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Heavy metal phytoremediation of aqueous solution by *Typha domingensis*

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Abstract More has yet to be indicated on the ability of microphyte plants for the removal of heavy metals from contaminated environments. In the present research, the ability of the aquatic macrophyte, *Typha domingensis* species, for the phytoremediation of heavy metals (Zn, Cd, Ni, Pb, and Cr) in aqueous solution was investigated. Accordingly, 50 plants of *T. domingensis* species were harvested from Shadegan International Wetland, Iran. The plants were then translocated in the aquariums containing water contaminated with heavy metals (Zn, Cd, Ni, Pb, Cr) at concentrations between 0 (as control) and 20 mg L^{-1} in two different pHs (4 and 7) for 30 days. Plant absorption of heavy metals, determined for different plant tissues, increased with increase in heavy metal concentration and decrease in water pH. The highest total uptake of heavy metals was in the following order: Zn (77.5%) > Pb (70.2%) > Ni (63.1%) > Cr (47.8%) > Cd (38.2%), with the order tissue of roots > stems > leaves > flowers. Plant roots had the highest values of bioconcentration (BCF) factor for Zn (2.16) > Pb (1.66) > Ni (1.46) > Cr (1.09) > Cd (0.94). However, compared with the leaves and flowers, plant aerial parts indicated the highest TF values, by the following order: Zn (0.95) > Pb (0.94) > Ni (0.90) > Cr (0.85) > Cd (0.79). *T. domingensis* is a heavy metal hyperaccumulator and can be efficiently used for the phytoremediation of aqueous solutions, contaminated with heavy metals including Zn, Pb, Ni, Cr, and Cd.

Keywords Bioremediation · Shadegan International Wetland · Water pH · Water pollution

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Introduction

The metals and metalloids with the density higher than 5.8 g cm^{-3} are considered as heavy metals (Chandra et al. 2017), and due to their toxicity, stability and bioaccumulation properties are among the most important environmental pollutants (Miransari 2011). Different human activities including mining, agriculture, and industry contaminate the environment. Heavy metals are not favorable for human health as they are accumulated in the food chain and disrupt the balance of physiological processes (Jiang et al. 2020).

Different methods including physical, chemical, and biological ones have been used for the treatment of polluted environments with heavy metals. However, the physical and chemical methods are expensive, time-consuming, and environmentally not recommendable. Due to their benefits, green and environmentally friendly technologies including phytoremediation, which is the use of plants for the removal of heavy metals from the polluted environments, are now used to treat heavy metals in the contaminated areas (Pandey et al. 2019). It is an environmentally and economically friendly method, using natural or genetically modified plants with a high ability of absorbing and accumulating heavy metals (Mojiri et al. 2015).

Although there has been previous research on the use of aquatic plants for the bioremediation of aquatic solutions, more has to be investigated on the selection of the most appropriate ones for the removal of heavy metals from the contaminated aquatic environments. Different aquatic plant species including *Typha domingensis* have been tested for the bioremediation of polluted aquatic areas as such plants have high ability to grow in aquatic environments such as the wetlands. However, the phytoremediation ability of *T. domingensis* for heavy metals has yet to be investigated. The aquatic macrophyte species acts as a suitable biological biofilm for the absorption of heavy metals in the aquatic environments, as they have high ability to remove heavy metals from contaminated areas. The plant is found in wetlands, swamps, marshes, rice fields, irrigation canals, and on the shore of the rivers (Di Luca et al. 2019; Pandey et al. 2020).

There has not been much research on the use of *T. domingensis* for the removal of heavy metals from aquatic environments. For example, Dube et al. (2019) investigated the removal of heavy metals by different tissues of *T. domingensis* from a tropical reservoir and found that the absorption of heavy metals (Zn, Fe, Cr, and Cr) was in the following order: root > stem > leaves; however, the order for Pb, Cd, and Mn was root > leaf > stem.

In another research, Hadad et al. (2018) examined the phytoremediation of heavy metals by different tissues of *T. domingensis* from a constructed wetland contaminated by a metallurgical effluent for 5 years. According to their results, the bioaccumulation factors of Ni and Cr were around 1, and for Zn and P were higher than 1, indicating root bioaccumulation of heavy metals. The translocation factor > 1 for P compared with the other elements indicated the necessity of P for plant growth. Accordingly, the authors indicated the suitability of the plant for P phytoextraction, and for heavy metals phytostabilization.

The Shadegan International Wetland, located in the southern part of Iran, is of environmental and health significance; however due to anthropogenic activities, it has been contaminated with heavy metals. It is accordingly important to find the most suitable aquatic plant species, which can be efficiently used for the bioremediation of the Wetland. Due to the abundance of *T. domingensis* in the Wetland, we collected the plant and tested its ability for the removal of heavy metals. Accordingly, the objective of the present research was to investigate the ability of *T. domingensis*, as a heathy method, for the phytoremediation of heavy metals including Zn, Pb, Ni, Cr, and Cd from aqueous solutions.

Materials and methods

Sampling

In this study, 50 plants of *Typha domingensis* species were harvested from the Shadegan International Wetland in south of Iran (Fig. 1). The plants, transferred to a laboratory and cultured in an aquarium, were treated with heavy metals including Zn, Cd, Ni, Pb, and Cr at concentrations of 0 (control), 5, 10, 15, and 20 mg/l (Feng et al. 2018) with the water pHs of 4 and 7 (Sinha et al. 2017) for 30 days (Fig. 1). The plants were then collected from the aquarium and washed with distilled water. Different plant tissues (roots, stems, leaves, and flowers) were dried in an oven at 70 °C, for 24 h, and the tissues were then powdered with opal mortar and digested by Jackson method (1980) according to the following.

Chemical analyses

The plant samples were digested according to the following: 0.5 g of the powdered plant sample was added to 100 ml Erlenmeyer flask, and was treated with 1 mL of nitric acid and hydrochloric acid. A glass

◀**Fig. 1** *Typha domingensis* in the Shadegan International Wetland and during the experiment

jar was mounted on each Erlenmeyer flask and the samples were placed under the hood for 24 h. The flasks were then placed on a heater at the temperature of 70 to 80 C and gently heated resulting a palm color vapor of all the samples. Then, 3 mL of the sample was treated with nitric acid and hydrochloric acid to intensify the heat treatment and complete the oxidation of the plant material. This process continued until the sample size was reduced to 2 mL and the sample became completely colorless. The samples were completely discolored, reduced in volume, and cooled down, and were brought up to volume using distilled water.

In addition, the soluble samples were filtered through filter paper No. 45, poured into a 50 mL-balloon, and were treated with 1% nitric acid, which reduced the sample volume to 50 mL. The samples were then placed in plastic containers and read by atomic absorption spectrometry (MacFarlane et al. 2003). The samples were then measured using atomic absorption spectrophotometer.

Bioconcentration (BFC) and translocation (TF) factors

The two indices of BCF and TF can determine if the plant is a hyperaccumulator for heavy metals, and if most of the absorbed heavy metals are compartmentalized into the roots, so the plant would detoxify the stressful effects of heavy metals. The BCF index indicates the translocation of heavy metals from the aqueous environment into the plant. The TF index indicates the translocation of absorbed heavy metals from the plant roots to the aerial tissues. Plant BFC and TF were calculated for each heavy metal (Zn, Pb, Ni, Cr, and Cd) according to the following details (Branquinho et al. 2006).

$$\text{Bioconcentration Factor (BCF)} = \text{C Plant}/\text{C Water}$$

To determine the translocation factor, the amount of heavy metal transfer from the root to the aerial section was calculated (Komar et al. 2001).

$$\text{Translocation factor (TF)} = C_{\text{aerial section of plant}}/C_{\text{Root}}$$

Statistical analyses

Data were subjected to analysis of variance using SAS 9.3. Means were compared by least significant difference (LSD) at $p \leq 0.05$. The graphs were plotted using SAS Proc Plot.

Results

Analyses of variance

Analyses of variance indicated the single effects of the experimental treatments including plant tissue, heavy metal type, and concentration, and water pH significantly affected plant absorption of heavy metals. Among the double interaction effects, the interactions of tissue and heavy metal type, tissue and pH, and heavy metal type and pH were not significant on heavy metal absorption (Table 1).

Heavy metal absorption affected by heavy metal concentration

Table 2 presents the mean values and the corresponding standard deviations of plant absorption of heavy metals and the removal percentage for different tissues, at different concentrations of heavy metals and different pHs. With increase in the heavy metal concentration, plant absorption (the highest at 20 mg L^{-1}) and removal percentage increased (Fig. 2A, Table 2). The highest amount of heavy metals removal from water by *T. domingensis* was according to the following order: Zn (49.4%) > Pb (38.7%) > Ni (35.6%) > Cr (30.4%) > Cd (28.3%).

Heavy metals absorbed by different plant tissues

The results indicated that plant roots absorbed the highest, and plant flowers absorbed the least amount of heavy metals. The order of heavy metal absorption was according to the following: root > aerial part > leaves > flower (Fig. 2B, Table 2). Plant roots absorbed higher concentration of heavy metals (mg L^{-1}) compared with the aerial parts, leaves, and flowers, by the following order: Zn (21.83) > Pb (20.33) > Ni (18.77) > Cr (15.18) > Cd (13.42). The corresponding values for plant aerial part were in the following order: Zn (20.74) > Pb (19.13) > Ni (16.83) > Cd (10.57) > Cr (8.21). According to the results, the amount of heavy metal removal from water by *T. domingensis* species was higher at pH 4 than PH 7 (Fig. 2C).

Interaction effects

Regarding the interaction of plant tissue and water pH, plant roots and plant flowers at the pH of 4 absorbed the highest and the least amounts of heavy metals, respectively (Fig. 3B). The interaction of heavy metal

Table 1 Analysis of variance indicating the significant effects of the experimental treatments on the uptake of heavy metals by *Typha domingensis*

S.V	D.f	Type I SS	Mean square	F Value	Pr > F
T	3	1047.24552	349.08184	167.50	< .0001**
H	4	1770.26644	442.56661	212.36	< .0001**
Con	4	14,350.63229	3587.65807	1721.47	< .0001**
pH	1	68.95870	68.95870	33.09	< .0001**
T*H	12	12.18418	1.01535	0.49	0.9222
T*Con	12	417.35351	34.77946	16.69	< .0001**
T*pH	3	1.55748	0.51916	0.25	0.8620
H*Con	16	918.46423	57.40401	27.54	< .0001**
H*pH	4	7.53180	1.88295	0.90	0.4618
Con*pH	4	40.23571	10.05893	4.83	0.0008**
T*H*Con	48	14.41221	0.30025	0.14	1.0000
T*Con*pH	12	3.39968	0.28331	0.14	0.9998
H*Con*pH	16	15.41435	0.96340	0.46	0.9634
T*H*Con*pH	60	9.16053	0.15268	0.07	1.0000

S.V.: source of variation, d.f.: degree of freedom, T: plant tissue, H.: heavy metal, Con: heavy metal concentration

Table 2 Plant uptake of heavy metals (presented with the standard deviation (SD) values) from the aqueous solution, affected by the experimental treatments

T	HM	Con	pH	Ab	SD	*R*(%)	T	HM	Con	pH	Ab	SD	*R*(%)
A	Cd	0	4	0.04	0.01	–	F	Cd	0	4	0.03	0.00	–
A	Cd	0	7	0.04	0.02	–	F	Cd	0	7	0.03	0.01	–
A	Cd	5	4	1.50	0.28	29.91	F	Cd	5	4	1.11	0.25	22.13
A	Cd	5	7	1.39	0.38	27.78	F	Cd	5	7	0.81	0.19	16.24
A	Cd	10	4	3.65	0.89	36.53	F	Cd	10	4	2.09	0.40	20.86
A	Cd	10	7	3.26	0.73	32.62	F	Cd	10	7	1.85	0.41	18.47
A	Cd	15	4	6.30	1.26	41.97	F	Cd	15	4	3.23	0.45	21.51
A	Cd	15	7	5.18	0.86	34.55	F	Cd	15	7	3.13	0.36	20.84
A	Cd	20	4	10.57	1.58	52.83	F	Cd	20	4	6.16	0.86	30.81
A	Cd	20	7	9.67	2.01	48.37	F	Cd	20	7	5.94	0.84	29.71
A	Cr	0	4	0.12	0.04	–	F	Cr	0	4	0.12	0.04	–
A	Cr	0	7	0.12	0.03	–	F	Cr	0	7	0.09	0.03	–
A	Cr	5	4	2.28	1.01	45.52	F	Cr	5	4	1.48	0.66	29.51
A	Cr	5	7	1.82	0.73	36.39	F	Cr	5	7	1.07	0.43	21.42
A	Cr	10	4	5.04	1.73	50.42	F	Cr	10	4	3.26	1.12	32.64
A	Cr	10	7	4.53	1.71	45.31	F	Cr	10	7	2.76	1.04	27.56
A	Cr	15	4	8.21	1.52	54.72	F	Cr	15	4	4.80	0.89	31.97
A	Cr	15	7	7.14	0.98	47.57	F	Cr	15	7	4.74	0.65	31.63
A	Cr	20	4	12.86	1.69	64.29	F	Cr	20	4	8.54	1.12	42.68
A	Cr	20	7	10.99	1.16	54.96	F	Cr	20	7	7.32	0.77	36.60
A	Ni	0	4	0.15	0.01	–	F	Ni	0	4	0.12	0.01	–
A	Ni	0	7	0.19	0.01	–	F	Ni	0	7	0.14	0.01	–
A	Ni	5	4	2.98	0.62	59.64	F	Ni	5	4	1.77	0.23	35.38
A	Ni	5	7	2.47	0.63	49.38	F	Ni	5	7	1.42	0.16	28.44
A	Ni	10	4	6.35	1.81	63.52	F	Ni	10	4	3.96	0.40	39.63
A	Ni	10	7	5.56	1.17	55.63	F	Ni	10	7	3.03	0.40	30.26
A	Ni	15	4	10.21	1.04	68.10	F	Ni	15	4	6.33	0.73	42.23
A	Ni	15	7	9.02	1.86	60.15	F	Ni	15	7	5.45	0.71	36.35
A	Ni	20	4	16.83	4.58	84.17	F	Ni	20	4	12.55	1.21	62.73
A	Ni	20	7	13.56	1.79	67.82	F	Ni	20	7	9.86	1.78	49.31
A	Pb	0	4	0.25	0.02	–	F	Pb	0	4	0.17	0.03	–
A	Pb	0	7	0.28	0.03	–	F	Pb	0	7	0.19	0.08	–
A	Pb	5	4	3.62	0.48	72.49	F	Pb	5	4	2.47	0.64	49.46
A	Pb	5	7	3.27	0.37	65.34	F	Pb	5	7	2.19	0.61	43.83
A	Pb	10	4	8.09	0.82	80.91	F	Pb	10	4	5.76	1.30	57.63
A	Pb	10	7	7.30	0.97	73.01	F	Pb	10	7	5.19	1.35	51.93
A	Pb	15	4	12.86	1.48	85.76	F	Pb	15	4	9.65	2.13	64.36
A	Pb	15	7	11.54	1.51	76.92	F	Pb	15	7	8.77	1.54	58.45
A	Pb	20	4	19.13	1.84	95.63	F	Pb	20	4	14.78	2.77	73.92
A	Pb	20	7	17.48	3.15	87.38	F	Pb	20	7	13.56	2.35	67.81
A	Zn	0	4	0.31	0.05	–	F	Zn	0	4	0.21	0.01	–
A	Zn	0	7	0.28	0.12	–	F	Zn	0	7	0.19	0.02	–
A	Zn	5	4	4.06	0.64	81.18	F	Zn	5	4	2.71	0.56	54.17
A	Zn	5	7	3.90	0.94	77.90	F	Zn	5	7	2.52	0.65	50.33

Table 2 continued

T	HM	Con	pH	Ab	SD	*R*(%)	T	HM	Con	pH	Ab	SD	*R*(%)
A	Zn	10	4	9.15	1.89	91.53	F	Zn	10	4	6.56	1.87	65.61
A	Zn	10	7	8.45	1.61	84.51	F	Zn	10	7	5.94	1.25	59.42
A	Zn	15	4	14.18	1.72	94.55	F	Zn	15	4	10.85	1.10	72.35
A	Zn	15	7	12.98	1.37	86.52	F	Zn	15	7	9.87	2.04	65.82
A	Zn	20	4	20.74	2.24	103.69	F	Zn	20	4	16.15	4.40	80.76
A	Zn	20	7	19.24	3.34	96.19	F	Zn	20	7	14.50	1.92	72.48
L	Cd	0	4	0.04	0.01	–	R	Cd	0	4	0.11	0.01	–
L	Cd	0	7	0.04	0.01	–	R	Cd	0	7	0.11	0.01	–
L	Cd	5	4	1.28	0.20	25.66	R	Cd	5	4	2.95	0.61	59.06
L	Cd	5	7	1.03	0.25	20.54	R	Cd	5	7	2.79	0.72	55.86
L	Cd	10	4	3.09	0.64	30.89	R	Cd	10	4	5.98	1.70	59.84
L	Cd	10	7	2.47	0.47	24.65	R	Cd	10	7	5.73	1.20	57.34
L	Cd	15	4	5.13	0.62	34.22	R	Cd	15	4	9.27	0.94	61.78
L	Cd	15	7	4.02	0.43	26.79	R	Cd	15	7	8.80	1.82	58.65
L	Cd	20	4	8.02	0.87	40.11	R	Cd	20	4	13.42	3.65	67.12
L	Cd	20	7	7.40	1.28	37.01	R	Cd	20	7	12.94	1.71	64.70
L	Cr	0	4	0.11	0.01	–	R	Cr	0	4	0.33	0.08	–
L	Cr	0	7	0.11	0.01	–	R	Cr	0	7	0.31	0.14	–
L	Cr	5	4	1.67	0.35	33.38	R	Cr	5	4	3.23	0.62	64.65
L	Cr	5	7	1.42	0.37	28.44	R	Cr	5	7	2.98	0.83	59.69
L	Cr	10	4	4.17	1.19	41.68	R	Cr	10	4	6.68	1.62	66.77
L	Cr	10	7	3.56	0.75	35.62	R	Cr	10	7	6.34	1.43	63.39
L	Cr	15	4	6.31	0.64	42.05	R	Cr	15	4	9.93	1.99	66.23
L	Cr	15	7	5.67	1.17	37.78	R	Cr	15	7	9.69	1.60	64.63
L	Cr	20	4	11.27	3.07	56.34	R	Cr	20	4	15.18	2.27	75.91
L	Cr	20	7	8.59	1.14	42.94	R	Cr	20	7	14.01	2.91	70.04
L	Ni	0	4	0.14	0.01	–	R	Ni	0	4	0.38	0.14	–
L	Ni	0	7	0.16	0.02	–	R	Ni	0	7	0.45	0.12	–
L	Ni	5	4	2.00	0.26	39.90	R	Ni	5	4	3.74	1.66	74.76
L	Ni	5	7	1.74	0.20	34.86	R	Ni	5	7	3.59	1.45	71.82
L	Ni	10	4	4.96	0.50	49.57	R	Ni	10	4	7.65	2.63	76.51
L	Ni	10	7	3.97	0.52	39.68	R	Ni	10	7	7.16	2.70	71.62
L	Ni	15	4	7.86	0.91	52.40	R	Ni	15	4	12.94	2.40	86.24
L	Ni	15	7	6.38	0.84	42.51	R	Ni	15	7	10.45	1.44	69.70
L	Ni	20	4	14.98	1.44	74.88	R	Ni	20	4	18.77	2.46	93.85
L	Ni	20	7	11.76	2.12	58.82	R	Ni	20	7	16.98	1.79	84.88
L	Pb	0	4	0.21	0.05	–	R	Pb	0	4	0.55	0.09	–
L	Pb	0	7	0.25	0.12	–	R	Pb	0	7	0.62	0.26	–
L	Pb	5	4	2.98	0.57	59.66	R	Pb	5	4	4.47	0.70	89.32
L	Pb	5	7	2.69	0.75	53.83	R	Pb	5	7	4.12	0.99	82.30
L	Pb	10	4	6.76	1.64	67.57	R	Pb	10	4	9.92	2.05	99.17
L	Pb	10	7	5.89	1.33	58.85	R	Pb	10	7	8.43	1.60	84.35
L	Pb	15	4	10.98	2.20	73.21	R	Pb	15	4	14.30	1.73	95.35
L	Pb	15	7	9.27	1.53	61.78	R	Pb	15	7	13.05	1.38	87.01
L	Pb	20	4	15.96	2.38	79.78	R	Pb	20	4	20.33	2.20	101.66

Table 2 continued

T	HM	Con	pH	Ab	SD	*R*(%)	T	HM	Con	pH	Ab	SD	*R*(%)
L	Pb	20	7	16.06	3.34	80.31	R	Pb	20	7	19.71	3.42	98.56
L	Zn	0	4	0.27	0.10	–	R	Zn	0	4	0.63	0.04	–
L	Zn	0	7	0.23	0.06	–	R	Zn	0	7	0.56	0.06	–
L	Zn	5	4	3.36	1.49	67.16	R	Zn	5	4	4.70	0.62	94.06
L	Zn	5	7	3.02	1.22	60.41	R	Zn	5	7	4.58	0.52	91.51
L	Zn	10	4	7.60	2.61	76.01	R	Zn	10	4	10.26	1.04	102.64
L	Zn	10	7	6.85	2.59	68.52	R	Zn	10	7	9.56	1.26	95.61
L	Zn	15	4	11.52	2.13	76.77	R	Zn	15	4	15.43	1.78	102.88
L	Zn	15	7	10.57	1.45	70.49	R	Zn	15	7	14.52	1.90	96.83
L	Zn	20	4	18.78	2.46	93.90	R	Zn	20	4	21.83	2.10	109.13
L	Zn	20	7	17.15	1.81	85.76	R	Zn	20	7	20.95	3.78	104.75

T: tissue, HM: heavy metal, Con: concertation, R: removal, Ab: absorption, A: aerial part, F: flower, L: leaf, and R: root

concentration and water pH indicated the highest absorption of heavy metals at 20 mg L^{-1} and pH 4 (Fig. 3C).

Bioconcentration factor (BCF) Translocation factor (TF)

The highest root BCF values for different heavy metals were related to pH 4 and 20 mg L^{-1} concentration, and was according to the following order: Zn (2.16) > Pb (1.66) > Ni (1.46) > Cr (1.09) > Cd (0.94). For the aerial parts, the values were equal to Zn (2.05) > Pb (1.56) > Ni (1.31) > Cr (0.92) > Cd (0.74). Plant aerial part had the TF values according to the following order: Zn (0.95) > Pb (0.94) > Ni (0.90) > Cr (0.85) > Cd (0.79). The values for plant leaves were in the following order: Zn (0.86) > Pb (0.82) > Ni (0.80) > Cr (0.74) > Cd (0.60); and for plant flowers followed the order: Zn (0.74) > Pb (0.73) > Ni (0.67) > Cr (0.56) > Cd (0.46).

Discussion

According to the results, plant tissue, heavy metal type and concentration, and water pH are the important factors determining the absorption of heavy metals by *T. domingensis*. The significant interactions indicated that the combined effects of the experimental treatments can also affect the phytoremediation ability of the plant for heavy metals. The increased absorption of heavy metals and removal percentage with increase in heavy metal concentration indicated the high ability of plant for the bioremediation of aquatic areas.

Bonanno and Cirlli (2017) investigated the uptake and transport of heavy metals in three different species of *Typha* plants including *T. domingensis*, *T. latifolia*, and *T. angustifolia* grown in a natural wetland, contaminated with municipal wastewater. The bioremediation capacity of the three species was not different, and accordingly, the concentration and mobility of the heavy metals in the plant species were similar. The highest amount of Cd uptake by the whole plant was 0.84 mg kg^{-1}, with the roots, stems, and leaves absorption of 0.61, 0.15, and 0.08 mg kg^{-1}, respectively. The conclusion was that due to the high absorption of heavy metals and high biomass production, the *Typha* species are among the best aquatic macrophyte for the phytoremediation of aqueous environments, contaminated with heavy metals (Bonanno and Cirlli 2017).

According to our results, plant uptake of heavy metals increased with increase in heavy metals concentration and with decrease in water pH. The plant tissues had the highest tendency for the removal of Zn from the aqueous solution, and the least for the removal of Cd. The specific genes of hyperaccumulators, which are expressed at the time of plant exposure to heavy metals, make the plant localize heavy metals to different plant tissues without the

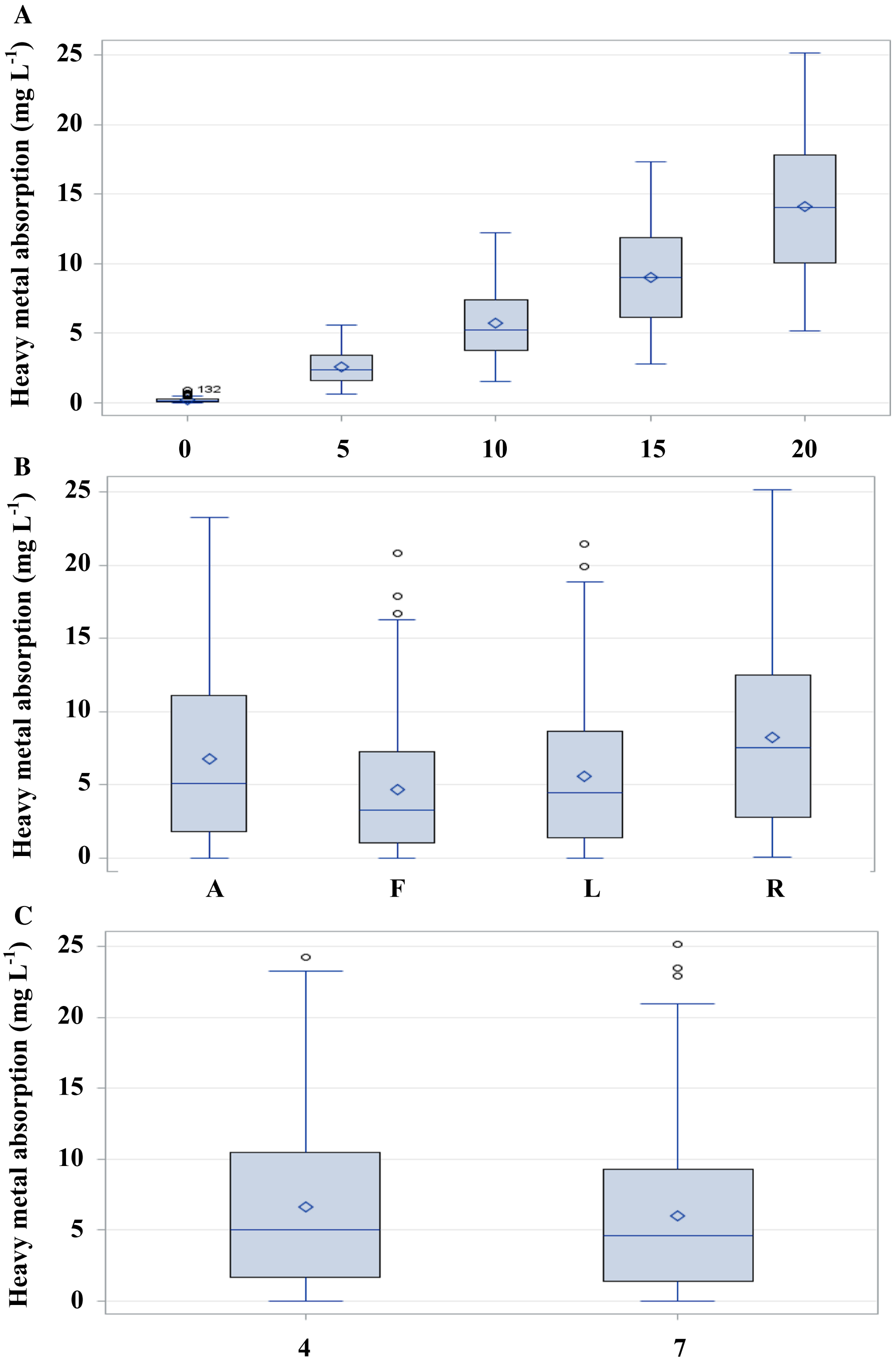

Fig. 2 Plant absorption of heavy metals affected by **A** plant tissue, **B** heavy metal concentration, and **C** solution pH, A: aerial part, F: flower, L: leaf, and R: root

appearance of toxic symptoms. Hyperaccumulators have Zn transporters with high affinity, affecting the translocation of Zn across the plasma membrane of root cell and xylem. Such mechanisms are also controlled by plant gene expression of such transporters (Miransari 2011).

Our results are similar to the results of Dube et al. (2019) who investigated the uptake of Zn, Pb, Cu, Cd, and Cr from contaminated water and sediment. In another research, Hegazy et al. (2011) investigated the phytoremediation potential of *T. domingensis* species from industrial wastewater. The complete harvested

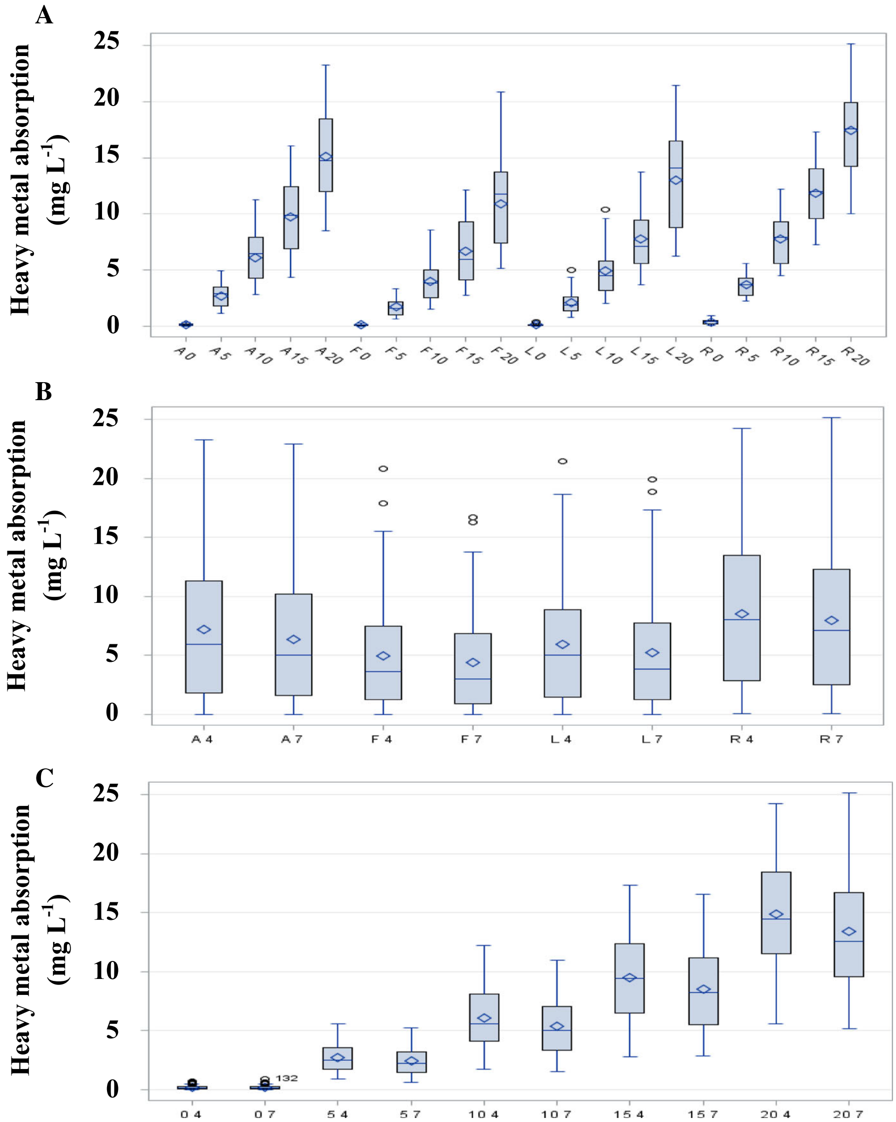

Fig. 3 Plant absorption of heavy metals affected by the interactions of **A** plant tissue and heavy metal concentration, **B** plant tissue and solution pH, and **C** solution pH and heavy metal concentration, A: aerial part, F: flower, L: leaf, and R: root

plant indicated the highest Zn removal of 36% and Zn absorption of 322.9 mg kg^{-1}. The corresponding absorption values for the roots, stem, green, and yellow parts were equal to 149.60, 131.36, 17.44, and 24.5 mg kg^{-1}, respectively. Our results also indicated that *T. domingensis* species were able to absorb and accumulate large amounts of Zn (1.26–77.50 mg L^{-1}) in their tissues, indicating that the plant is a Zn hyperaccumulator.

Plant tissue was also an important factor significantly affecting heavy metal absorption according to the following order: roots > aerial part > leaves > flowers. Accumulation of heavy metals in plant roots is a mechanism by plant to avoid the toxic effects of heavy metals in the aerial parts, so that the plant would be able to have its regular activities and growth in polluted environments (Bonanno et al. 2017). The important mechanism utilized by plant aerial part is the exclusion of heavy metals. Plant tissues may also tolerate higher levels of heavy metals by the compartmentalization and complexation using different ligands including amino and organic acids, as well as mugineic acids found in different plant tissues (Bonanno and Cirelli 2017).

The mechanisms by which plant hyperaccumulators absorb and tolerate high concentrations of heavy metals include: (1) the formation of organometallic complexes with different donor ligands including glutathione and organic and amino acids, (2) ability of translocation, (3) compartmentalization potential, (4) ability of localization and storage of heavy in different plant tissues (Miransari 2011). Research has indicated that the detoxification ability of *T. domingensis* for heavy metals is determined by the structure of root cell wall and presence of vacuoles, glutathione, and glutethimide peroxidase. The antioxidants can also importantly affect the detoxification ability of aquatic plants for the bioremediation of heavy metals (Compaore et al. 2020).

Plant tolerance to heavy metals is a function of plant physiology, growth stage, metal speciation, and water chemistry. Different parameters including pH, plant physiology, and compartmentalization potential affect the translocation of heavy metals in plant tissues (Bonanno et al. 2017). Roots are the organ, which accumulate the highest amounts of heavy metals, compared with the other plant tissues, and accordingly can be used for the long-term monitoring of heavy metals removal from contaminated aquatic areas. It is because, roots have large intercellular air spaces in their cortex parenchyma. The translocation of heavy metals from the roots to the other plant organs, especially the leaves, is also another detoxifying strategy. This strategy, in addition to the compartmentalization strategy, is used by the aquatic plants for the removal of heavy metals from the contaminated environments by the regeneration of the leaves (Maine et al. 2021; Mufarrege et al. 2021). The higher absorption of heavy metals by plant in pH 4 is probably due to the increased solubility of heavy metals in acidic pHs compared with neutral and alkaline pHs.

Although the results indicated the plant had the highest tendency for the removal of Zn and Pb from the contaminated aqueous solution, the BCF values, higher than 1 (especially for plant roots), for all the tested heavy metals are also another confirmation for the hyperaccumulating ability of the plant and subsequent phytoremediation of heavy metals. The highest BCF value for Zn indicates that the plant is the most suitable hyper accumulator for Zn and can be efficiency used for the bioremediation of aqueous environments polluted with Zn followed by Pb. Accordingly, the accumulation of Zn in the roots indicated the phytostabilization ability of the plant, rather than phytoextraction, for the bioremediation of aquatic polluted areas (Hadad et al. 2018). The bioaccumulation of heavy metals in aquatic plants is a function of plant species, the mechanisms of translocation, and the chemical properties of the element (Vymazal and Brezinová 2016). However, the TF values for different plant tissues were less than 1, indicating that most absorbed heavy metals were accumulated in plant roots, so that the plant would be able to have its regular activities and avoid the toxic effects of heavy metals.

Conclusions

According to the results, while plant absorption of heavy metals, and BCF and TF values were directly related to the concentration of heavy metals in the aqueous solution, they were inversely related to the medium pH. The results indicate that the plant is a hyperaccumulator and can absorb large amounts of heavy metals from contaminated environments. The highest absorption of the plant was related to Zn and Pb, which were mainly accumulated in the roots, as also indicated by BCF and TF values. The higher accumulation of heavy metals in plant roots (compartmentalization strategy) is a mechanism used by the plant to be able to grow in highly polluted environments and avoid the toxic effects of heavy metals. Increase in heavy metal concentrations increased plant absorption and removal percentage of heavy metals, which clearly show the hyperaccumulating ability of the plant for the phytoremediation of the environments polluted with heavy metals.

Permission for plant samples

The plant samples were collected from Shadegan International Wetland with permissions from the local authorities.

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Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

Data availability All data obtained for this research are presented in the manuscript.

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