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Heavy Metal Accumulation Potential of Some Wetland Plants Growing Naturally in the City of Kolkata, India

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Abstract

Freshwaters are not only used locally in many developing countries but they are often over exploited for domestic purposes, agriculture and disposal of industrial wastes which result in an overload of excess nutrients, harmful chemicals and heavy metals. Plant species together with sediments and water samples collected from eleven aquatic water bodies in the vicinity of industrial units in Kolkata were studied for their potential to uptake Pb, Cd and Cr under field conditions. Cd and Cr concentrations in the sediments were higher than background values considered to be toxic. *Alternanthera philoxeroides* and *Eichhornia crassipes* were the two invasive species present, with the former being more widely distributed. Among native plants, *Ipomoea aquatica* was the most abundant. Metal uptake in the plants differed among species, tissues and sites. Pb and Cd accumulation in root tissues for all plants in most sites suggested an exclusion strategy for metal tolerance. Since *I. aquatica* is widely consumed in many parts of SE Asia, its metal content should be checked before use since it was found to efficiently translocate both Pb and Cd from roots to shoots. The potential of *A. philoxeroides* as a metal excluder needs to be explored further since it translocates less to its shoots as compared to *E. crassipes* and *I. aquatica*.

Keywords

Alternanthera philoxeroides, *Eichhornia crassipes*, Invasive, *Ipomoea aquatica*, Lead (Pb), Cadmium (Cd), Chromium (Cr)

1. Introduction

Rapid urbanization and industrialization are occurring in many parts of the world.

Human activities such as mining, landfill leachates, industrial emissions, vehicular emissions, fossil fuels, fertilizer erosion from agricultural run-off, herbicides and pesticides, sewage and municipal wastes all contribute to the accumulation of pollutants in nearby aquatic systems [1] [2], which are thought to be a safe site for disposal of polluted sediments [3]. Among the worst environmental contaminants are the heavy metals which are elements with atomic number > 20, specific density > 5 gm/cm^3 and relative atomic mass above 40 [4] [5]. Pb ranks second, Cd seventh and hexavalent Cr ranks seventeen based on frequency, toxicity and potential for human exposure according to the Priority List of Hazardous Substances, U.S. Department of Health & Human Services [ATSDR, website: http://www.atsdr.cdc.gov/spl/]. Beside arsenic and mercury, these are the only three heavy metals among the top twenty in this list. These metals gradually accumulate in some plants and animals and can interfere with normal human metabolic activity when taken in through the food chain [6]. These elements, which are non-essential and phytotoxic both at low as well as very high concentrations, are commonly detected in wastewaters and can be critical because of their persistence in the environment. Their accumulation in the sediments and subsequent transfer from soil/sediments to plants is thus of great concern [7].

Freshwater ecosystems, which have greater biodiversity per surface area, are subject to more anthropogenic impacts compared to terrestrial or marine ecosystem [8] [9]. As one of the main biological components of freshwater systems, aquatic plants or macrophytes not only assimilate pollutants directly into their tissues, but can also act as catalysts for purification reactions by increasing environmental diversity in the rhizosphere, thereby promoting various chemical and biochemical reactions that enhance purification [10]. These plants are also important since they are a source of oxygen, provide food, shade and cover for fish and other aquatic organisms. However, freshwater ecosystems seem to be at particular risk from invasive plant species because of threats to biodiversity [11] and human needs for water resources [12]. In India too, many aquatic bodies including rivers, lakes, ponds and canals are now fully covered by excessive growth of invasive plants [13], which if left unchecked become extremely difficult to control. Thus, together with other plants, invasive aquatic macrophytes appear to be a good choice for metal accumulation studies since they can grow rapidly, are tolerant to harsh conditions, produce sufficient biomass and are easy to harvest [14].

The use of aquatic plants for heavy metal removal has been extensively reviewed [5] [6] [15]-[17] and widely studied both under laboratory [18]-[20] as well as field conditions [21]-[27]. Insights from all these studies point to the existence of a wide variation in the ability of different plants to accumulate heavy metals and the ability of a particular genera or species to accumulate different amounts of the same heavy metal from different sites. This variability depends upon environmental factors like metal speciation of the sediment, initial concentration of the metal present at a particular site, pH, redox potential, sediment organic matter, interaction of different heavy metals among each other and the plant growth form [28]-[30]. Moreover, the concentration of heavy metals in the root tissues of freshwater macrophytes from polluted areas has been found to be higher compared to that of their aboveground parts [15] [21] [22]. Due to this great variability in the ability of plant species to accumulate and translocate metals, the potential of regionally abundant plant species, well adapted to local climatic and edaphic conditions, should be explored in view of the plethora of contaminated urban sites around the world which pose risk to humans and other organisms. This study was, therefore, formulated to throw some light on the total concentration of selected heavy metals (Pb, Cd and Cr) in water, sediments and plants growing in contaminated sites in the metropolitan city of Kolkata in India. The uptake of the three metals was determined in the root and shoot tissues of the plants present at each site and the metal accumulation into the plant parts was calculated to assess their bioaccumulation potential.

2. Materials and Methods

2.1. Study Area and Sites

Contaminated sites along canals and ponds with direct discharge of raw industrial effluents, untreated sewage and wastewater from commercial, industrial and domestic establishments were extensively surveyed in and around the metropolitan city of Kolkata, India. Eleven accessible sites with presence of plant species were finally selected for the study. A global positioning system (GPS) was used for recording the coordinates of the sites chosen for sampling. Table 1 gives the location of the study sites with their probable source of contamination and the number of plant species present in them.

2.2. Sample Collection and Analysis

At each site, a quadrat of size 0.5×0.5 m^2 was floated on stands of vegetation present at

Table 1. Location of study sites.

Site number	Location	Latitude (N)	Longitude (E)	Waterbody type	Probable source of contamination	Number of plant species present	
						Invasive	Native
1	Chowbaga	22˚31'15.4"	88˚25'15.0"	Pond	Tannery effluents	2	2
2	Sodepur	22˚43'01.7"	88˚23'36.8"	Canal	Domestic waste	2	1
3	Dunlop	22˚38'58.3"	88˚22'36.9"	Pond	Vehicular emission and construction	1	1
4	Kamalgachi	22˚27'00.1"	88˚23'29.7"	Pond	Servicing and repairing of motor vehicles	1	2
5	Old Delhi road	22˚43'59.7"	88˚18'51.2"	Canal	Iron industry	1	3
6	Bighati	22˚48'25.7"	88˚18'53.4"	Pond	Logs products industry	1	1
7	Satragachi	22˚35'18.9"	88˚15'56.6"	Pond	Domestic waste dumping ground	2	1
8	Chingrighata	22˚33'30.8"	88˚24'35.1"	Canal	Sewage canal	2	0
9	Khalpole	22˚26'56.1"	88˚17'21.7"	Canal	Sewage canal	2	0
10	Nilganj	22˚44'53.9"	88˚25'17.8"	Canal	Brick industry	1	2
11	Anandapur	22˚30'26.8"	88˚24'16.3"	Canal	Slum waste	1	2

the junction of the littoral slope and the water body. Species with adequate growth to cover the quadrat area were sampled along with contiguous sediments. Sparsely present species were not considered for the study. Samples collected for each plant species were labeled, put in individual polythene bags and brought to the laboratory. The plant samples were separated into root and shoot portions and thoroughly washed with distilled water to remove all adhering soil and dirt particles. Fresh weight of root and shoot were recorded for all plants. Samples were then oven dried to constant weight at 70˚C for 72 hours and dry weights recorded. Each dried sample was ground to powder using a Cyclotec Mill (Model 1093 sample mill, Tecator) and stored for subsequent analysis. The labeled sediment samples were brought to the laboratory, air dried to constant weight, ground into a fine powder using a mortar and pestle and sieved through a 2 mm mesh. Water samples from each site were collected using a Van Dorn sampler and on-site measurements for pH and conductivity were done using hand held probes (pHTestr 30, Eutech Instruments; ECTestr11+, Eutech Instruments). A 250 ml bottle and three 1 litre bottles were filled separately, preserved with 2 mL concentrated HNO_3 and brought to the laboratory under ice for other water quality and heavy metal analysis.

Turbidity was measured in the laboratory using a turbidimeter (Model 2100P, HACH Company, USA) while total dissolved and suspended solids in the water samples were measured using standard methods [31]. For heavy metal analysis, water samples (1 litre) were initially evaporated to dryness while sediments (1 g) and plant parts (shoots: 1 g; roots: 0.5 g) were directly digested with nitric and perchloric acid till a clear solution was obtained and then diluted to 50 mL with double distilled water [31] [32]. Pb, Cd and Cr were analyzed by direct aspiration of the sample solution into a Perkin-Elmer Analyst-400 Atomic Absorption Spectrophotometer following the method of Nayek *et al.*, [24]. Below detection limit for Pb, Cd and Cr were 0.015 ppm, 0.008 ppm and 0.003 ppm respectively.

In order to estimate a plant's potential for phytoremediation purpose, bioaccumulation factor for shoot (BAFs) and root (BAFr) together with translocation factor (TF) were determined from the metal content in the sediments and plant parts as follows:

Bio-accumulation Factor (BAFs) = metal concentration in shoot/metal concentration in sediment.

Bio-accumulation Factor (BAFr) = metal concentration in root/metal concentration in sediment.

Translocation factor (TF) = metal concentration in shoot/metal concentration in root.

Bio-accumulation Factor (BAF) is used to quantify the toxic element accumulation efficiency in plants by comparing the concentration in the plant part and an external medium [33]. BAF has been categorised as: <1 excluder, 1 - 10 accumulator and >10 hyperaccumulator [34]. A plant's ability to translocate metals from the roots to the shoots is measured using the TF [33] and TF > 1 signifies that the plant effectively translocates heavy metals from roots to the shoots [35].

3. Results and Discussion

3.1. Plant Species and Dry Weights

The plants which satisfied the "adequate growth" criterion, within each quadrat, at their sites of occurrence were *Alternanthera philoxeroides*, *Commelina benghalensis*, *Eichhornia crassipes*, *Enhydra fluctuans*, *Ipomoea aquatica*, *Ludwigia adscendens*, *Sagittaria sagittifolia* and the sedges. Among these, *A. philoxeroides* (alligator weed) and *E. crassipes* (water hyacinth) were the only two invasive species while the rest were native plants. While *A. philoxeroides* was present in all sites, *E. crassipes* occurred in 5 sites. *Ipomoea aquatica* (water spinach), the most commonly occurring native species, was present in 6 sites. It is interesting to note the complete absence of native species from Sites 8 and 9 (both sewage canal sites, **Table 1**) while invasive species (at least one or both) were present in all sites, irrespective of water body type. The widespread occurrence of both *A. philoxeroides* and *E. crassipes* in the warm waters of the tropics has been widely reported together with their negative impacts on biodiversity [36]-[38].

The overall shoot dry matter content in the plants studied ranged from 7.07% - 12.28% in *A. philoxeroides* (n = 11), 4.98% - 6.85% in *E. crassipes* (n = 5), 7.40% - 8.25% in *I. aquatica* (n = 6), 14.20% - 16.41% in the sedges (n = 3), 8.30% - 8.52% in *C. benghalensis* (n = 2), 5.55% - 6.12% in *S. sagittifolia* (n = 2), 4.42% in *E. flutuans* (n = 1) and 12.91% in *L. adscendens* (n = 1). In case of roots, dry matter values ranged from 6.33% - 11.22% in *A. philoxeroides*, 5.40% - 6.64% in *E. crassipes*, 7.25% - 9.80% in *I. aquatica*, 14.04% - 14.75% in the sedges, 8.00% - 8.33% in *C. benghalensis*, 7.25% - 8.37% in *S. sagittifolia*, 4.67% in *E. flutuans* and 6.67% in *L. adscendens*. *E. fluctuans* had lowest dry matter content for both shoot and root while the sedges showed highest dry matter content for both shoot (16.41% in site 11) and root (14.75% in site 5) among all the plants. Among sites, minimum variation in dry matter content of both shoot and root was observed in *C. benghalensis* while maximum variation was observed in *A. philoxeroides.*

3.2. Water Quality

The results of water quality analysis pertaining to the 11 sites are given in **Table 2**. The pH, which greatly affects mobility and bioavailability of metals [39], was >8 at Sites 6, 8 and 10 but were generally within the prescribed limits (5.5 to 9.0) as described by the Central Pollution Control Board, India for discharge of environmental pollutants into inland surface waters (CPCB, http://www.cpcb.nic.in/GeneralStandards.pdf). Conductivity values, a measure of the dissolved salts present in water, were quite high (>1000 μS) in most of the sites possibly due to elevated levels of total dissolved solids (r = 0.904, p value < 0.01), which is known to influence conductivity [40] [41]. Turbidity varied widely between sites ranging from low values (<20 NTU) in Sites 3 and 11 to a much higher value (>400 NTU) in Site 7. The most turbid waterbody (Site 7) had suspended solid values >300 mg·L^{-1} which could be responsible for its decreased water transparency. A positive correlation (r = 0.809, p value < 0.01) between turbidity and suspended solids accounts for the linear relationship [42].

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Table 2. Analysis of wastewater.

Site number	Mean ± standard error				
	pH	Electrical conductivity (μs/cm)	Turbidity (NTU)	Total dissolved solid ($mg \cdot L^{-1}$)	Suspended solid ($mg \cdot L^{-1}$)
1	7.23 ± 0.17	972.10 ± 10.43	33.33 ± 2.34	371.00 ± 34.25	20.77 ± 3.78
2	7.70 ± 0.06	1317.67 ± 34.14	70.27 ± 32.87	610.87 ± 92.69	98.86 ± 55.22
3	7.53 ± 0.14	910.33 ± 28.37	11.16 ± 3.14	384.47 ± 54.86	11.44 ± 6.39
4	7.73 ± 0.09	1719.67 ± 21.46	190.00 ± 29.67	876.97 ± 47.05	27.54 ± 2.68
5	7.82 ± 0.06	1343.67 ± 13.32	94.03 ± 44.75	724.31 ± 84.37	158.31 ± 69.93
6	8.30 ± 0.25	1036.67 ± 49.78	60.70 ± 29.08	656.99 ± 34.39	83.88 ± 66.84
7	7.86 ± 0.10	1968.67 ± 216.35	435.00 ± 143.15	999.76 ± 147.03	325.90 ± 59.52
8	8.42 ± 0.14	719.67 ± 22.84	37.93 ± 4.71	98.69 ± 0.32	63.49 ± 6.72
9	7.37 ± 0.09	1200.00 ± 5.77	47.67 ± 7.36	590.00 ± 0.00	29.78 ± 2.24
10	8.09 ± 0.16	832.67 ± 78.86	307.67 ± 129.62	343.37 ± 43.37	151.12 ± 54.14
11	7.33 ± 0.24	1620.00 ± 40.00	15.43 ± 0.32	810.00 ± 20.00	24.07 ± 3.66

3.3. Heavy Metals in Water

The Pb, Cd and Cr content in the water collected from all 11 sites have been reported in Table 3.

The low concentrations of all the three metals were probably because the sites were not located at the pollution source and were subject to dilution effects. However, Pb (0.022 $mg \cdot L^{-1}$) and Cd (0.032 $mg \cdot L^{-1}$) concentration in water was similar to those reported for an East Kolkata wetland site [43], while the Cr concentration (3.6 $mg \cdot L^{-1}$) was low compared to that of a sewage fed fish pond in East Kolkata wetland [44]. All values were within the prescribed limits for metals (Pb: 0.1 ppm, Cd and Cr: 2.0 ppm) as recommended by FAO water quality criteria for irrigational water and the Central Pollution Control Board, India for the discharge of environmental pollutants into inland surface waters [CPCB, http://www.cpcb.nic.in/GeneralStandards.pdf]. However, values for Cd were higher than the USEPA recommended values for aquatic life criteria.

Due to variation in water levels and a low resting time, analysis of water for estimation of heavy metals may not be conclusive [3]. The sediments derived from the settling of particulates from water itself could be more useful and confirmatory as residence time for contaminants are very high in the sediment [45]. Moreover, all the plants were collected from littoral areas and were mostly rooted to the bottom which could greatly influence metal uptake from the sediments rather than from the water. Sediments are dynamic bodies in equilibrium with environmental forces acting on them and chemical reactions induced by the roots of plants, in the sediments that they grow in, is also known to influence the sediment's capacity to uptake metals [46].

Table 3. Heavy metal concentration in wastewater.

Site number	Mean ± standard error (mg·L^{-1})			
	Lead	Cadmium	Chromium	
1	0.012 ± 0.000	0.002 ± 0.000	0.029 ± 0.008	
2	0.015 ± 0.002	0.002 ± 0.000	0.022 ± 0.005	
3	0.018 ± 0.003	0.002 ± 0.000	0.019 ± 0.004	
4	0.021 ± 0.001	0.003 ± 0.000	0.036 ± 0.004	
5	0.016 ± 0.001	0.003 ± 0.000	0.028 ± 0.004	
6	0.016 ± 0.001	0.003 ± 0.000	0.034 ± 0.001	
7	0.020 ± 0.003	0.004 ± 0.000	0.048 ± 0.004	
8	0.013 ± 0.003	0.003 ± 0.000	0.018 ± 0.003	
9	0.014 ± 0.001	0.002 ± 0.000	0.010 ± 0.001	
10	0.013 ± 0.002	0.002 ± 0.000	0.024 ± 0.007	
11	0.021 ± 0.001	0.003 ± 0.000	0.024 ± 0.006	
Safe limit (mg·L^{-1})				
CPCB*	0.1	2.0	2.0	
FAO**	5.0	0.01	0.1	
US EPA***	0.065	0.0018	Cr(III) 0.570	Cr(VI) 0.016

*Values provided by Central Pollution Control Board, India for discharge of environmental pollutants into the inland surface water. (Website: http://www.scpcb.nic.in/GeneralStandards.Pdf) **FAO water quality criteria for irrigational water (website: http://www.fao.org/docrep/t0551e/t0551e04.htm#2.4 water quality guidelines for maximum crop production). ***EPA National recommended aquatic life criteria table (website: https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table).

3.4. Heavy Metals in Sediments

The heavy metal content of the sediments collected from the different sites are shown in **Figures 1(a)-(c)**. The sediments were not polluted in terms of Pb (**Figure 1(a)**) since concentrations were below the background values of 70 mg·kg^{-1} [47] [48]. Similar Pb concentrations have been reported from the sediments (50.5 mg·kg^{-1}) of an East Kolkata wetland [43]. Soil Pb levels in heavily polluted industrial areas of India ranged from 2 to 293 mg·kg^{-1} [49] [50].

Cd concentration in the sediments for all sites (**Figure 1(b)**) were quite high compared to the background value of 1.0 ppm [47] [48]. The highest Cd concentration was observed in the sediment from Site 1, which could be attributed to a tannery in the neighbourhood. The Cd concentration in the sediments from other sites were similar to values of Cd (10.1 mg·kg^{-1}) reported for a Ramsar site [43]. Cr concentration (**Figure 1(c)**) was also particularly high in Site 1 and Site 6. Tannery industry, where Cr salts are

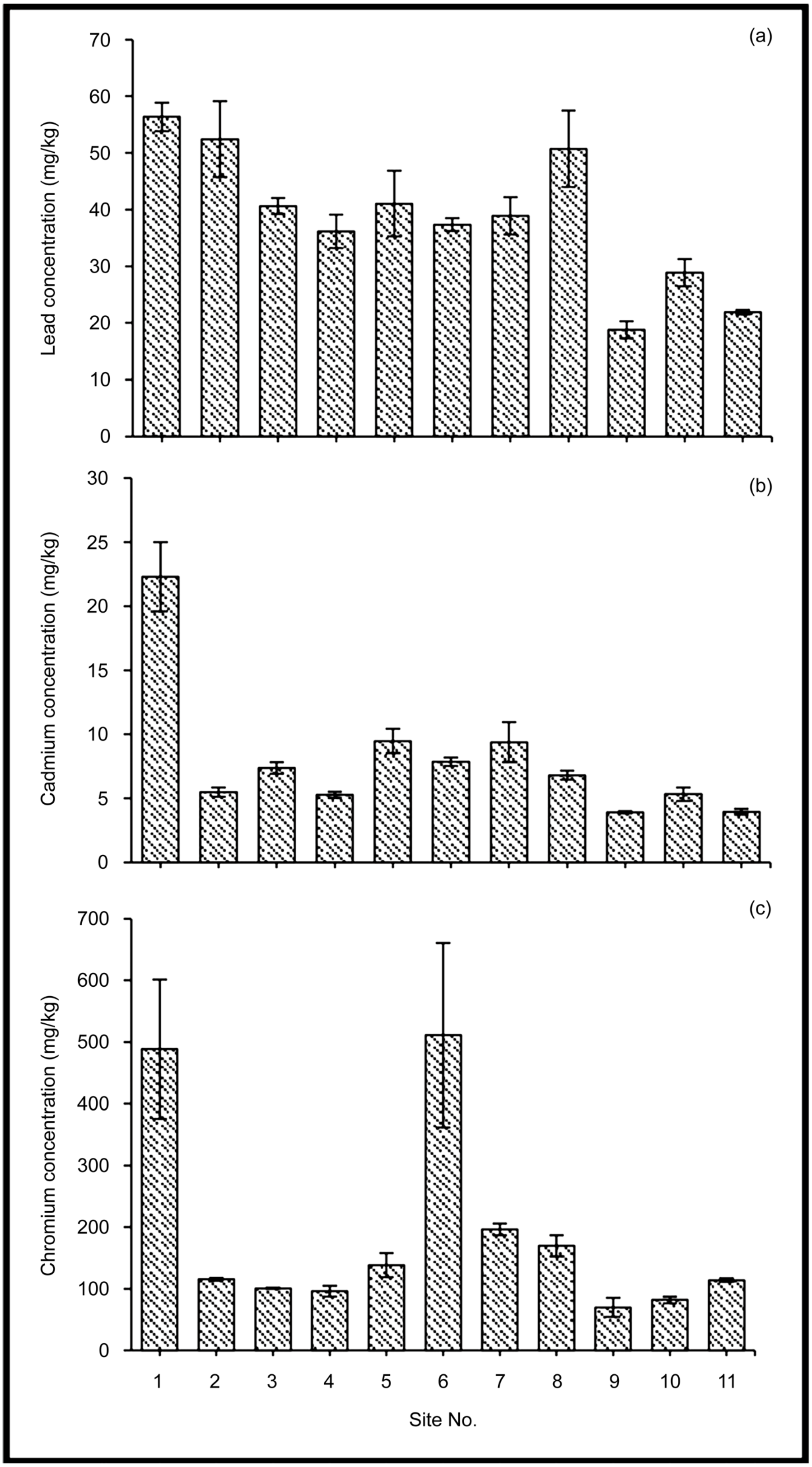

Figure 1. Concentrations of Lead (a), Cadmium (b) and Chromium (c) in the sediments across 11 sites.

used for tanning leather products [51], is a large contributor of Cr pollution in India [52]. Chromated copper arsenate used as a wood preservative [53], could be probable reasons for the high Cr deposition in Site 6. Cr concentration was higher than the background value of 90 $mg \cdot kg^{-1}$ [47] [48] for all sites except Sites 9 and 10.

3.5. Heavy Metals in Plant Parts

The overall Pb, Cd and Cr contents in the above and below ground portions of the plants studied have been provided in **Table 4**. It is clearly evident from the median values of each metal that the shoots and roots of individual plants accumulated metals in the order Pb > Cr > Cd. All plants had greater than phytotoxic concentrations of both Pb (5.0 $mg \cdot kg^{-1}$) and Cd (0.5 $mg \cdot kg^{-1}$) in their shoots [24] [54]. All the plants harvested during this study were healthy and did not show any toxicity symptoms although excess Pb in plants is reported to inhibit growth while Cd can inhibit photosynthesis and mineral assimilation with leaf chlorosis, necrosis, and abscission [55] [56]. Minimum values of Cr for shoots of most plants were "below detection limit" while maximum uptake of Cr values in shoots were detected in both the invasive species (*E. crassipes*: 18.45 $mg \cdot kg^{-1}$ and *A. philoxeroides*: 15.32 $mg \cdot kg^{-1}$).

Maximum Pb concentrations (>80 $mg \cdot kg^{-1}$) could be detected in roots of both invasive (*A. philoxeroides* and *E. crassipes*) and native plants (*C. benghalensis* and sedges). The highest median Pb concentration was evident in the roots of *C. benghalensis* (76.4 $mg \cdot kg^{-1}$) while the lowest was present in *I. aquatica* (42.18 $mg \cdot kg^{-1}$). The median Cd concentration in roots varied from 7.89 $mg \cdot kg^{-1}$ in *I. aquatica* to 25.30 $mg \cdot kg^{-1}$ in *C. benghalensis*. Accumulation of high concentrations of Pb and Cd in plant tissues of *C. benghalensis* above normal concentrations of 5 $mg \cdot kg^{-1}$ Pb and 10 $mg \cdot kg^{-1}$ Cd was observed by Zu *et al.*, [57]. The roots of *E. fluctuans* exhibited low median Cr values (2.84 $mg \cdot kg^{-1}$) while the highest median value was evident in sedges (57.63 $mg \cdot kg^{-1}$). Cr concentrations in roots of plants, where it could be detected, far exceeded the phytotoxic concentration of 1.5 $mg \cdot kg^{-1}$ [24]. The general trend also indicates that the roots accumulated greater elemental concentrations compared to the shoots which seem to indicate that these are absorbed from the sediments rather than from the water. Elemental species can have different bioavailability to macrophytes because of physiological differences with respect to uptake sites and uptake mechanisms [58]. Sediment geochemistry control metal speciation in sediments while plant physiology and genotypic differences control the ability of plants to accumulate plant-available forms of metals [16].

In order to get an idea about the site specific metal uptake ability of individual plant species, the site-wise details for metal concentrations in sediments, shoots and roots of all the plants for Pb (**Table 5**), Cd (**Table 6**) and Cr (**Table 7**) have also been presented. The transfer factors and bioaccumulation factors for both shoots and roots have also been provided to understand their accumulation potential. It can be seen from the tables that the extent of accumulation of heavy metals by individual plants differed not only with the type of metal but also with the site of study.

Table 4. Range and median values of Lead, Cadmium and Chromium in shoot and root of different plants pooled over sites.

Metal	Plant	No. of sites present	Metals in shoot (mg·kg^{-1})			Metals in root (mg·kg^{-1})		
			Min	Max	Median	Min	Max	Median
Lead	*Alternanthera philoxeroides*	11	16.06	27.13	17.08	46.64	91.79	70.98
	Ipomoea aquatica	6	14.29	34.49	16.97	28.64	57.50	42.18
	Eichhornia crassipes	5	18.69	26.97	24.97	34.88	80.95	61.66
	Sedges	3	15.51	33.70	16.80	45.27	92.79	63.77
	Commelina benghalensis	2	17.74	33.85	25.79	60.16	92.70	76.43
	Sagittaria sagittifolia	2	17.12	32.53	24.83	67.25	72.71	69.98
	Enhydra fluctuans	1	NA	NA	25.49	NA	NA	59.25
	Ludwigia adscendens	1	NA	NA	15.79	NA	NA	74.52
Cadmium	*Alternanthera philoxeroides*	11	2.57	5.64	3.79	8.48	45.03	15.72
	Ipomoea aquatica	6	2.65	8.00	2.80	3.88	14.30	7.89
	Eichhornia crassipes	5	3.52	5.79	5.06	8.32	30.88	14.05
	Sedges	3	2.49	8.05	2.63	9.01	26.77	14.49
	Commelina benghalensis	2	3.01	7.44	5.23	12.94	37.67	25.30
	Sagittaria sagittifolia	2	3.06	5.69	4.38	16.58	27.24	21.91
	Enhydra fluctuans	1	NA	NA	5.51	NA	NA	13.60
	Ludwigia adscendens	1	NA	NA	3.08	NA	NA	16.84
Chromium	*Alternanthera philoxeroides*	11	<0.15[a]	15.32	10.47	<0.30[a]	81.28	41.51
	Ipomoea aquatica	6	<0.15[a]	4.48	2.57	<0.30[a]	43.26	19.07
	Eichhornia crassipes	5	<0.15[a]	18.45	16.46	6.21	133.75	20.65
	Sedges	3	<0.15[a]	10.74	10.74	38.34	73.39	57.63
	Commelina benghalensis	2	<0.15[a]	11.62	11.62	<0.30[a]	20.10	20.10
	Sagittaria sagittifolia	2	9.49	15.17	12.33	10.49	18.23	14.36
	Enhydra fluctuans	1	NA	NA	1.74	NA	NA	2.84
	Ludwigia adscendens	1	NA	NA	4.27	NA	NA	28.59

[a]Values below detection limit. NA: not applicable.

Table 5. Lead concentration in plants across 11 sites.

Site No.	Plant species	Lead concentration (mg·kg^{-1})			Translocation factor (TF)	Bioaccumulation factor	
		Sediment	Shoot	Root		Shoot (BAFs)	Root (BAFr)
1	*A. philoxeroides*	56.36	16.06	51.09	0.31	0.29	0.91
	E. crassipes		18.69	34.88	0.54	0.33	0.62
	I. aquatica		16.76	41.32	0.41	0.30	0.73
	Sedges		16.80	45.27	0.37	0.30	0.80
2	*A. philoxeroides*	52.44	16.31	57.59	0.28	0.31	**1.10**
	E. crassipes		24.97	61.66	0.41	0.48	**1.18**
	I. aquatica		17.17	57.50	0.30	0.33	**1.10**
3	*A. philoxeroides*	40.64	25.75	84.45	0.31	0.63	**2.08**
	I. aquatica		32.08	28.64	**1.12**	0.79	0.71
4	*A. philoxeroides*	36.15	27.13	91.79	0.30	0.75	**2.54**
	I. aquatica		15.93	35.98	0.44	0.44	**1.00**
	C. benghalensis		17.74	60.16	0.30	0.49	**1.66**
5	*A. philoxeroides*	41.06	18.17	85.00	0.21	0.44	**2.07**
	I. aquatica		34.49	43.05	0.80	0.84	**1.05**
	Sedges		33.70	92.79	0.36	0.82	**2.26**
	C. benghalensis		33.85	92.70	0.37	0.82	**2.26**
6	*A. philoxeroides*	37.35	16.19	46.64	0.35	0.43	**1.25**
	I. aquatica		14.29	50.47	0.28	0.38	**1.35**
7	*A. philoxeroides*	38.89	17.08	62.48	0.27	0.44	**1.61**
	E. crassipes		26.97	60.78	0.44	0.69	**1.56**
	S. sagittifolia		32.53	67.25	0.48	0.84	**1.73**
8	*A. philoxeroides*	50.71	17.57	71.56	0.25	0.35	**1.41**
	E. crassipes		19.94	69.34	0.29	0.39	**1.37**
9	*A. philoxeroides*	18.80	20.34	70.98	0.29	**1.08**	**3.78**
	E. crassipes		26.84	80.95	0.33	**1.43**	**4.31**
10	*A. philoxeroides*	28.85	16.74	59.91	0.28	0.58	**2.08**
	S. sagittifolia		17.12	72.71	0.24	0.59	**2.52**
	E. fluctuans		25.49	59.25	0.43	0.88	**2.05**
11	*A. philoxeroides*	21.88	14.45	75.38	0.19	0.66	**3.45**
	Sedges		15.51	63.77	0.24	0.71	**2.92**
	L. adscendens		15.79	74.52	0.21	0.72	**3.41**

Bold values indicate values > 1 for (TF) and (BAF).

Table 6. Cadmium concentration in plants across 11 sites.

Site No.	Plant species	Cadmium concentration ($mg \cdot kg^{-1}$)			Translocation factor (TF)	Biaccumulation factor	
		Sediment	Shoot	Root		Shoot (BAFs)	Root (BAFr)
1	*A. philoxeroides*	22.30	2.57	8.48	0.30	0.12	0.38
	E. crassipes		3.52	8.32	0.42	0.16	0.37
	I. aquatica		2.87	5.46	0.53	0.13	0.25
	Sedges		2.63	9.01	0.29	0.12	0.40
2	*A. philoxeroides*	5.49	2.93	12.72	0.23	0.53	**2.32**
	E. crassipes		5.06	9.61	0.53	0.92	**1.75**
	I. aquatica		2.74	13.45	0.20	0.50	**2.45**
3	*A. philoxeroides*	7.38	5.01	18.94	0.26	0.68	**2.57**
	I. aquatica		7.37	5.99	**1.23**	**1.00**	0.81
4	*A. philoxeroides*	5.28	5.64	12.03	0.47	**1.07**	**2.28**
	I. aquatica		2.65	3.88	0.68	0.50	0.74
	C. benghalensis		3.01	12.94	0.23	0.57	**2.45**
5	*A. philoxeroides*	9.48	3.79	32.72	0.12	0.40	**3.45**
	I. aquatica		8.00	14.30	0.56	0.84	**1.51**
	Sedges		8.05	26.77	0.30	0.85	**2.82**
	C. benghalensis		7.44	37.67	0.20	0.79	**3.97**
6	*A. philoxeroides*	7.84	2.74	10.01	0.27	0.35	**1.28**
	I. aquatica		2.70	9.78	0.28	0.34	**1.25**
7	*A. philoxeroides*	9.39	3.86	15.72	0.25	0.41	**1.67**
	E. crassipes		5.36	14.05	0.38	0.57	**1.50**
	S. sagittifolia		5.69	27.24	0.21	0.61	**2.90**
8	*A. philoxeroides*	6.81	4.56	32.47	0.14	0.67	**4.77**
	E. crassipes		5.05	30.88	0.16	0.74	**4.54**
9	*A. philoxeroides*	3.92	4.31	45.03	0.10	**1.10**	**11.50**
	E. crassipes		5.79	18.20	0.32	**1.48**	**4.65**
10	*A. philoxeroides*	5.33	3.48	13.77	0.25	0.65	**2.58**
	S. sagittifolia		3.06	16.58	0.19	0.57	**3.11**
	E. fluctuans		5.51	13.60	0.41	**1.03**	**2.55**
11	*A. philoxeroides*	3.96	3.32	16.55	0.20	0.84	**4.19**
	Sedges		2.49	14.49	0.17	0.63	**3.66**
	L. adscendens		3.08	16.84	0.18	0.78	**4.26**

Bold values indicate values > 1 for (TF) and (BAF).

Table 7. Chromium concentration in plants across 11 sites.

Site No.	Plant species	Chromium concentration ($mg \cdot kg^{-1}$)			Translocation factor (TF)	Biaccumulation factor	
		Sediment	Shoot	Root		Shoot (BAFs)	Root (BAFr)
1	*A. philoxeroides*	488.76	<0.15[a]	81.28	-	-	0.17
	E. crassipes		7.58	20.65	0.37	0.02	0.04
	I. aquatica		<0.15[a]	19.07	-	-	0.04
	Sedges		10.74	73.39	0.15	0.02	0.15
2	*A. philoxeroides*	115.52	<0.15[a]	9.07	-	-	0.08
	E. crassipes		18.45	6.21	**2.97**	0.16	0.05
	I. aquatica		4.48	<0.30[a]	-	0.04	-
3	*A. philoxeroides*	100.85	5.97	<0.30[a]	-	0.06	-
	I. aquatica		0.65	<0.30[a]	-	0.01	-
4	*A. philoxeroides*	96.17	<0.15[a]	<0.30[a]	-	-	-
	I. aquatica		<0.15[a]	<0.30[a]	-	-	-
	C. benghalensis		<0.15[a]	<0.30[a]	-	-	-
5	*A. philoxeroides*	138.66	14.97	35.62	0.42	0.11	0.26
	I. aquatica		<0.15[a]	14.55	-	-	0.11
	Sedges		<0.15[a]	57.63	-	-	0.42
	C. benghalensis		11.62	20.10	0.58	0.08	0.15
6	*A. philoxeroides*	511.17	<0.15[a]	44.12	-	-	0.09
	I. aquatica		<0.15[a]	43.26	-	-	0.09
7	*A. philoxeroides*	196.39	15.32	38.17	0.40	0.08	0.19
	E. crassipes		<0.15[a]	14.05	-	-	0.07
	S. sagittifolia		15.17	18.23	0.83	0.08	0.09
8	*A. philoxeroides*	169.66	<0.15[a]	72.58	-	-	0.43
	E. crassipes		17.89	133.75	0.13	0.11	0.79
9	*A. philoxeroides*	69.86	2.14	38.89	0.06	0.03	0.56
	E. crassipes		15.02	49.92	0.30	0.22	0.72
10	*A. philoxeroides*	82.00	<0.15[a]	<0.30[a]	-	-	-
	S. sagittifolia		9.49	10.49	0.91	0.12	0.13
	E. fluctuans		1.74	2.84	0.61	0.02	0.04
11	*A. philoxeroides*	113.82	<0.15[a]	49.07	-	-	0.43
	Sedges		<0.15[a]	38.34	-	-	0.34
	L. adscendens		4.27	28.59	0.15	0.04	0.25

[a]Values below detection limit. Bold values indicate values > 1 for (TF).

The shoot DM values were higher for most plants growing naturally (excepting *E. crassipes* and *E. flutuans*) when compared to an earlier study which was conducted in less contaminated sites [59]. The dry matter trends observed in this study could simply be indicative of plant maturation since tissue fiber content is positively related to dry matter content [60]. Although a decrease in dry matter content of both shoot and root has been observed in many higher plants as a result of heavy metal toxicity [61], no such relationship between dry matter % of root or shoot of plants and uptake of Pb, Cd or Cr was observed in this study.

3.5.1. Lead (Pb)

Pb exhibits long residence time, is sparingly soluble as a result of rapid conversion to $PbSO_4$ at the soil surface and forms relatively stable organo-metal complexes or chelates with organic matter in soil making it the least phytoavailable amongst all toxic heavy metals. Only 1% of the total Pb in soil is water soluble and exchangeable for uptake by plants [62] and its extraction is limited by solubility and diffusion through root surface [63].

Shoot concentration of Pb for all plants (**Table 5**) were above the normal levels (5 - 10 $mg \cdot kg^{-1}$) suggested for plants, though most of them were below the toxic (30 to 300 $mg \cdot kg^{-1}$) or critical limits [64]. Pb concentrations in shoots of the invasive species, *A. philoxeroides* and *E. crassipes*, did not exceed the critical levels at any site although their roots exhibited >80 $mg \cdot kg^{-1}$ Pb concentrations at some of the sites. Much higher concentrations of Pb (>100 $mg \cdot kg^{-1}$) in shoots of *A. philoxeroides* have been reported from field studies [65] [66]. Higher root Pb concentrations in *E. crassipes* (145 to 1110 $\mu g \cdot g^{-1}$) have also been recorded in a wetland receiving urban run-off [67]. Bioaccumuation of Pb in shoots (BAFs > 1) was evident only in Site 9, where only *A. philoxeroides* and *E. crassipes* were present. None of the other plants including the two invasive plants could accumulate Pb in its shoots.

In some of the sites, native species like *I. aquatica*, *C. benghalensis*, *S. sagittifolia* and the sedges exhibited high shoot Pb concentrations which were above critical values (>30 $mg \cdot kg^{-1}$). Of the four plants present in Site 5, which was near an iron industry, three native species had greater than critical shoot Pb concentrations. Steel and iron manufacturing industries are a potential source of Pb [68] and the soil, sediments, surface and runoff water of an industrial area were also found to be contaminated with Pb metal pollution [69]. Root Pb content was also the highest (>90 $mg \cdot kg^{-1}$) in *C. benghalensis* and the sedges. The only invasive plant at this site, *A. philoxeroides*, had 85 $mg \cdot kg^{-1}$ of Pb in its roots with very low shoot Pb content was very low (18.17 $mg \cdot kg^{-1}$). The exclusion of metals from aboveground tissues of this plant indicates the low mobilization of heavy metals from roots to the shoots, which has been suggested to be a metal tolerant strategy [70].

Except for all plants in Site 1 and *I. aquatica* in Site 3, all plants indicated high accumulation potential of Pb in roots (BAFr > 1), while in plants present in Sites 9 to 11 (with lowest sediment Pb contents) the bioaccumulation factors in roots were close to ≥3. From the translocation factors in **Table 5**, *I. aquatica* was the only native plant with

TF > 1 implying efficient translocation of Pb from root to shoot, which is one of the criterion for "hyperaccumulators".

3.5.2. Cadmium (Cd)

Cd enters aquatic systems as effluents mainly through electroplating, pigments, plastic stabilizers and batteries [71] and much of it accumulates in sediments where it presents a risk to benthic biota. The Cd ion is the most bioavailable to aquatic biota and factors affecting availability include salinity, dissolved organic matter and pH which affect the chemical forms of Cd [72]. Cd bioavailability is also dependent on physiological attributes of roots, plant age and genetics of plant species [73].

The sedges exhibited minimum and maximum shoot Cd levels of 2.49 mg·kg^{-1} in Site 11 and 8.05 mg·kg^{-1} in Site 5 respectively (**Table 6**). Although normal Cd levels are generally low in most plant species, shoot concentrations of Cd for all plants were above the normal levels (0.05 - 0.2 mg·kg^{-1}). Cd levels in shoots of most species in Sites 3 and 5 were above the critical or toxic (5 to 30 mg·kg^{-1}) limits suggested for plants [64]. While Site 3 was a construction site near a major road, Site 5 was also located on a major highway where vehicular emissions from fuel consumption, engine oil consumption, tire wear, brake wear, and road abrasion are the most likely sources of Cd and Pb [74] [75]. The only plant that could uptake critical concentration of Cd (>5 mg·kg^{-1}) in its shoots from different sites was *E. crassipes.* Although it could not bioaccumulate significant amounts in its shoots at any site, the potential of *E. crassipes* for phytoremediation of Cd has been reported [76] [77]. The sites where at least one plant showed high bioaccumulation in shoots (BAFs > 1) were Site 3 (*I. aquatica*), Site 4 (*A. philoxeroides*) and Site 10 (*E. fluctuans*). Moreover, *I. aquatica* exhibited transfer factors >1 for both Pb and Cd at Site 3.

Of concern is the transfer factor of 1.23 in *I. aquatica* and high bioaccumulation of Cd in shoots of both *I. aquatica* and *E. fluctuans*. The leaves and stems of *I. aquatica* (water spinach) and the young shoots of *E. fluctuans* (water cress or marsh herb) are commonly used as green leafy vegetables in Southeast Asia, India and China [78]-[80]. Both plants have a high food value and is a good source of β-carotenes and minerals [81] [82]. The value of Cd in the shoots of *Enhydra fluctuans* (5.51 mg·kg^{-1}) in Site 10, the only site where it was present, were above toxic limits which is a source of concern since the plant has reported medicinal values also [83]. The presence of Cd in shoots of edible plants could be a problem, since a significantly high half-life, faster absorption and low rate of excretion promotes the bioaccumulation of Cd above toxic level in humans within a short span of time [84].

Most of the plants in the study sites also showed a high bioaccumulation for Cd in their roots (BAFr > 1), except in Site 1 where none of the plants present could accumulate the element. Site 1 also had the with the highest sediment concentration among sites. In Site 9, *A. philoxeroides* exhibited exceedingly high accumulation of Cd in its roots (BAFr 11.5) compared to *E. crassipes* (BAFr 4.65) while its accumulation in shoots (BAFs 1.10) was less than that of *E. crassipes* (BAFs = 1.48), thereby showing its potential to limit transfer of Cd to its above ground tissues. Moreover, it appears that the two invasive plants present in Site 9 bioaccumulated large amounts of Pb and Cd in their shoots (BAF > 1) as well as in roots (BAF ≥ 4). The production of organic acids by fungi and bacteria present in sewage, which was a constituent of Site 9, promotes solubilization, mobility and bioavailability of metals in sediments by lowering pH through the process of nitrification and microbial carbon dioxide production [85]-[87]. Considering the fact that this site had low Pb and Cd sediment concentrations, the complete absence of native plants in Site 9 could possibly be due to the effect of root exudates secreted from these plants and their toxic effects. An alternative hypothesis proposes that elemental hyperaccumulation in soil may serve an allelopathic function [88] [89]. Some tests have demonstrated defense by hyperaccumulated As, Cd, Ni, Se and Zn, but relatively few plant taxa and natural enemies have been investigated [90].

3.5.3. Chromium (Cr)

Cr occurs in several oxidation states with trivalent and hexavalent states being the most stable. Hexavalent Cr (Cr^{6+}) is the principal species in surface waters and aerobic soils and has a long residence time and is very mobile [91]. Effluents discharged from electroplating, leather tanning, and textile industries release large amounts of Cr to surface waters [92] [93] which ultimately gets deposited in the sediment.

Despite higher than background levels of Cr in sediments at most sites, it is evident from **Table 7** that it was largely unavailable to some plants in most sites (being below detection limits) probably since (Cr^{3+}) binds to negatively charged particles especially clay and organic matter [94]. Shoot Cr concentrations were below detection limit for *I. aquatica* in 4 out of 6 sites and for the invasive *A. philoxeroides* in 7 out of 11 sites. Substantial accumulation of Cr in *I. aquatica* from polluted waters has been previously reported [95] [96], however this was not evident from our study. The highest uptake by *I. aquatica* shoots (4.48 mg·kg^{-1}) in Site 2 was below toxic concentration for plants.

For most other plants, shoot concentration of Cr was above the normal levels (0.1 to 0.5 mg·kg^{-1}) suggested for plants [64]. Some even had Cr values above toxic (5 to 30 mg·kg^{-1}) or critical limits e.g., shoot of the invasive *E. crassipes* (7.58 to 18.45 mg·kg^{-1}, except Site 7 where it was below detection levels) and those of *S. sagittifolia* (9.49 to 15.17 m mg·kg^{-1}) among the natives. However, none of the plants could accumulate Cr in either roots or shoots (BAFr and BAFs < 1). Accumulation of Cr in roots of plants was much higher compared to their shoots. Maximum Cr values were noted in the roots of *E. crassipes* (133.75 mg·kg^{-1}) and the native sedges (73.4 mg·kg^{-1}) at Site 1, which incidentally had the highest sediment Cr content of 488.8 mg·kg^{-1}. Domestic waste water effluents, a major Cr source in aquatic ecosystems [97], was the major source of contaminants in Site 2 (with 115.5 ppm sediment Cr values) where *E. crassipes* appears to be the only species that could be regarded as an "accumulator species" with a translocation factor >1 (TF = 2.97). The roots of *E. crassipes* show promise as a Cr accumulating plant [98] [99] and have also been used in China for removal of Cr^{6+} [100]. *Sagitaria sagitifolia*, another native emergent plant, had elevated levels (though not >1) of Cr at both sites of occurrence (translocation factors of 0.8 in Site 7 and 0.9 in Site 10) and could be considered as "accumulators". For hyperaccumulation, plants should be able to accumulate concentrations of metals above the threshold concentration or the natural capacity of plants to concentrate metals in their above ground parts which is >100 mg·kg^{-1} for Cd and >1000 mg·kg^{-1} for Pb and Cr [101]. Since the concentrations of both Pb and Cd in *I. aquatica* and that of Cr in *E. crassipes* were far below the natural capacity of plants for metal accumulation, they do not satisfy the "hyperaccumulator" criterion.

Efficient translocation of elements from roots to shoots in plants was not evident from this study as has been reported for wetland plants which only depend on metal exclusion for their metal tolerance due to reduced translocation [22]. However, since the metal uptake by the three most commonly occurring species in the study sites, namely *Alternanthera philoxeroides*, *Eichhornia crassipes* and *Ipomoea aquatica*, were mostly tissue (root) specific [102], it was thought worthwhile to compare their ability to translocate the accumulated metals from their roots to their shoots. The transfer factors for the three plants have been separately shown for Pb (**Figure 2(a)**), Cd (**Figure 2(b)**) and Cr (**Figure 2(c)**) and it is clearly evident from the figures that *A. philoxeroides* was not a potential accumulator of any of the three metals (TF < 1 for all metals in all sites), unlike *E. crassipes* for Cr (TF = 2.97) in Site 2 and *I. aquatica* for both Pb (TF = 1.12) and Cd (TF = 1.23) in Site 3. Infact, *A. philoxeroides* exhibited considerably low translocation potential for all the three toxic elements in most sites as compared to the other two plants indicating that the metals have been sequestered in the roots. High accumulation of heavy metals in roots and low translocation in shoots may indicate appropriateness of a plant species for phytostabilisation [7] [103]. This mechanism of partitioning is a common strategy of plants to concentrate harmful ions in the roots in order to prevent toxicity to the leaves which is the site of photosynthesis and other metabolic activities [104] thereby reducing metal bioavailability for entry into the food chain. This strategy could prove to be beneficial for *A. philoxeroides*, the twigs and shoots of which are cooked and consumed as a vegetable in many parts of India [105]-[107].

4. Conclusion

In urban areas where heavy metal pollution of freshwater ecosystems is constantly on the rise, this study highlights the ability of some emergent rooted plants to phytostabilize contaminants in the sediments by accumulation in roots thereby reducing the risk to human health and the environment. Both invasive as well as some native plants were equally capable of accumulating Pb and Cd into their roots. However with regard to the widespread consumption and distribution of *I. aquatica* across large parts of the Asian sub-continent, this native species needs to be carefully monitored due to its ability to accumulate Pb and Cd in its above ground parts without any obvious visible symptoms. On the other hand, *A. philoxeroides*, being a cosmopolitan species shows considerable promise not only as an efficient accumulator of Pb and Cd in its roots but its ability to rapidly uptake heavy metals even at very low ambient levels could also make it an efficient indicator of the aquatic ecosystem quality. Moreover, due to its restricted transfer of metals to its above ground parts, the plant can additionally be promoted for feed/

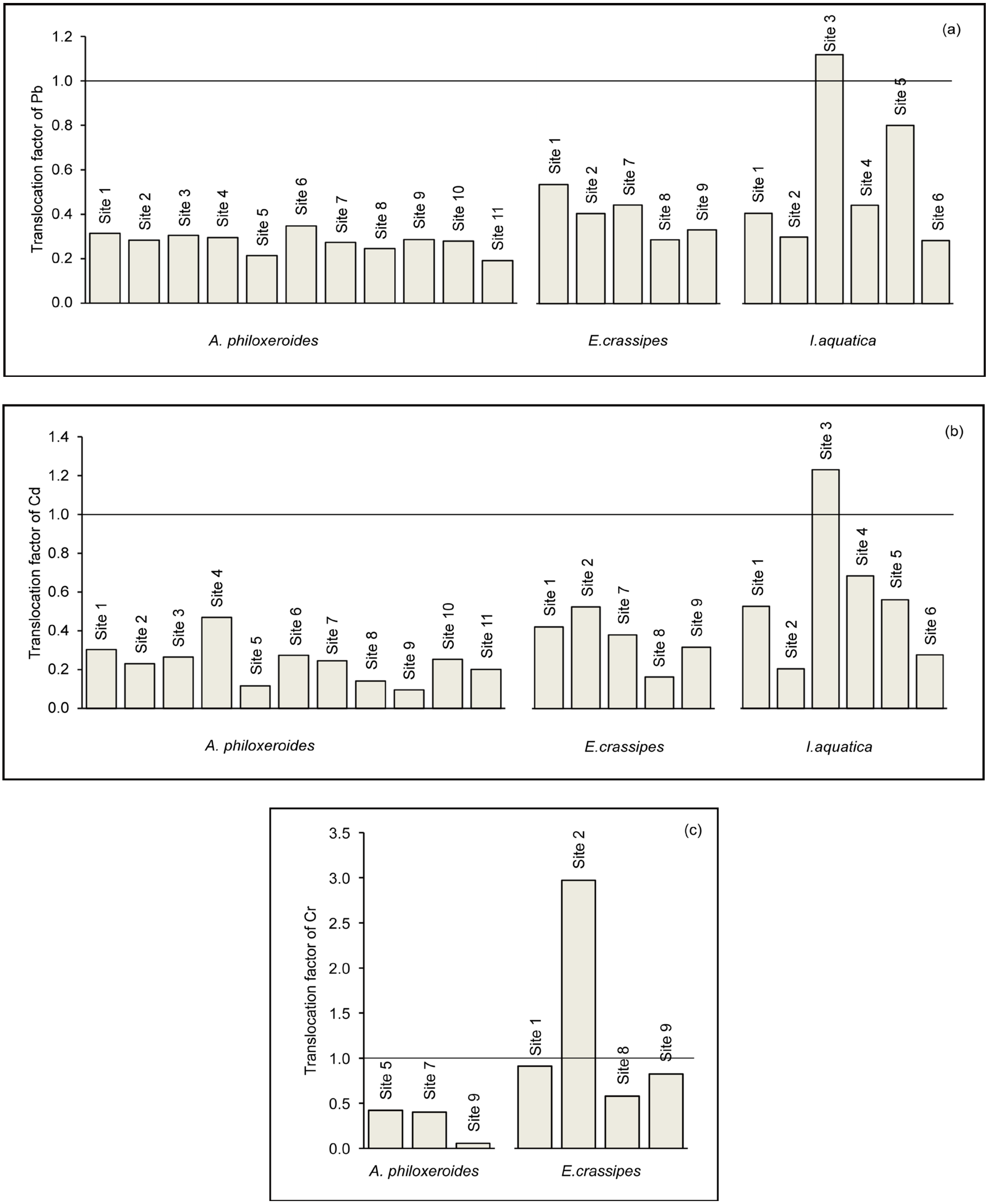

Figure 2. Translocation factor of Lead (a), Cadmium (b) in *A. philoxeroides*, *E. crassipes* and *I. aquatica* and Chromium (c) in *A. philoxeroides* and *E. crassipes*. The horizontal line indicates effective translocation of element from roots to shoots.

food use. Repeated harvesting of *A. philoxeroides* plant parts from water bodies would doubly contribute to its use as well as restrict its spread potential, a negative aspect of all invasive plants. The potential of *A. philoxeroides* as a metal excluder needs to be explored since it translocates less to its shoots as compared to *E. crassipes* and *I. aquatica*.

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