between the geochemical approach and distribution of sampling in three mediums (i.e., water, sediment, and plants), a third medium has been selected in this study, and the toxicity and PTEs pollution in the mangroves of Chabahar Bay, which is one of the shallow coasts with high bio-production capacity and great environmental diversity, were investigated. In this study, spatial changes, mobility, and bioavailability of PTEs in sediment, plants, and water along the flow path at four stations were investigated, and for the first time, the contribution of each media in absorbing the PTEs at Chabahar Bay was identified. Variety of pollution indicators were used to estimate the extent of heavy metal contamination as the core of PTEs in the study area. Furthermore, the findings were compared with existing data from other wetlands and plant sediments.

2. Materials and methods

2.1. Study area

One of the important environmental feature of shallow coastline at the northern region of Persian Gulf (Moradi and Moradi, 2020) and Sea of Oman is extended mangrove forest with rich biodiversity and important ecosystem e.g. this area is the inhabitant of 107 different species of fish (Eagderi et al., 2019), including two endangered fish species, six species of shrimp, ten species of crabs (Ghotbeddin et al.,

2012; Mehanna et al., 2012; Moradmamand and Sari, 2007), five species of fish snakes, and one species of marine mammals.

The study area is located at 25°.24' North latitude and 60°.36' East longitude, in the southeast of Iran at Makran coastline and the northern region of the Sea of Oman. The study area is shown in Fig. 1. The most important environmental threats in this free zone and industrial regions are a) industrial shipping b) the existence of a petrochemical unit and steel plant, c) the discharge of domestic sewage into the sea environment d) massive desalination plants. The mean annual rainfall in this area is equal to 117 mm with high inter-annual variability due to the influence of the Indian subcontinent monsoon. The average monthly temperature of this region is about 25.8 °C with no freezing throughout the year. The area is affected by the sea tide which is about 350 ha in some areas with dense vegetation and others with little or no vegetation. The length of

the studied reach is 4700 m from the beginning of vegetation to the entrance to Chabahar Bay, which is connected to the wetland by a canal at about 200 m after the vegetation starts. Since there was no previous research in this area, the lowest catchment for flow into the sea was selected as the sampling site for water and sediment. Upon analysing the initial experimental results and considering the path length and wastewater input, we identified four stations along the path for sampling water, sediment, and plants. These stations (see Fig. 1) were chosen based on their strategic locations as described in Table 1.

2.2. Sampling

The water, sediment, and roots of the plant were sampled at four stations. The methods used for sampling and PTEs measurement were

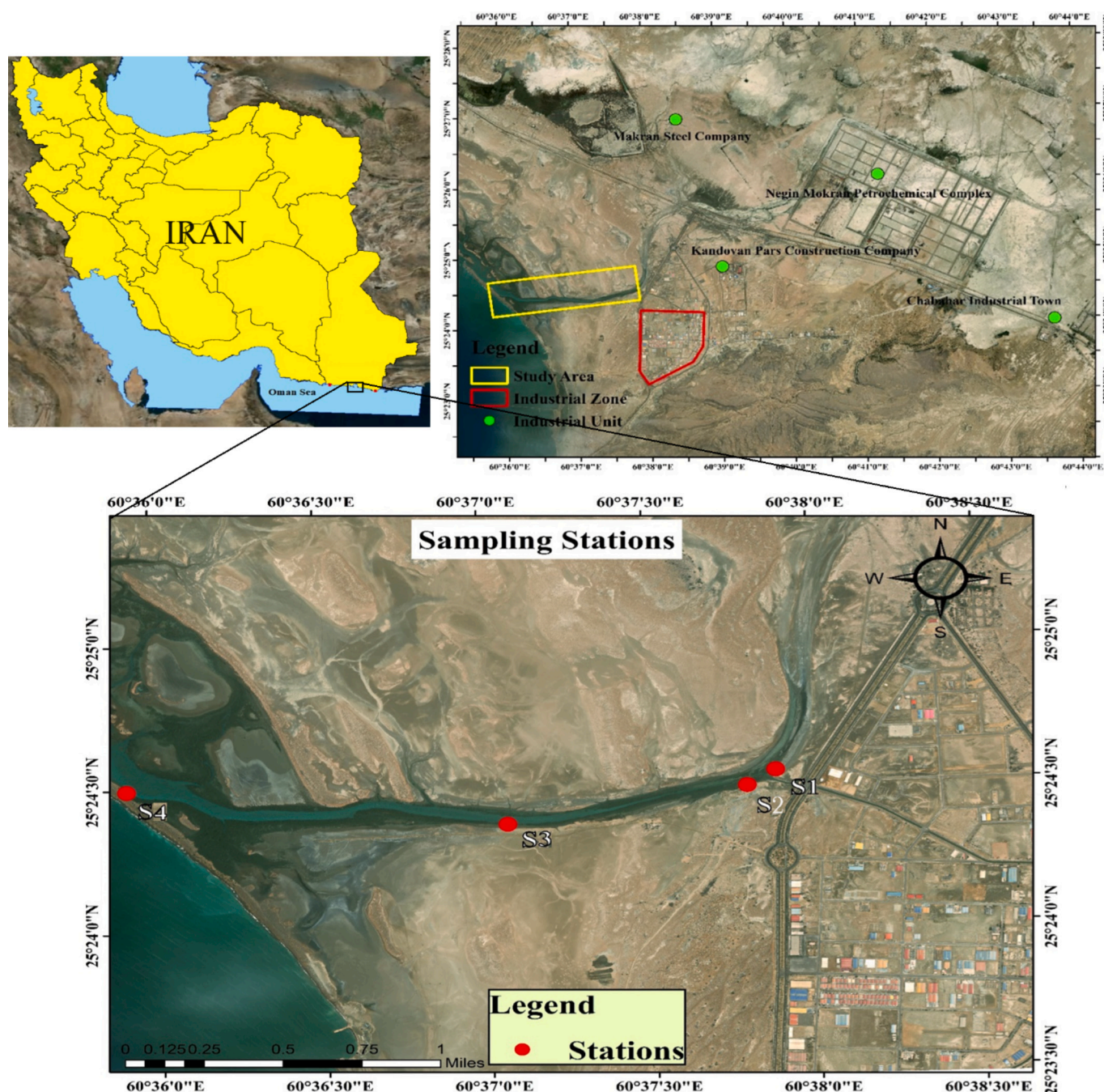


Fig. 1. A schematic overview of our study area and the location of taken samples.

Table 1
Location of sampling stations.

Station	Location	Distance from vegetation start area (m)
S1	100 m before connecting sewage canal	100
S2	100 m after connecting the sewage canal to the industrial city	300
S3	Beginning of the connected and massive mangrove cover	1650
S4	1200 m before connecting to sea/end of mangrove cover	3500

based on WHO, UNESCO, and the US Environmental Protection Agency (EPA) sampling guidelines. Table S1 listed the variable testing and measurement methods. The samples were placed in special containers in the monolithic chamber containing ice and transported to a trusted laboratory for required analysis. To prevent unknown contamination, all the sampling containers were washed with distilled water. The sediment samples were dried in an oven and turned into powder so that the digestion process could be done well. Acidic digestion operations have been carried out at 100 °C. Perchlorate was done in a ratio of 1 to 4 for 4 h. Then, the concentration of heavy metals was determined using the ICP-OES device.

A one-day monitoring was conducted in the stream at the mangroves' habitat to gather information on the flow path, inputs and outputs, and vegetation growth locations. Table 2 shows the measured parameters of water quality in stations 1 (before wastewater inlet) and 2 (after wastewater release).

Flow velocities were measured at the stations using a cork and a stopwatch. Moreover, the height of the water surface from the bed and the timing of the movement of the cork at the water surface to a specified distance at several points along the flow path were measured. It should be noted that these measurements were performed before the lowest tide height. Also, the water velocity measurements were done when the height of the water was sufficient to have flow through the roots but not much higher than the roots which influenced the water velocity and its relation to changes in the number of PTEs.

Flow velocity measurements indicate that Station 2 exhibits a higher velocity compared to Station 1. Consequently, Station 2 experiences greater turbulence and disturbance, which increases the surface area of water exposed to the atmosphere. This enhanced exposure facilitates a higher rate of oxygen transfer from the air into the water, resulting in elevated levels of DO at Station 2.

2.3. Root index of bioaccumulation factor (BCF)

To measure the amount of heavy metal which can state PTEs uptake and distribution in plants tissue, root index of Bioaccumulation factor (BCF) was used in this study. As expressed in Eq. (1), BCF is the ratio of the PTEs concentration in aerial roots of plant (C_{root}) to the PTEs concentration in sediment ($C_{sediment}$), which is usually less than one.

$$BCF = \frac{C_{root}}{C_{sediment}} \tag{1}$$

Table 2
Water quality measurements at Chabahar Mangrove site.

Water quality parameters	Station 1	Station 2
pH	8.61	8.15
Air temperature (°C)	20.4	20.6
DO (mg/L)	5.3	8.7
Water temperature	20	20.5
EC (mS/cm)	67.4	51.3
Salt (ppt)	-	34.8

2.4. Hakanson contamination coefficient and pollution load index

The pollution coefficient of Hakanson (Hakanson, 1980) or Cf is used to determine the degree of contamination of anthropogenic heavy metals (Eq. (2)).

$$Cf = \frac{Me_{sample}}{Me_{background}} \tag{2}$$

Four levels of contamination are listed in Table 3 to describe the level of metal pollutants.

The pollution load index (PLI) (Eq. (3)) was developed by Tomlinson et al. (1980) to understand the status of heavy metals that can state PTE's pollution. The PLI is close to one indicates that the load or concentration of heavy metals that is close to the background concentration, and if it is more than one it indicates that the sediment is contaminated:

$$PLI = \sqrt[n]{\prod_{i=1}^n Cf, i = 1.2.3...n} \tag{3}$$

where the Cf is the pollution coefficient of Hakanson.

2.5. Quality control/assurance (QA/QC)

QA/QC cases were considered to ensure that the study method did not qualitatively interfere. Therefore, during the sampling operation, two samples were taken from all stations (double sampling) and transferred to the laboratory in two separate freezers. Also, from the samples transferred to the laboratory, samples from each station were re-measured. The least numerical value was given to the mathematical equations in the processing of laboratory data that had minimal amounts, and the laboratory gave very low values.

3. Results

3.1. Flow velocity and cross-sectional area

Spatiotemporal distributions of the solute and heavy metals may exhibit different characteristics upon the flow velocity at different cross sections (Zhu et al., 2023). In the present study, the cross-sectional area was calculated from the sum of the trapezoidal regions whose two sides were the depth of path and the height of the transverse points of the points. Also, the flow rate at each cross-section was calculated from the product of the average real water velocity on both sides of each trapezoid in its trapezoid area that the actual water velocity was 0.85 m/s. Also, the surface water velocities measured at each station which is shown in Fig. 2.

3.2. Vegetation density and flow characteristics

Vegetation plays an important role in root water absorption and improving slope stability (Cheng et al., 2024). As mentioned earlier, station 1 does not have permanent flow. Water only reaches the area when the sea level is at its highest, and after the tide begins, this part of the lagoon drains sediments from the pond. The elements of this section are therefore excluded from consideration. According to the data

Table 3
Hakanson contamination factor grouping.

Sediment contamination coefficient	Cf
Low pollution factor	1≤
Average contamination coefficient	1–3
Significant contamination coefficient	3–6
Very high pollution factor	≤6

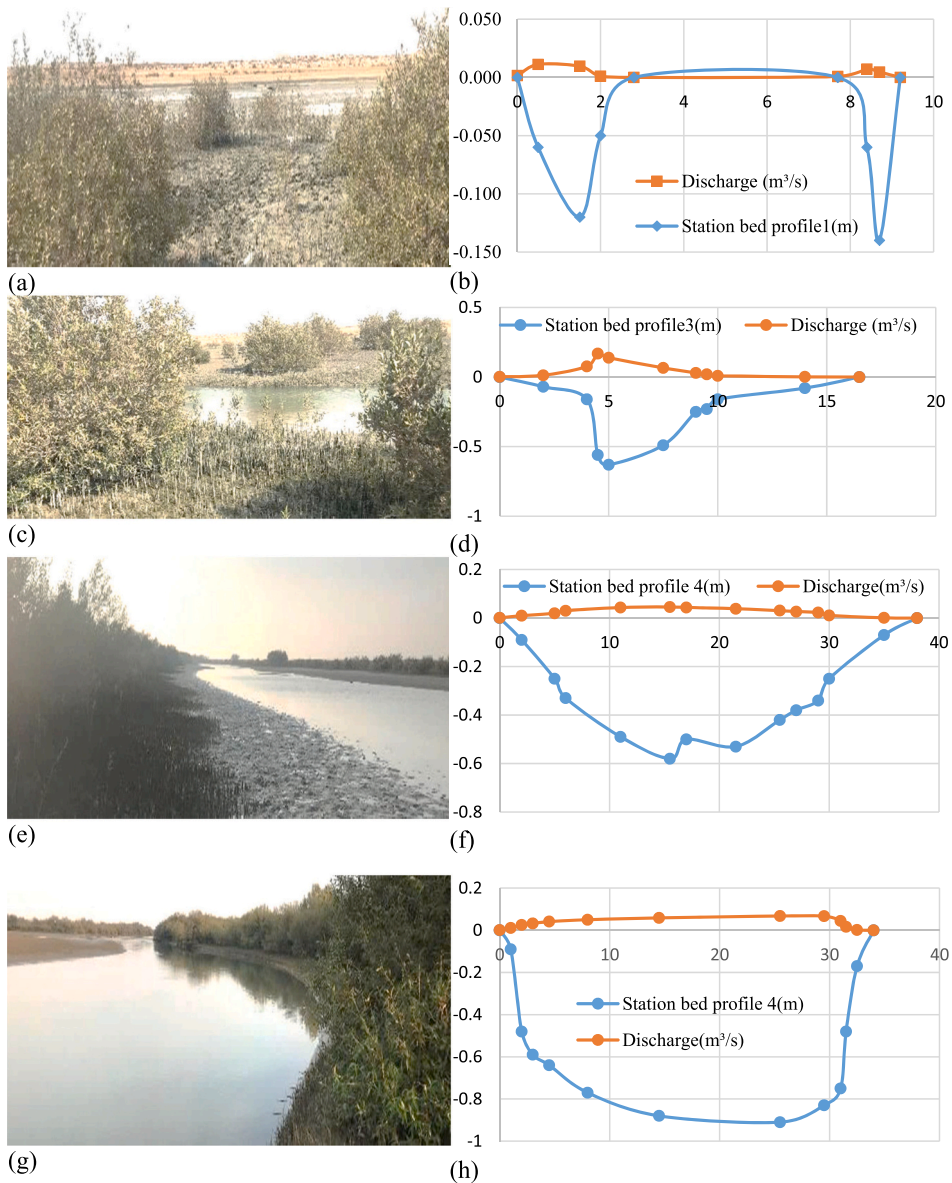


Fig. 2. Cross-section and discharge of flow in (a, b) station 1, (c, d) station 2, (e, f) station 3, and (g, h) station 4.

collected from the flow path sections, Flow characteristics (hydraulic parameter) in the wetland to calculated, at station 3, the width of the flow path was low, and the maximum water velocity was measured at this station. Its value at this point was approximately three times the maximum velocity of stations 3 and 4. The high-water velocity at the inlet of the sewage to the wetland and the change in direction of its movement caused eddy currents and soil slip, creating a large depth of water to the right. At this station, the water depth drops rapidly at the side of the track and adheres to a low slope surface reducing the flow rate by one-third. These conditions may have created a suitable environment for the deposition of fine particulate matter and sediment formation along the channel.

Although the cross-sectional area of the flows was one-quarter of the total cross-sectional area of the waterway, calculations showed that water flow in this area was one-tenth of the total flow at this station. At station 3, the channel width increased and therefore, water velocity was lower than at station 2, decreasing by one-third. Additionally, water velocity at station 3's edge was 70 % of that in the middle of the flow path. This deceleration created favourable environmental conditions for sediment deposition. The process of increasing flow path width and

decreasing water velocity continued up to about 1000 m ahead of station 3, improving conditions for sedimentation. Vegetation also increased and expanded. Station 4 had steeper banks than station 3. The cross-sectional area, which included roots and plants, accounted for 2 % of the whole cross-sectional area of the watercourse. This area at stations 2 and 3 was 25 % and 12 %, respectively. As a result, water velocity in the middle of this route was not different from station 3 but slightly lower on its sides. However, steep slopes made this path's margin less extensive. Vegetation width also declined. In general, it can be said that with decreasing water flow velocity, especially on sloping sides of streams, PTE concentrations in sediments increased while vegetation grew and expanded.

3.3. Concentrations of the selected PTEs' in water, sediment, and plant root

Tables S2 and S3 listed the elements and their concentrations in sediment and areal root of mangroves, respectively. Among 50 elements (see Table S3) measured, eight elements including Cu, Pb, Ni, Cr, Co, Fe, Cd, As, and Zn that have commonly been explored in other mangrove

forests (e.g., [Awal et al., 2009](#); [Cheraghi et al., 2013](#)) were considered as PTEs in this study. It is worth to mention that while Fe is an essential element for many biological processes, an excess of Fe²⁺ (ferrous iron) can be harmful. Organisms that inhabit or are near the sediment can be adversely affected by elevated Ee levels, which may disrupt their habitat and interfere with their physiological processes. Therefore, Fe was considered toxic in this study.

[Table 4](#) tabulated the measured concentrations of selected PTEs in water, sediment, and aerial roots of mangrove forest at each sampling station. The relative percentage of selected PTEs concentration in water, sediments, and plants roots were also presented in [Fig. 3](#). When the concentration values of these metals (except iron) in water were <0.005 ppm, they were eliminated from analysis. For iron concentration, 0.1 ppm was considered as the threshold value. As a result, for numerical analysis, the most moderate values were considered.

According to [Table 4](#) and [Fig. 3](#), the lowest concentrations of the PTEs are in the water and the highest are in the sediment. Fe and Ca are respectively the highest and lowest concentrations of PTEs in all three media. Except station 2 where Zn is higher at the root of the plant ([Table 4](#)), this trend is evident in all the elements. PTEs concentration also increased compared to station 3. The increase in PTEs concentrations in sediments and vegetation growth in this area are well correlated. Zn is an essential element for plant growth and involved in many metabolic and physiological processes of the plant ([Macfarlane and Macfarlane, 2003](#)). Also, the average order of concentration of PTEs in the sediment of Chabahar Bay is Fe > Cr > Zn > Ni > Cu > Pb > Co > As > Cd, and the order of PTEs concentration in plant roots is in the form of Fe > Zn > Ni > Cr > Cu > Co > As > Pb > Cd. So, after iron, Cr has the highest concentration in the sediment, but in the plant root, Zn has the highest content after iron.

3.4. The vegetation of area and amount of selected PTEs

The study channel is started from the vegetation growth site and continued to the junction with a length of 4700 m. Mangrove density at the beginning of this habitat (station 1) is low. On the other hand, the sewage canal of the industrial town was connected to the wetland about 200 m after the plants started. The vegetation on the channel bank was strengthened shortly after the sewage junction (station 2) too. At 1500 m, the mangrove density decreases again, but at 1600 m, it began with denser cover (station 3). According to Google's photo review, vegetation was expanding between stations 2 and 3, which will continue to lead to continued vegetation in the area. Moreover, the route continues after

station 3 with a mass coverage of approximately 2000 m (station 4). The highest density and area of vegetation was in the middle of stations 3 and 4. This density extends up to 300 m off the main route. Also, the last 1000 m of the route was after station 4 with no vegetation. The number of mangrove roots per square meter for the stations was measured as 39, 56, 84, and 48, respectively.

Since station 1 situated in upstream, and seawater reaches this point twice a day during the highest tide, and after 2 to 3 h, this part of the wetland becomes empty. The high concentration of metals in station 1 can be due to the longer water retention time of the wetland and thus a greater chance of sediment absorption. Also, it enters the sewage canal at the highest water level. But shortly after the tide begins, the stream flows back and the water mixed with sewage returns to the wetland. It seems that the velocity of inflow into the wetland and the creation of a rotating flow at the third station have eliminated the conditions for fine-grained sedimentation. Toward downstream, the slower flow, especially along the riverbank, increases the chance for PTEs to be absorbed by sediment, and the results of experiments show that the concentration of metals in station 3 sediment has also increased. At the downstream, the number of metals in the sediment decreased, probably due to the hydrodynamic effects of the tide, increased flow velocity shortly after the start of the tide, and high volumes of water withdrawal from the lagoon and greater mixing of seawater. The most notable observation is the positive correlation between PTEs concentration in sediment and vegetation cover extent. From station 3 to station 4, the channel width is increasing. Thus, the flow velocity is decreasing. This situation creates more time for deposition and uptake of metals in root and is expected to be an effective factor in increasing vegetation cover in this reach. The calculated cross-correlation coefficients were presented in [Tables 5 and 6](#).

The results show that Zn, As, and Cd show a reverse trend in a deposition with other metals and vegetation. However, the amount of Zn in the plant correlated well with the increase in plant density. As previously mentioned, some metals are essential for plant growth and involved in many metabolic and physiological processes of the plant. Increased vegetation causes a large amount of Zn to enter the plant tissues. This could be the reason behind the decrease concentration of Zn in the sediment. Considering [Tables 5 and 6](#), vegetation had a little effect on the amount of Co and its changes in sediment perhaps due the flow velocity and sedimentation along the wetland.

[Table 7](#) summarised the ratio of changes in the concentration of PTEs in sediment and root between successive stations. For an individual metal, the ratio is calculated by dividing the difference of the desired

Table 4
Concentrations of selected PTEs' in water, sediment, and root (ppm).

Media	Station	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Water	S1	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	S2	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	S3	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	S4	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	Average	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	Min	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
	Max	<0.005	<0.005	<0.005	<0.005	<0.005	>0.1	<0.005	<0.005	<0.005
Sediment	S1	24	13	51	102	11	21,743	0.25	4.3	33
	S2	18	11	30	111	6	14,941	0.29	5.6	46
	S3	38	14	47	138	9	22,091	0.25	4.7	29
	S4	11	10	15	67	3	10,622	0.3	7.7	42
	Average	22.75	12.00	35.75	104.50	7.25	17,350	0.27	5.58	37.50
	Min	11	10	15	67	3	10,622	0.25	4.3	29
	Max	38	14	51	138	11	22,091	0.3	7.7	46
Root	S1	14	1.965	21.674	20.042	4.173	9491	0.01	1.998	39.918
	S2	14	1.083	13.023	12.751	2.426	6082	0.01	1.953	27.983
	S3	8	1.236	15.82	14.878	2.639	7544	0.01	1.987	39.951
	S4	8	1.524	14.652	16.746	2.323	7263	0.01	2.471	31.253
	Average	11.00	1.45	16.29	16.10	2.89	7595	0.01	2.10	34.78
	Min	8	1.083	13.023	12.751	2.323	6082	0.01	1.953	27.983
	Max	14	1.965	21.674	20.042	4.173	9491	0.01	2.471	39.951

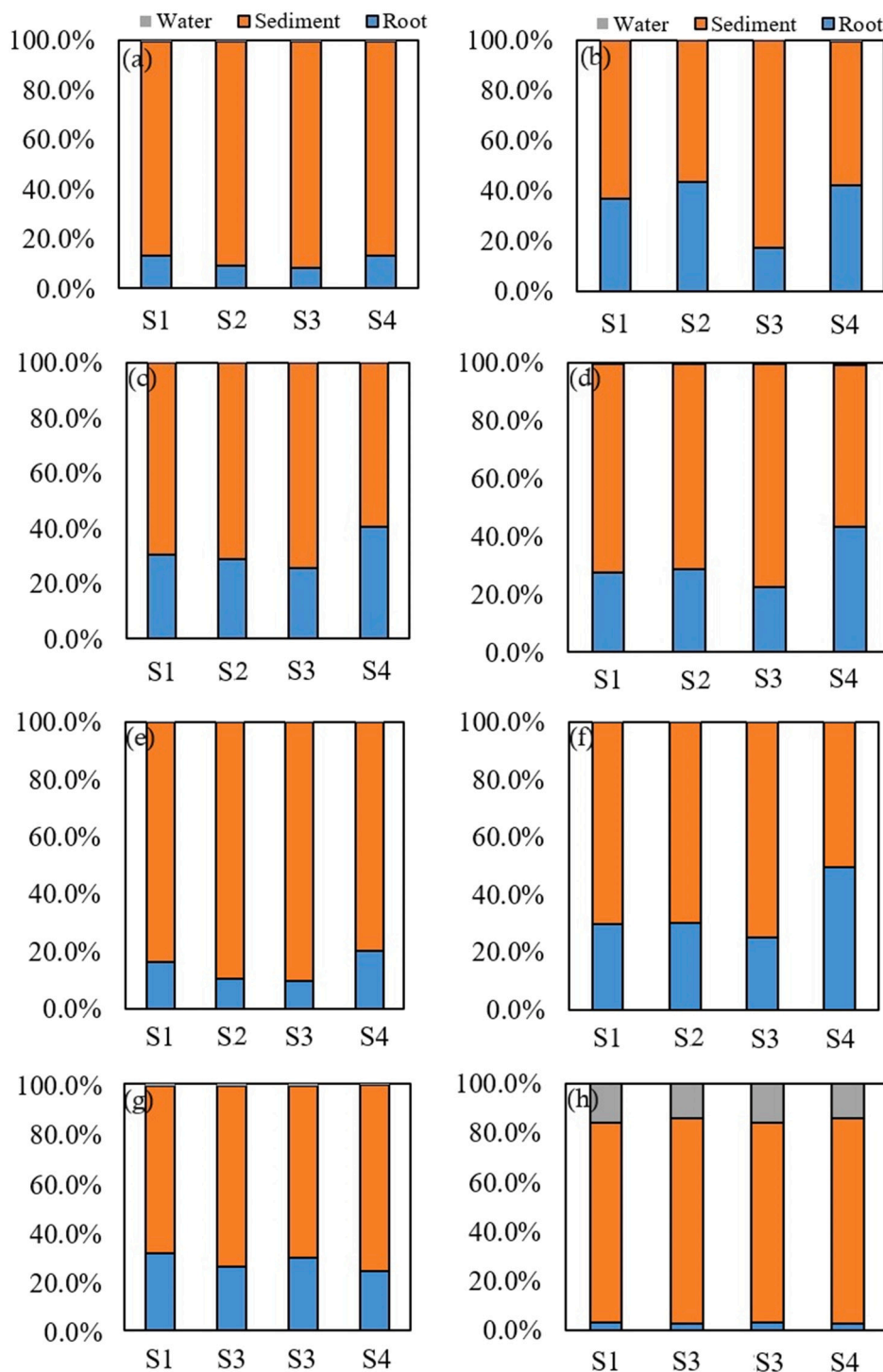


Fig. 3. Percentage of the selected PTEs concentration in water, sediments and plants roots [(a) Pb; (b) Cu; (c) Fe; (d) Co; (e) Cr; (f) Ni; (g) As; (h) Cd].

metal concentrations to its concentration in previous station. This ratio is generally lower in the root zone in comparison to sediments of the same area. In cases where these changes are greater, this is could because of the release of sewage into the lagoon between Station 1 and Station 2. As can be seen from the values in Table 5, the increase in flow velocity was inversely correlated with the increase in vegetation cover and the amounts of metals (except Zn, As, and Cd) in the sediment.

3.5. Concentration of selected PTEs in the root

Plants absorb the metals present in the sediment by their roots, so

PTEs may be found in their tissues. The calculation of root BCF showed the ratio of PTEs uptake by mangrove root (Table 8).

Increasing the concentration of a metal in sediment generally increases the amount of the same metal in plant root. As mentioned earlier, the changing ration in the plant roots is usually lower than in the sediments, so this increase may not be seen in BCF. Except for Zn, As, and Cd, which have the opposite behaviour of other metals, this ratio at station 4 is significantly increased compared to station 3 (Fig. 4). This is not due to an increase in the amount of PTEs in the plant root, but rather due to a decrease in the concentration of metals in sediments at station 4, which is also the end of the vegetation. This is also true for the Zn, As,

Table 5

Correlation coefficient - sediment metal concentration, plant density (number of roots per square meter) and average flow path velocity- Stations 2, 3 and 4. S.D. and $V_{average}$ stands for vegetation density and average velocity, respectively.

Sediment	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn	V.D.	$V_{average}$
Cu	1										
Pb	1.000	1									
Ni	0.972	0.970	1								
Cr	0.918	0.914	0.985	1							
Co	0.963	0.961	0.999	0.991	1						
Fe	0.992	0.990	0.994	0.961	0.990	1					
Cd	-0.998	-0.999	-0.956	-0.891	-0.945	-0.982	1				
As	-0.878	-0.874	-0.966	-0.996	-0.974	-0.933	0.847	1			
Zn	-0.887	-0.892	-0.755	-0.631	-0.731	-0.820	0.914	0.559	1		
V.D.	0.999	1.000	0.963	0.901	0.952	0.986	-1.000	-0.859	-0.905	1	
$V_{average}$	-0.810	-0.816	-0.651	-0.510	-0.623	-0.727	0.845	0.431	0.989	-0.832	1

Table 6

Correlation coefficient of plant root concentration, plant density (number of roots per square meter) and average flow path velocity - Station 2, 3, and 4.

Root	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn	V.D.	$V_{average}$
Cu	1										
Pb	-0.766	1									
Ni	-0.909	0.429	1								
Cr	-0.884	0.978	0.610	1							
Co	-0.197	-0.480	0.587	-0.284	1						
Fe	-0.983	0.637	0.970	0.785	0.371	1					
Cd	-	-	-	-	-	-	1				
As	-0.550	0.958	0.153	0.876	-0.710	0.390	-	1			
Zn	-0.711	0.092	0.939	0.300	0.829	0.827	-	-0.196	1		
V.D.	-0.305	-0.378	0.674	-0.175	0.994	0.473	-	-0.627	0.887	1	
$V_{average}$	0.782	-0.198	-0.970	-0.400	-0.765	-0.882	-	0.091	-0.994	-0.832	1

Table 7

The ratio of changes in concentration of PTEs in sediment and root between successive stations.

Factors	Stations ratio	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Sediment	S2/S1	-0.25	-0.15	-0.41	0.09	-0.45	-0.31	0.16	0.30	0.39
	S3/S2	1.11	0.27	0.57	0.24	0.50	0.48	-0.14	-0.16	-0.37
	S4/S3	-0.71	-0.29	-0.68	-0.51	-0.67	-0.52	0.20	0.64	0.45
Root	S2/S1	0.00	-0.45	-0.40	-0.36	-0.42	-0.36	0.00	-0.02	-0.30
	S3/S2	-0.43	0.14	0.21	0.17	0.09	0.24	0.00	0.02	0.43
	S4/S3	0.00	0.23	-0.07	0.13	-0.12	-0.04	0.00	0.24	-0.22

Table 8

Distribution factor of selected PTEs (ppm) from sediment to root.

Parameter/factor		Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Sediment	S1	24	13	51	102	11	21,743	0.25	4.3	33
	S2	18	11	30	111	6	14,941	0.29	5.6	46
	S3	38	14	47	138	9	22,091	0.25	4.7	29
	S4	11	10	15	67	3	10,622	0.3	7.7	42
Root	S1	14.00	1.97	21.67	20.04	4.17	9491	0.01	2.00	39.92
	S3	14.00	1.08	13.02	12.75	2.43	6082	0.01	1.95	27.98
	S4	8.00	1.24	15.82	14.88	2.64	7544	0.01	1.99	39.95
	S6	8.00	1.52	14.65	16.75	2.32	7263	0.01	2.47	31.25
Root BCF	S1	0.58	0.15	0.42	0.20	0.38	0.44	0.04	0.46	1.21
	S3	0.78	0.10	0.43	0.11	0.40	0.41	0.03	0.35	0.61
	S4	0.21	0.09	0.34	0.11	0.29	0.34	0.04	0.42	1.38
	S6	0.73	0.15	0.98	0.25	0.77	0.68	0.03	0.32	0.74

and Ca, which means that the increase in the concentration of these three metals in the sediment has reduced the coefficient, which again confirms the reverse behaviour of these three PTEs.

3.6. Results of CF and PLI

According to the Hakanson's coefficient of contamination, the concentration level of Ag and Ca is high, the Sr element is medium to significant, and for the other elements is medium or low. The results are

presented in Table 9.

Also, the calculation of PLI value for selected elements in the all-measured metals was less than one and indicated low metal contamination of the area (Table 10).

3.7. Sediment gradation

Sieve analysis was used for better understanding the physical features of the sediment samples. Based on the particle size distribution

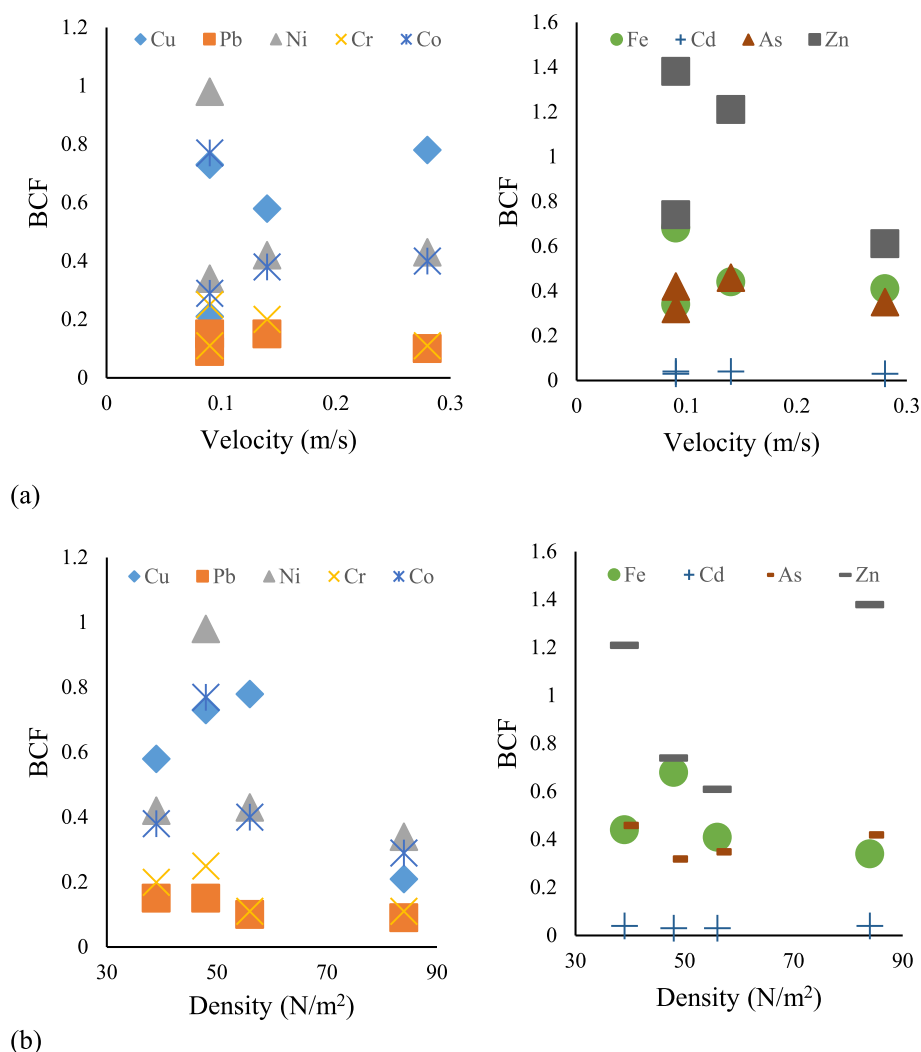


Fig. 4. (a) Flow velocity (b) plant density - root BCF for Zn, As, Cd, Fe, Cu, Pb, Ni, Cr, Co.

graph (Fig. S1), all samples are placed on the sand or gravel class. According to unified soil classification, S1, S2, and S3 are poor gravel (GP), well gravel (GW) and well sand., respectively. All S1, S2 and S3 samples categorized in poor sand (SP) category.

PTE accumulation in sediments is influenced by many environmental factors, including acidity, the type and concentration of organic and inorganic substances in sediments, particle size, and metal content in the environment (Nitopi et al., 2024). When metals enter the environment, they rapidly attach to fine particles and accumulate on the sediment affected by wetlands during the day and its aggregation is more consistent with the surrounding environment. Water velocity rises at its highest level and water reaches station 1 after crossing a low slope. This relaxation provides sedimentary conditions for grains before reaching station 1. Additionally, a higher volume of water enters the sewage canal from the deep part of the route at station 2, causing the number of fine grains transferred to station 1 to be low. As a result, the percentage of coarse grains in station 1 sediments is high. The constant discharge of sewage at station 2 and the rate of water discharge during tide have caused fine-grained washings and even fine-grained sediments return to the wetland (station 2) before settling. Grading results show that the number of coarse grains at station 2 is higher than at all other stations. Station 2 is near the lagoon's endpoints when seawater reverses; water slowly reaches station 2, where the water level rises and spreads in the low slope margin of the flow path. Since this is a good location for fine-grained sedimentation, fine grains are larger than at stations 1 and 2 and

may be one reason for increased vegetation cover between stations 2 and 3. After station 2, the wetland returns to normal. That is, as we move toward the sea, as water flows and the lagoon relax, coarse grains and then fine grains become more likely to settle. This trend is well observed at stations 3, and 4. There appears to be a good relationship between increasing PTE content in sediment, fine-grained sedimentation, reduced flow rate, and increased vegetation cover from station 3 to station 4. The station 4 is characterized by fine-grained sediments, leading to the highest absorption of arsenic in the sediment environment at this location. Additionally, the convergence of salt and fresh water, along with wave forces in a substantial water body, results in the lowest velocity according to Fig. 5, observed at station 4. Consequently, this station also exhibits the longest retention time due to these environmental factors.

In addition, the increase of total organic matter has an inverse relationship with absorption (Tangahu et al., 2011; Zhou et al., 2024a), therefore, with the increase of this substance from station 1 to 2, it is expected that the absorption of PTEs in the sedimentary environment will decrease and predictable, except for the metal's arsenic, cadmium and chromium. Another factor that affects the absorption of PTEs is the flow rate (Partani et al., 2024b). Therefore, with the decrease in flow velocity in station 3 compared to its previous section (increase in retention time) due to the high density of pneumatophores vegetation, it is expected that in station 3 PTE absorption in sediment is higher than in station 2. Since the size of the sediments in this place was fine-grained.

Table 9
CF contamination coefficient in sediment.

Element	Sediment CF				Sediment pollution			
	S1	S2	S3	S4	S1	S2	S3	S4
Ag	7.86	7.86	5.71	8.00	Very high	Very high	Significant	Very high
Al	0.50	0.34	0.47	0.18	Low	Low	Low	Low
As	0.33	0.43	0.36	0.59	Low	Low	Low	Low
Ba	0.18	0.17	0.18	0.13	Low	Low	Low	Low
Be	0.37	0.33	0.33	0.33	Low	Low	Low	Low
Ca	3.50	4.52	4.36	4.52	Significant	Significant	Significant	Significant
Cd	0.83	0.97	0.83	1.00	Low	Low	Low	Low
Ce	0.59	0.47	0.59	0.37	Low	Low	Low	Low
Co	0.58	0.32	0.47	0.16	Low	Low	Low	Low
Cr	1.13	1.23	1.53	0.74	Medium	Medium	Medium	Low
Cu	0.53	0.40	0.84	0.24	Low	Low	Low	Low
Fe	0.46	0.32	0.47	0.23	Low	Low	Low	Low
K	0.41	0.28	0.40	0.18	Low	Low	Low	Low
La	0.17	0.14	0.17	0.11	Low	Low	Low	Low
Li	0.42	0.27	0.38	0.15	Low	Low	Low	Low
Mg	1.04	0.71	0.95	0.49	Medium	Low	Low	Low
Mn	0.57	0.66	0.61	0.60	Low	Low	Low	Low
Mo	0.23	0.25	0.27	0.28	Low	Low	Low	Low
Na	2.55	1.52	1.73	0.96	Medium	Medium	Medium	Low
Ni	0.75	0.44	0.69	0.22	Low	Low	Low	Low
P	0.73	0.85	1.17	1.82	Low	Low	Medium	Medium
Pb	0.65	0.55	0.70	0.50	Low	Low	Low	Low
S	0.91	0.49	1.17	0.64	Low	Low	Medium	Low
Sb	0.44	0.41	0.43	0.36	Low	Low	Low	Low
Sc	0.58	0.42	0.57	0.31	Low	Low	Low	Low
Sr	1.77	2.63	1.54	3.04	Medium	Medium	Medium	Significant
Th	0.42	0.42	0.42	0.42	Low	Low	Low	Low
Ti	0.49	0.36	0.49	0.21	Low	Low	Low	Low
U	1.35	2.95	2.51	2.57	Medium	Medium	Medium	Medium
V	0.39	0.26	0.39	0.17	Low	Low	Low	Low
Y	0.50	0.50	0.54	0.46	Low	Low	Low	Low
Yb	0.50	0.42	0.54	0.38	Low	Low	Low	Low
Zn	0.48	0.31	0.44	0.18	Low	Low	Low	Low
Zr	0.28	0.19	0.26	0.10	Low	Low	Low	Low

Table 10
The PLI results for all measured and selected metals.

Station	Selected metals (last chapter)	Measured metals
S1	0.60	0.63
S2	0.49	0.54
S3	0.64	0.65
S4	0.35	0.43

Therefore, the conditions of settling are provided in this place, which makes the effect of the surface velocity on the absorption of pollutants more colourful.

4. Discussion

To discuss the finding of this study, PTEs concentrations in sediment were compared with international standards (Table 11) as well as those of other wetlands reported in the literature (Table 12). Similarly, PETs concentration in the roots of Mangroves were compared with those of

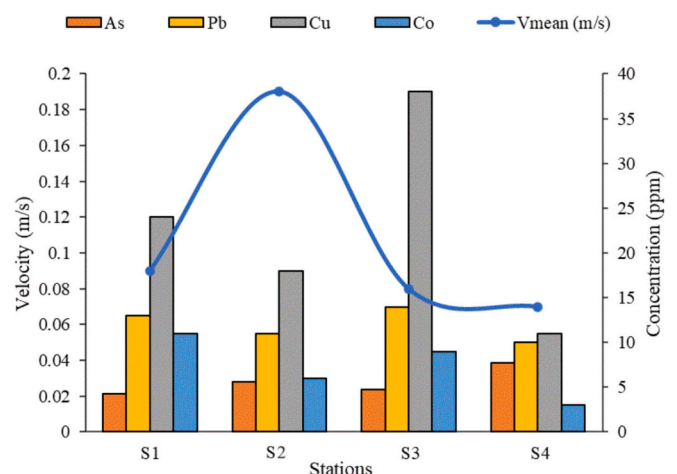


Fig. 5. Changes in retention time versus metal absorption in sediment.

Table 11
Comparison of PTEs concentrations in sediment with international standards.

		Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Geochemical Background	Shale ^a	45	20	68	90	19	47,000	0.3	13	95
	Continental crust	55	12.5	75	100			0.2	1.8	70
China CSBTS	Class I	35	60		80			0.5	20	150
	Class II	100	130					1.5		350
	Class III	200	250		270				93	600
US DOE	TEC	28	34.2	39.6	56			0.59	12.1	159
	PEC	77.7	396	38.5	159			11.7	57	1532
	HNEC	54.8	68.7	37.9	312			41.1	92.9	541
Canadian EQG	ISGQ	35.7	35	16	37.3			0.6	5.9	123
	PEL ^b	197	91.3	36	90			3.5	17	315
NOAA	ERL	34	47	20.9	81			1.2	8.2	150
	ERM ^c	270	220	51.6	370			9.6	70	410
	LEL	16	31	16	26			0.6	6	120
Probable Effect Concentration (PEC) Sediment Quality Guidelines (SQGs) Ontario MOE	TEL	197	91.3	36	90			3.53		315
	ERM	390	110	50	145			9		270
	TET ^d	86	170	61	90			3		540
	SEL ^e	110	250	75	110			10	33	820
Japan MOE	EQS	125	0.01					1	0.01	
Japan's river Sediment Average		30.6	23.1	25.1	65.2			0.158	9.32	118
New York	Low	16	32	16				0.6		120
	Sever	110	110	50				9		270
USEPA Region I For Mangrove		18.7	30.2	15.9	52.3			0.68	7.24	124
USEPA Region II For Mangrove	TEL	17.02	28.39		50.21			0.66	7.02	119.04
	TEL	108	112	42.8	160			4.2	41.6	271
	RCF ^f	1.07	0.23	5.6				0.28	0.97	0.3
EU 2002		140	300	75	150			3		300
SQO Netherland target	Low	36	85					0.8	2.9	140
	High	36	530					2	55	480
Hong Kong ISQV	Low	65	75	40	80			1.5	8.2	200
	High	270	218		370			9.6	70	410
IAEA 405		47.7	74.8	32.5	84		37,400	0.73	23.6	279
Threshold Effect Contamination	LEL ^g	26	31	16	26			0.6		120
	TEL ^h	35.7	35	18	37.3			0.596		123
	ERL ⁱ	70	35	30	80			5		120
	S1	24	13	51	102	11	21,743	0.25	4.3	33
S2	18	11	30	111	6	14,941	0.29	5.6	46	
S3	38	14	47	138	9	22,091	0.25	4.7	29	
S4	11	10	15	67	3	10,622	0.3	7.7	42	

^a The average shale values suggested by Bowen (1979) were used to calculate the indices and coefficients of metal pollution (see Table S4).

^b Probable Effect Level.

^c Effect Range Medium.

^d Toxic Effect Threshold.

^e Sever Effect Level.

^f Relative Contamination Factor.

^g Lowest Effect Level.

^h Threshold Effect Level.

ⁱ Effect Range Low.

international wetlands in Table 13.

Comparison of concentration of PTEs in Chabahar Bay with world standards shows that Zn, As, Ca, Fe, Co, and Pb contents are lower than world standards, but wetland is not free of contamination.

In the standard table, the ERL is the limit at which 20 % of biological communities are at risk, the ERM is at the limit of 50 % of the biological communities at risk, and the PEL levels cause adverse effects. In the New York sediment quality standard, the two areas were considered the least impacted and the most severely impacted. LEL is the lowest effect level, SEL is the extreme effect level and TEL is the threshold effect level. The amount of copper present at station 3 is higher than the Chinese primary standard and at stations 1 and 4 above the USEPA standard, but its concentration is not higher than the Chinese secondary standard and the US secondary environmental standard. Ni at station 4 is low and at station 2 is moderate but at stations 1 and 3 it is above the US Secondary Environmental Standard. Also, concentrations of this element are within the boundary of the US NOAA Sediment Quality Standard (ERM) and are within the range of USEPA adverse effects level (PEL) that should be considered. Further, the chromium content is moderate at all stations, and only at station 4, its concentration tends to be low, but is above the

standard US environmental standard. As a result, according to comparisons with world standards, the amounts of chromium, nickel, and copper should be controlled to avoid severe contamination. Compared to Bandar Anzali in the north of Iran, Cu and Ni elements are less, but more for Pb.

The comparative investigation of lakes and wetlands in the world (Table 12) showed a wide variation of concentrations in PTEs which the variance of them could be assigned to anthropogenic land uses such as industrial but the mean values are flowing a same boundary of concentrations. These human activities can introduce a range of pollutants into aquatic ecosystems, influencing the concentrations of PTEs found in these environments. According to Table 12, the concentration of lead, copper, cadmium, and chromium is slightly higher than the average of the wetlands. Despite the notable differences in individual concentration levels across various locations, this observation suggests that local conditions can drastically affect PTE levels, potentially leading to spikes in contamination due to industrial discharge or runoff.

Comparison of root concentrations with other wetlands with *Avicennia marina* showed that the amount and ability of PTEs to be absorbed by the roots of plants in the Chabahar region is like other wetlands.

Table 12
Comparison of PTEs concentrations in sediment with other wetlands in the world.

Source	Climate	Location	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Kishe and Machiwa, 2003	Tropical	Victoria lake, Tanzania, Africa	38.6	29.6	44.7				0.9		
Awal et al., 2009	Tropical	Sundarbans-Bangladesh	10.5	19.3	76.1	15.7		173,890	0.6		73.6
Hashem, 1993	Tropical	Yanbu-Saudi Arabia	31	26.1				43	2.3		13.3
McAlister et al., 2005	Tropical	Rio de Janeiro, Brazil	290.6	368.9	73.1	97.3					1284.1
Yongming et al., 2006	Temperate	Xi'na, China	95	230.5		167.3					421.5
Imperato et al., 2003	Mediterranean	Naples Urban region, Italy	74	262		11					2.5
Murray et al., 2004	Sub-tropical	Residential area, South-eastern, US.	30	160	24	31					120
Murray et al., 2004	Sub-tropical	Commercial area, South-eastern, US	32	93	16	27					130
Liang and Wong, 2003	Sub-tropical	Mai Po, Hong Kong	78.5	79.2		39.2			2.6		240
Davari et al., 2013	Sub-tropical	Bidkhood, Basatin, Persian Gulf	46	94.8	64.1						181.5
Einollahi Peer and Safahieh, 2011	Sub-tropical	Life Booseif, Northwest of Persian Gulf	21.8	23.5	73.6						68.6
Einollahi Peer and Safahieh, 2011	Sub-tropical	Northern coast of Oman sea, Summer	38.3	50.4	26.9						
Einollahipeer et al., 2013	Sub-tropical	Gulf of Gwatr, Oman Sea	22.1		71.1						53.6
Einollahipeer et al., 2013	Sub-tropical	Qeshm Island	42.1	47.9	54.1						43.6
Morillo et al., 2004	Sub-tropical	Southwest coast of Spain	49.6	254.4	16.3				1.1		
Puttaiah and Kiran, 2008	Sub-tropical	Jannapura lake, India	89.8	20.8	40.1				1.9		
Bai et al., 2011	Sub-tropical	Yilong lake, China	31.4	53.2	36				0.8		
Nasirian et al., 2015	Sub-tropical	Shadegan, Iran	14.8	14.2	47.1				4.7		
Ghazban and Zare Khosh Eghbal, 2011	Sub-tropical	Anzali, Iran	62.3	24.5	75.9				0.3		
Karbassi and Bayati, 2005		Average in earth	50	14	80				0.2		
		Average	54.9	101.5	51.2	55.5		86,967	1.5		204.9
		Max	290.6	368.9	80	167.3		173,890	4.7		1284.1
		Min	4.7	14	16	11		43	0.2		2.5
This study		S1	24	13	51	102	11	21,743	0.25	4.3	33
		S2	18	11	30	111	6	14,941	0.29	5.6	46
		S3	38	14	47	138	9	22,091	0.25	4.7	29
		S4	11	10	15	67	3	10,622	0.3	7.7	42
		Average	22.75	12	35.8	104.5	7.3	17,350	0.27	5.58	37.5

Table 13
Comparison of Some PTEs concentrations in plant root and root BCF with other wetlands in the world.

Source	Location	Cu	Pb	Ni	Cr	Co	Fe	Cd	As	Zn
Chen et al., 2003, Ting Kok, Hong Kong	Sediment	13	33							55
	Root	13	15							16
	Root BCF	1.02	0.44							0.29
Alongi et al., 2003, Western Australia	Sediment	16								34
	Root	18								16
	Root BCF	1.16								0.48
Zheng and Lin, 1996, Shenzhen, China	Sediment	36	31							99
	Root	14	3.4							79
	Root BCF	0.39	0.11							0.71
Peng et al., 1997, Shenzhen, China	Sediment	36	34							106
	Root	13	3.5							79
	Root BCF	0.37	0.1							0.75
MacFarlane et al., 2003, SE Australia	Sediment	61	100							243
	Root	101	164							295
	Root BCF	1.66	1.64							1.21
Cheraghi et al., 2013, Mahshahr, Iran	Sediment	11.19	23.98					5.6		79.93
	Root	11.19	11.66					3.34		31.32
	Root BCF	1	0.486					0.596		0.392
This study	Root S1	14	1.97	21.67	20.04	4.17	9491	0.01	2	39.92
	Root S2	14	1.08	13.02	12.75	2.43	6082	0.01	1.95	27.98
	Root S3	8	1.24	15.82	14.88	2.64	7544	0.01	1.99	39.95
	Root S4	8	1.52	14.65	16.75	2.32	7263	0.01	2.47	31.25
	Root BCF S1	0.58	0.15	0.42	0.2	0.38	0.44	0.04	0.46	1.21
	Root BCF S2	0.78	0.1	0.43	0.11	0.4	0.41	0.03	0.35	0.61
	Root BCF S3	0.21	0.09	0.34	0.11	0.29	0.34	0.04	0.42	1.38
	Root BCF S4	0.73	0.15	0.98	0.25	0.77	0.68	0.03	0.32	0.74

These kinds of comparisons are essential to comprehending the biological behaviour and environmental adaptation of mangrove species. The BCF coefficient is also in the range of similar metals in other wetlands. Compared to the Mahshahr wetland, cadmium concentration and BCF coefficient are much lower, probably due to the absence of plating industries in the region. Also, the concentration of Cu and Zn in the root of

the study area of Hong Kong and Australia is like the Chabahar region but the BCF coefficient is lower in the Chabahar region and higher for Zn (Table 13). Also, the concentration of Cu in Shenzhen, China, is the same as this research, while it is higher for Zn and Pb.

Compared to the finding of the study conducted by Almahasheer et al. (2018) for coastal lagoon of the Red Sea, their BCF coefficient was

lower for Pb and Cd. On the other hand, Cr and Cu were in a similar range, while Fe and Zn were higher.

5. Conclusions

Our surveys on field measurements revealed that the amount of PTEs in sediment is generally higher than in plant roots, with the lowest concentration found in wetland water, except for Zn, As, and Cd. The concentration of PTEs in sediments shows an inverse relationship with the streamflow rate; specifically, a decrease in flow velocity results in an increase in the quantity of PTEs in the sediment. Additionally, the results indicate that the concentration of PTEs in sediments is directly related to the extent of vegetation cover, meaning a higher concentration of metals is associated with more extensive vegetation. However, this correlation does not apply to Zn, As, and Cd.

In addition, we found that the concentration of PTEs in the sediments has a direct correlation with the sedimentation process. As the sediments become finer in texture, there is an increase in the concentration of PTEs. Furthermore, there is an inverse relationship between the flow velocity and the presence of fine-grained sediment. This means that a slower flow rate results in a higher quantity of fine-grained sediment. Additionally, an increase in sedimentation promotes the growth and development of vegetation in the area.

This study discovered that the order of concentration of metals in the sediment of Chabahar Bay is in the form of Fe > Cr > Zn > Ni > Cu > Cd and plant root is in the form of Fe > Zn > Ni > Cr > Cu > Pb > Cd. The PTEs were low in the wetland water, so their order was not well characterized. The intensity of changes in PTE content in the wetland path at the root of the plant is lower than that of the sediments. In addition, the changes in trace amounts of Zn, As and Cd in sediment and their relation to changes in flow characteristics and sedimentation of other PTEs reverse sediments. Also, PTE pollution is generally low by international standards and pollution indicators. We concluded that the amount of PTE absorbed by the plant root was like other wetlands in the study. Due to the increasing vegetation of the wetland, it is suggested that the PTE content and the relationship between the characteristics of the wetland and the PTE content will be reiterated over the coming years and evaluate the impact of industrial town growth on PTEs. Since the Chabahar Port dock has just been set up Marine transportation traffic is expected to increase, greater emissions of pollutants and higher risks of accidental spills are expected. This can result in more contaminants, including PTEs, being introduced into the seawater. Consequently, the concentration of PTEs in the study area may rise, posing a threat to the mangrove ecosystem and local human health.

Given the current circumstances and the urgent need to advance the oil and gas industries on a transnational scale, the most critical management and executive solution is implementing robust programs and algorithms for monitoring and assessing environmental impacts. This includes ensuring strict compliance with the ecological requirements outlined in the environmental impact assessment report for areas directly affected by oil and gas industrial activities. Considering the sensitivity to PTEs and the associated health risks, polluting enterprises need to install effective pollutant purification systems and filters. Additionally, research should focus on analysing the concentration of these metals in aquatic environments and living organisms, such as fish, birds, and their eggs. Our study was limited to investigate the distribution and toxicity of eight metals (Fe, Cr, Zn, Ni, Cu, Pb, Co, As, and Cd) in water and belowground part of mangrove ecosystem. Further studies are suggested to consider the above ground biomass portion that provides additional information of overall phytoremediation and upward metal transport trend, sediment to leaf via root and wood.

CRedit authorship contribution statement

Sadeh Partani: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation,

Data curation, Conceptualization. **Ali Danandeh Mehr:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Kaveh Amir Ahmadi:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Milad Alaei:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Mohsen Maghrebi:** Writing – review & editing, Resources, Formal analysis, Conceptualization. **Ricardo Hideo Taniwaki:** Writing – review & editing, Validation, Conceptualization. **Ali Jafari:** Writing – original draft, Software, Investigation, Formal analysis.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176635>.

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