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Assessment of Heavy Metals in Water, Sediment and Macrophytes in Old Glasswork Sites: Implications for Phytoremediation Management

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Abstract Our study found that sediment heavy metal content is the primary factor influencing heavy metal uptake by emergent macrophyte species. This research aimed to quantify the concentrations of heavy metals and metalloids (As, Cd, Cu, Pb, Si, and Zn) in emergent macrophytes—*Lysimachia thyrsiflora, Sagittaria sagittifolia, Phragmites australis, Glyceria fluitans, Carex nigra, Equisetum fluviatile,* and *Juncus effusus*—as well as in the corresponding water and sediment samples from Orrefors, Läen, and Emmaboda, to assess their net accumulation and translocation capacity for application in phytoremediation management. Our results revealed that the sediment As concentration at the Emmaboda site was 23 times higher than the Swedish Environmental Protection Agency (Swe EPA) guideline value. At the Orrefors and Läen sites, the concentrations of heavy metals and the metalloid in water followed the descending order: Zn > Pb > Cu > As > Cd. Among the studied species, *L. thyrsiflora* was the most abundant across locations and exhibited the highest As accumulation (1,603 mg/kg) in its roots, with minimal translocation to its shoots. Si and Zn showed relatively high translocation to the shoots in most of the surveyed emergent macrophytes, regardless of location. This preliminary study indicates the substantial heavy metal accumulation in *L. thyrsiflora* and *J. effusus*. In combination with their limited translocation to the shoots, this underscores their strong potential for phytoremediation-based management of contaminated glasswork sites.

Keywords Arsenic · Emergent · Glassworks · Macrophyte · Nature-based solutions · Sediment · Phytoremediation

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1 Introduction

Heavy metal contamination represents a significant global concern due to its environmental persistence, toxicity, and tendency to accumulate in organisms (Liu et al., 2022; Xiao et al., 2022). The adverse effects of heavy metals and metalloids, such as lead (Pb), chromium (Cr), cadmium (Cd) and metalloids, such as arsenic (As) on human health have been well documented (Greger & Landberg, 2015; Sandhi et al., 2018a, 2022), and include chronic and acute diseases, such as gastrointestinal problems, nervous system disorders, skin lesions and disruption of the reproductive system (Balali-Mood et al., 2021; Sandhi et al., 2022). Heavy metals from contaminated sites are highly mobile in the soil and tend to leach into the surrounding aquatic sphere (Dhote & Dixit, 2009; Li et al., 2018). Climate change exacerbates this issue by increasing the frequency of high precipitation events, stormwater runoff, and flooding, which transport even more toxic pollutants into adjacent water bodies, such as wetlands (Gill et al., 2014; Ponting et al., 2021; Qiao et al., 2023). Once heavy metals enter aquatic ecosystems, they become bioavailable, and owing to their toxicity, they may harm aquatic organisms and ecosystems (Gołdyn et al., 2018). According to the Swedish Environmental Protection Agency (Swe EPA), a national Swedish inventory of contaminated sites (1999–2015) identified approximately 85,000 polluted locations (Swedish EPA, 2021). In recent years, the environmental management of contaminated soil has received increasing attention, and the United Nations (UN) has incorporated this issue into its Sustainable Development Goals (SDG 11: Sustainable Cities and Communities) (UN General Assembly, 2015). According to a World Health Organization (WHO) report, approximately 694,000 sites in 29 countries located in the European Union (EU) have been officially registered in national or regional inventories for future contamination assessment (WHO, 2021).

Aquatic macrophytes play a vital role in aquatic ecosystems, particularly wetlands. They serve as food for aquatic bacteria, invertebrates, and vertebrates and as biofilters for various heavy metals and metalloids (Marchand et al., 2010; Nabi, 2021; Sandhi et al., 2018a). Heavy metal accumulation rates in macrophytes greatly depend on plant species (Galal et al., 2017), with high Pb and Cr accumulation capabilities reported in *Salvinia natans* (Lima et al., 2016); high iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), Cr, and Pb accumulation capabilities reported in *Pista stratiotes* and *Spirodela intermedia* (Miretzky et al., 2004); and high accumulation capability for Cr, Cd, and Pb in *Salvinia herzogii* and *Pistia stratiotes* (Paris et al., 2005). High metal-specific accumulation capabilities have been observed in *Typha latifolia* and *Elodea canadensis* (for Cr, As, Zn, Cu, and Cd; Fritioff & Greger, 2003; Rahman & Hasegawa, 2011), *Leptodictyum riparium* (for Cu, Zn, and Pb; Basile et al., 2011), *Warnstofia fluitans* (for As; Sandhi et al., 2018a, 2018b), *Azolla pinnata* (for Cu and Pb; Saralegui et al., 2021) and *Phragmites australis* (for Fe, cobalt (Co) and nickel (Ni); Abdelaal et al., 2021). In addition to its high accumulation capacity, fast heavy metal uptake has been observed in several aquatic plant species, and can be used for environmental management by phytoremediation (Sandhi et al., 2018a; Schück & Greger, 2020).

Phytoremediation, which involves the uptake and degradation of contaminants by plants, is an environmentally friendly approach and a nature-based solutions (NBS) for managing contaminated sites (Mench et al., 2009; Solomun et al., 2024). Macrophytes are known for their potential to be used as both rhizofilters (uptake metals in both root and shoot parts of aquatic plant species) and phytostabilizers (preventing heavy metal mobility by adsorption and complexation in plant roots) of heavy metals in contaminated water and sediment-soil systems (Galal et al., 2017; Rai, 2009). However, the phytoextraction and phytostabilization capacities of different macrophyte species depend on their bioconcentration factor (BCF) and translocation factor (TF) for each heavy metal (Abdelaal et al., 2021).

The glassworks region “kingdom of crystal” (*glasriket*) is one of Sweden’s most heavily metal-contaminated regions, with more than 50 glass-producing sites with total metal concentrations of 16,900 mg/kg Pb, 180 mg/kg Cd and 2600 mg/kg As reported in glass work site soils (Alriksson et al., 2023; Hagner et al., 2018). To the best of our knowledge, there are no previous field or laboratory studies that assessed heavy metal concentrations and accumulation in emergent macrophytes in wetland systems of contaminated glasswork sites in Sweden. This preliminary study aimed to quantify the heavy metal content of sediment–water and emergent macrophyte species at contaminated glasswork sites. Specifically, this study investigated the net accumulation and translocation of heavy metals and metalloids in emergent macrophytes to evaluate their phytoremediation potential.

2 Materials & Methods

2.1 Sampling Sites

The glassworks industrial region in southeast Sweden (Småland County) was selected for this investigation because of heavy metal mobilization from the contaminated sites to the adjacent aquatic system (Augustsson et al., 2016). Three study sites were selected based on earlier glasswork-related investigations conducted by the Kalmar County Administrative Board (Thunberg, 2020). Sampling was performed at three locations in May 2022: Orrefors, Läen, and Emmmboda (Fig. 1 in the supplementary file). During the summer period (June–August, 2022), the average day time temperatures in Kalmar County was 15.7 °C. During the winter (December-February, 2021–22), average daytime temperatures was −3.23 °C (SMHI, 2025).

2.1.1 Orrefors

In the Orrefors area, glasswork related activities were performed from 1897 until 2014, and it has been estimated that 17 tons of As, 62 tons of Pb, and 1.6 tons of Cd are contained in the soils of that region. (Thunberg, 2020). The landfills from this glasswork site were decommissioned in 1970, and natural vegetation with the dominant tree species were spruce (*Picea* spp., family Pinaceae) and pine (*Pinus* spp., family Pinaceae), have reestablished themselves (Hagner et al., 2018).

2.1.2 Läen

The Lake Läen in the Lessebo municipality is located between different glasswork factories. One of the oldest glassware-producing factories, Kosta, is located approximately 16 km northeast of Lake Läen and this lake has also been used for angling.

2.1.3 Emmaboda

The Emmaboda municipality has a long history of glasswork-related activities, with several glass-producing factories established in the mid-nineteenth century (Emmaboda Kommun, 2022). Confirmed glasswork activities in Emmaboda occurred from 1919 to 1930 and from 1934 to 1978 (Alriksson et al., 2023). The soils from several locations in the Emmaboda municipality were classified as 'severely contaminated' for As, Pb, Cu, Zn, and Cd and 'highly contaminated' for As in groundwater by the Swedish EPA (Höglund et al., 2007).

2.2 Sample Collection and Processing

2.2.1 Sediment

Three sediment samples of approximately 0.5 L (including water) from a wetland location within each study site were collected (depth from 0.2–0.7 m below the water surface) using a hand spade. Depending on the location, the distance between replicate was 5–15 m. The samples were stored in plastic boxes in the field and transported to the Environmental Chemistry Laboratory of the Department of Biology and Environmental Science, Linnaeus University (LNU), Kalmar, Sweden. Debris, rocks, and plant materials were removed from the sediment samples before drying at 60 °C for 72 h. The soil samples were stored in numbered plastic bags at room temperature for further heavy metal analysis in an accredited laboratory. The pH of the sediment was measured at the Environmental Chemistry Laboratory, LNU, using a pH meter (HI 2211pH/ORP meter, Hanna Instruments, USA) by adding 1 g of sediment to 10 mL of water (Greger & Landberg, 2015).

2.2.2 Water

Three wetland water samples (0.5 L for each sample) were collected from each study site. Before collection, the water-collecting vessel was rinsed thrice at the collection point. Water samples were collected to a depth of 0.3–0.5 cm above the sediment surface, stored in plastic bottles and transported to the Environmental Chemistry Laboratory, LNU. After measuring the pH (HI 2211pH/ORP meter, Hanna Instruments, USA), the water samples were filtered through a 0.45 μm membrane filter, 0.03% HNO_3 (7.5 μL HNO_3-analytical grade in 25 mL water) was added, and the samples were stored in a refrigerator (4 °C) until analysis.

2.2.3 Macrophytes

Emergent macrophyte species were collected from the same three locations as water and sediment samples. The emergent macrophyte species collected were tufted yellow-loosestrife (*Lysimachia thyrsiflora*), arrowhead (*Sagittaria sagittifolia*), common reed (*Phragmites australis*), floating sweet grass (*Glyceria fluitans*) from Orrefors; tufted yellow-loosestrife (*Lysimachia thyrsiflora*), common sedge/black sedge (*Carex nigra*), water horsetail (*Equisetum fluviatile*) from Läen and tufted yellow-loosestrife (*Lysimachia thyrsiflora*), floating sweet grass (*Glyceria fluitans*) and common/soft rush (*Juncus effusus*) from Emmaboda. A total of seven emergent macrophyte species were sampled. Information on their taxonomy (plant family) and growth duration is provided (Supplementary Table 1). Macrophyte species were selected on the basis of their availability and abundance at the study site. Three replicates of each plant species were collected from each site for heavy metal and metalloid content analysis.

Plant samples were collected from each site, cleaned, rinsed from sediment and debris with tap water, and gently dried using a paper towel. Root and shoot parts were separated using scissors, and fresh weights were measured. Plant samples were placed in an oven at 60 °C for 72 h to obtain dry weight (for procedure, see Sandhi et al., 2017). The dry weights of the plant samples (roots and shoots) were measured and they were consequently stored at room temperature until their heavy metal content was analysed by an accredited laboratory.

2.3 Analysis

2.3.1 Chemical Analysis

All collected samples were sent to an accredited analytical laboratory (ALS Scandinavia AB, Luleå, Sweden) for analysis of heavy metal and metalloid (As, Cd, Cu, Pb, Zn, and Si) content. Prior to analysis, the sediment samples were sieved to < 2 mm by following the ISO 11464:2006 method; to ensure homogeneity, sediment grinding was also performed. Before the analyses, the sediment samples were digested in 7 M HNO_3 in a hotblock, according to SE-SOP-0021. Macrophyte samples (including root and shoot parts) were digested with HNO_3 and H_2O_2 in a microwave oven following the SE -SOP-0128 (SS-EN 13805:2014) method. The heavy metal content in both the sediment and macrophytes was then determined according to SS-EN ISO 17294–2:2016 and the US EPA method 200.8:1994, and no digestion process was required for the water samples. The heavy metal content in the water samples and their concentrations in all three sample matrices were then determined according to SS-EN ISO 17294–2:2016 and the US EPA method 200.8:1994 using sector field inductively coupled plasma spectrometry (ICP-SFMS). In the case of measurement accuracy, the uncertainty from the analytical laboratory is given as extended uncertainty and (JCGM 100:2008 Corrected version 2010) calculated with a coverage factor of 2, which gives a level of approximately 95% certainty.

2.3.2 Calculation and Statistical Analysis

The total concentrations of the heavy metals (As, Cd, Cu, Pb, Zn, and Si) in the plant and sediment samples were calculated based on the total contents of the different heavy metals obtained from ICP-SFMS. Equations 1 and 2 were used to calculate the net accumulation and translocation in the shoot of heavy metals in the plants respectively (Pourghasemian et al., 2013).

Net accumulation of heavy metal by root (µg of whole plant/root g DWt)

$$= \frac{Total\ content\ of\ heavy\ metal\ in\ the\ whole\ plant\ (\mu g)}{Root\ dry\ weight\ (g)} \tag{1}$$

Translocation (%, total metal in shoot µg/total metal in whole plant µg) of heavy metal in the shoot

$$= \frac{Total\ content\ of\ heavy\ metal\ in\ the\ shoot\ part\ (\mu g)}{Total\ content\ of\ heavy\ metal\ in\ the\ whole\ plant\ (\mu g)} X100 \tag{2}$$

We performed one-way ANOVA followed by Fisher's Least Significant Difference (LSD) post-hoc test to evaluate the differences in heavy metal concentrations between species. One-way ANOVA followed by a post-hoc (LSD) test was also performed to determine the differences between heavy metal concentrations and other parameters in the sediment and water samples from all sites. All the above-mentioned statistical analyses were performed using SPSS, version 22 software (IBM SPSS Inc., Chicago, USA). The graphs were generated in the Microsoft office Excel package (MS office professional plus, 2021 version).

3 Results

3.1 pH and Heavy Metal Concentrations in Water and Sediment

Water pH was slightly higher at the Läen site than at the Orrefors and Emmaboda sites, but there were no significant differences in pH among the sites (Table 1). However, the sediment pH was significantly higher at the Orrefors site than at other sites.

The water concentrations of As, Cd, Cu, Pb, and Zn were significantly higher at the Emmaboda site than at other sites (Table 1). With the exception of As concentration, the lowest water heavy metal concentrations were found at the Läen site. The general trend of heavy metal and metalloid concentrations in water from the Orrefors and Läen sites was Zn > Pb > Cu > As > Cd.

Our results showed different patterns of heavy metal concentrations in sediments from the three sites, although similar patterns were observed in sediments from Orrefors and Läen, where concentrations followed the order Si > Pb > Zn > As > Cu > Cd and Si > Pb > Zn > Cu > As > Cd respectively; whereas from Emmaboda: Si > Zn > As > Pb > Cu > Cd (Table 1). Sediment As (230 mg/kg) concentrations at the Emmaboda site were significantly higher than at the other two sites and 23 times greater than the Swedish reference values for sediment (10 mg/kg) and sensitive land use, as specified by the Swedish EPA. Likewise, Pb concentrations at Orrefors exceeded the Swedish reference values for sediment by a factor of 12 and sensitive land use by factors of and 6. The highest Zn concentration in sediment was observed at the Emmaboda site. In contrast, Cd concentrations were similar across all three sites. Silicon concentrations in the sediments were significantly higher at the Orrefors site compared to the others.

3.2 Heavy Metals in Macrophytes

3.2.1 Concentration in Root & Shoot

Orrefors At the Orrefors site, significantly higher As concentrations were found in the roots of *L. thyrsiflora* (33 mg/kg DW) than in all plant species collected from the same site (Table 2). Meanwhile, *G. fluitans* from the same location accumulated higher Cu and Si concentrations in their roots than other macrophyte species. However, only the Si concentration in the roots of *G. fluitans* was significantly higher than that of all other plant species. The highest root and shoot Zn concentrations were observed for *S. sagittifolia*. However, its concentration in the shoots was significantly higher than that in other macrophyte species. Both Cd and Cu concentrations in shoots from the Orrefors site were higher in *S. sagittifolia* than in the other macrophyte species, except for Cu in *L. thyrsiflora.* The mean Cd concentration in the roots of *P. australis* was higher than that in other macrophyte species. In contrast, *L. thyrsiflora* showed higher As and Pb concentrations in shoots than the other macrophyte species examined from the Orrefors site did.

Läen At the Läen site, the highest Pb and Si concentrations were found in the roots of *E. fluviatile* compared to other plant species from this site (Table 2). In addition, higher As, Cd, and Zn concentrations were found in the roots of *E. fluviatile* than in the other macrophyte species. *E. fluviatile* showed higher shoot concentrations of Zn, Cu, and Si than other macrophyte species. However, this value was significantly higher for Zn only. Pb concentrations showed a different species-specific shoot accumulation pattern; *C. nigra* had significantly higher shoot Pb concentrations than all other macrophyte species collected from the Läen site.

Emmaboda At the Emmaboda site, As and Si concentrations in the roots were higher in *L. thyrsiflora* than in other plant species from the same site (Table 2). The shoot Cd and Zn concentrations of *J. effusus* were significantly higher than those of the other macrophytes. However, although not significant, shoot As, Cu, and Pb concentrations in *J. effusus* were higher than those in all other macrophytes. Significantly higher concentrations of Si (5.4 g/kg) were found in the shoots of *G. fluitans* than in those of all other plant species from the same site. In the roots, relatively higher Cd, Cu, Pb, and Zn concentrations were found in *J. effusus* than in the other species.

3.2.2 Net Accumulation

At the Orrefors site, a significantly higher As net accumulation was found in *L. thyrsiflora* than in all other plant species (Fig. 1a). A higher net accumulation of Pb and Zn was found in *P. australis* and *S. sagittifolia,* respectively, than in all other plant species at the Orrefors site. Significantly higher Si net accumulation was found in *G. fluitans* than in *L. thyrsiflora* and *S. sagittifolia* (Fig. 1b). *S. sagittifolia*

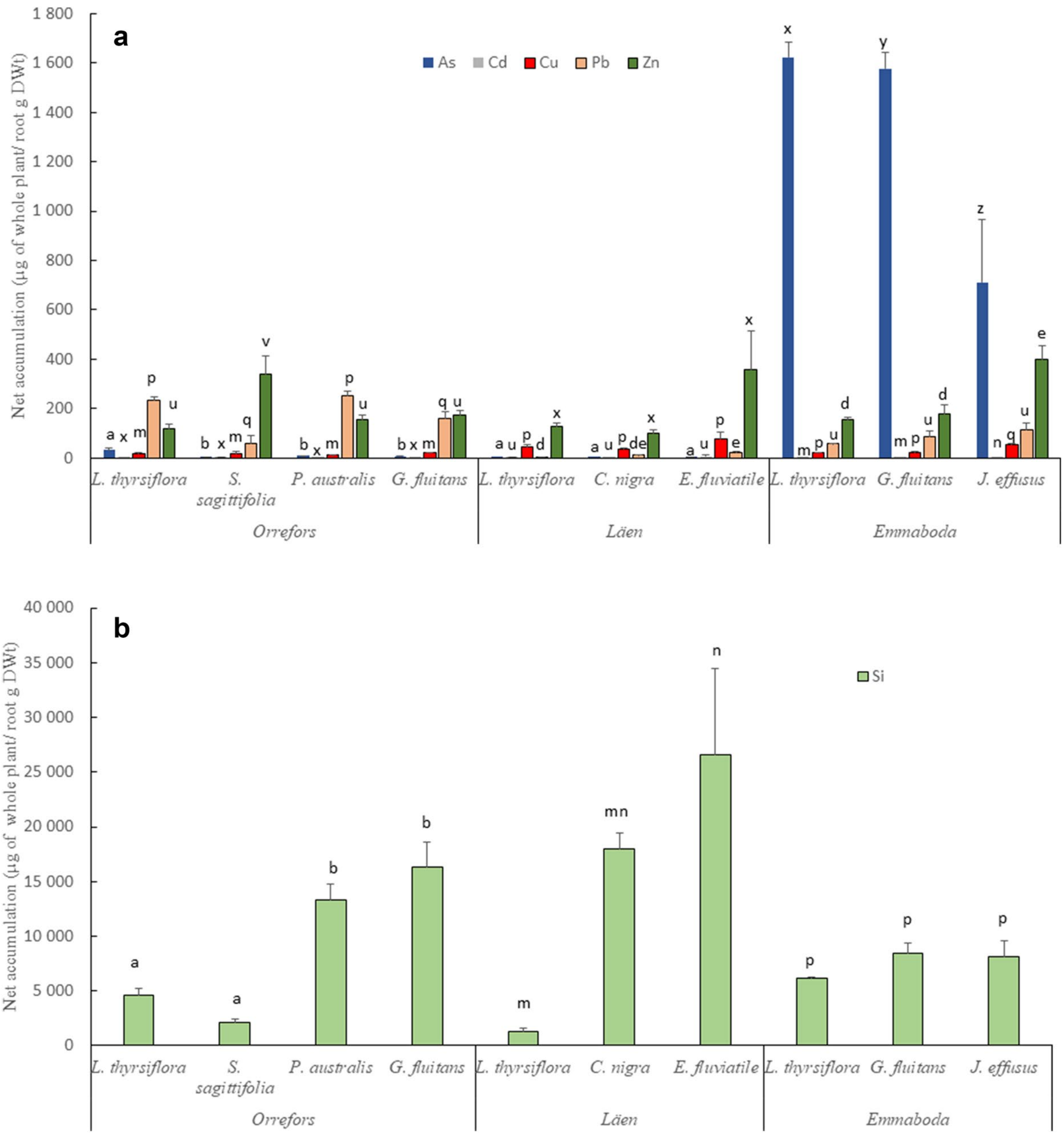

Fig. 1 Net accumulation (µg/g) of As, Cd, Cu, Pb, and Zn (**a**) and Si (**b**) in the macrophyte species collected from Orrefors, Läen and Emmaboda. Different letters indicate significant differences between the plant species at the same site and for the same element ($P < 0.05$, $n = 3 \pm$ SE)

Table 1 Heavy metal concentrations (mg/kg) in sediment, surface water (µg/L) and pH values of the three study sites (Orrefors, Läen and Emmaboda). Different letters (a-c) indicate significant differences between the sites for each element and pH ($P<0.05$, $n=3\pm$SE)

Parameters	Concentration in sediment (mg/kg) except Si (g/kg)			Swedish reference value for sediment (mg/kg) (Swe EPA 2000)	Swedish reference value for sensitive land use (mg/kg) (Swe EPA 2009)	Concentration in water (µg/L)			FAO/WHO recommended irrigation water quality (µg/L) (Ayes & Westcot, 1985)	Average value for surface water(µg/L) (Swe EPA, 2009)
	Orrefors	Läen	Emmaboda			Orrefors	Läen	Emmaboda		
As	8 ± 2^{a}	1.6 ± 0^{a}	230 ± 23^{b}	10	10	0.3 ± 0.00^{a}	0.4 ± 0.0^{a}	12.6 ± 0.2^{b}	100	0.37
Cd	0.5 ± 0.2^{a}	1 ± 0.1^{a}	0.8 ± 0.1^{a}	0.2	0.5	0.02 ± 0.00^{a}	0.02 ± 0.0^{a}	0.05 ± 0.0^{b}	10	0.014
Cu	7 ± 2^{a}	32 ± 3^{b}	47 ± 0.7^{b}	15	80	0.7 ± 0.01^{a}	0.67 ± 0.03^{b}	3.6 ± 0.1^{c}	200	0.68
Pb	318 ± 126^{a}	106 ± 4^{a}	214 ± 35^{a}	25	50	2 ± 0.05^{a}	1 ± 0.03^{a}	25 ± 1.0^{b}	5000	0.30
Zn	117 ± 12^{ab}	46 ± 6^{b}	276 ± 67^{a}	85	250	4 ± 0.6^{a}	2 ± 0.1^{b}	44 ± 1^{c}	2000	2.91
Si	268 ± 16^{a}	152 ± 22^{b}	124 ± 8.2^{b}							
pH	5 ± 0^{a}	4 ± 0.1^{b}	4.9 ± 0.0^{c}			6.3^{a}	6.5^{a}	6.4^{a}	6.5–8.4	

Table 2 Total concentrations of As, Cd, Cu, Pb, Zn (mg/kg) and Si (g/kg), and in roots and shoots of the different macrophyte species collected from Orrefors, Läen and Emmaboda. Different letters for root (a-c) and shoot (p-r) indicate significant differences between macrophyte species at the same site and for the same element ($P<0.05$, $n=3\pm$SE)

Location	Macrophyte species	Concentrations (mg/kg) except Si											
		As		**Cd**		**Cu**		**Pb**		**Si (g/kg)**		**Zn**	
		Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot
Orrefors	*L. thyrsiflora*	33 ± 6^{a}	0.3 ± 0.1^{p}	1 ± 0.1^{a}	0.07 ± 0.03^{q}	9 ± 0.3^{a}	9 ± 0.2^{p}	225 ± 18^{a}	9 ± 3^{p}	4 ± 1^{a}	0.6 ± 0.1^{p}	91 ± 6^{a}	33 ± 1^{pq}
	S. sagittifolia	2 ± 10^{b}	0.1 ± 0.0^{p}	1 ± 0.2^{a}	0.7 ± 0.2^{p}	10 ± 3^{a}	7 ± 1^{p}	57 ± 30^{b}	4 ± 1^{p}	2 ± 0.3^{b}	0.07 ± 0.05^{p}	138 ± 17^{a}	204 ± 9^{r}
	P. australis	9 ± 1^{b}	0.1 ± 0.0^{p}	1 ± 0.09^{a}	0.02 ± 0.01^{q}	8 ± 0.3^{a}	2 ± 0.07^{q}	245 ± 18^{a}	5 ± 0.7^{p}	6 ± 0.4^{a}	6 ± 1^{q}	88 ± 13^{a}	55 ± 11^{p}
	G. fluitans	6 ± 1^{b}	0.2 ± 0.04^{p}	1 ± 0.3^{a}	0.03 ± 0.0^{q}	15 ± 3^{a}	4 ± 1^{q}	151 ± 30^{a}	6 ± 1.4^{p}	7 ± 0.3^{c}	6 ± 1^{q}	126 ± 31^{a}	27 ± 3.2^{q}
Läen	*L. thyrsiflora*	0.2 ± 0.02^{a}	0.01 ± 0.0^{p}	2 ± 0.5^{a}	0.3 ± 0.0^{p}	13 ± 2^{a}	16 ± 3^{p}	3 ± 0.5^{a}	0.2 ± 0.03^{p}	$1.\pm0.3^{a}$	0.2 ± 1^{p}	49 ± 7^{a}	41 ± 1.3^{p}
	C. nigra	1 ± 0.1^{a}	0.2 ± 0.0^{p}	1 ± 0.1^{a}	0.1 ± 0.0^{p}	21 ± 2^{a}	7 ± 0.4^{q}	9 ± 2^{a}	2 ± 0.1^{q}	6 ± 0.3^{bc}	6.5 ± 0.3^{qr}	43 ± 3^{a}	32 ± 0.7^{p}
	E. fluviatile	2 ± 1^{a}	0.2 ± 0.1^{p}	3 ± 1.2^{a}	1 ± 0.5^{p}	31 ± 8^{a}	18 ± 0.6^{p}	19 ± 3^{b}	1 ± 0.2^{r}	7 ± 0.2^{c}	7.3 ± 0.2^{r}	92 ± 26^{a}	86 ± 14^{q}
Emmaboda	*L. thyrsiflora*	1603 ± 59^{a}	20 ± 2^{p}	0.4 ± 0.03^{a}	0.06 ± 0.0^{p}	12 ± 1^{a}	9 ± 0.1^{p}	49 ± 4^{a}	9 ± 0.7^{p}	5 ± 0.2^{a}	2 ± 0.4^{p}	106 ± 11^{a}	55 ± 2^{p}
	G. fluitans	1567 ± 66^{a}	17 ± 5^{p}	0.5 ± 0.1^{a}	0.03 ± 0.01^{r}	20 ± 3^{a}	4 ± 0.4^{q}	85 ± 22^{a}	5 ± 0.7^{p}	5 ± 0.2^{a}	5 ± 1^{q}	157 ± 39^{a}	32 ± 4^{q}
	J. effusus	627 ± 217^{b}	30 ± 17^{p}	0.6 ± 0.07^{a}	0.3 ± 0.06^{q}	29 ± 0.2^{a}	11 ± 1^{p}	90 ± 24^{a}	10 ± 3^{p}	4 ± 0.2^{a}	2 ± 1^{p}	193 ± 30^{a}	95 ± 4^{r}

showed higher Cd and Cu net accumulation than all other Orrefors macrophyte species. Similar to the Orrefors site, in Emmaboda, a higher As net accumulation was detected in *L. thyrsiflora* than in all other plant species from the same site. The net accumulation of Cu, Cd, Zn, and Pb was higher in *J. effusus* than in the other plant species, but the differences were only significant for Cd, Cu and Zn. The Si net accumulation in *G. fluitans* was not significantly higher than that in the other macrophyte species from Emmaboda. At the Läen site, the net accumulation of As, Cd, Cu, Pb, and Si was higher in *E. fluviatile* than that in other macrophyte species from the same site.

3.2.3 Translocation to the Shoot

At the Orrefors site, *P. australis* showed the highest Si translocation (> 50%) to the shoot, whereas *S. sagittifolia* showed the highest translocation (> 50%) of Zn. The translocation of Zn in *S. sagittifolia* was significantly higher than that in the other plant species (Fig. 2). Cd translocation was significantly higher in *S. sagittifolia* than in the other plant species. Macrophytes from the Läen site exhibited different translocation patterns. The translocation of Zn was similar among the macrophyte species. Significant differences in the translocation of As, Cd, Si, Pb, and Cu were observed among the plant species, with *C. nigra* exhibiting significantly lower Cu translocation compared to the other two species. At the Emmaboda site, *J. effusus* showed significantly higher Cd and Zn translocations than the other plant species. *J. effusus* also showed higher As, Cu, Pb and Si translocation compared to the other plant species; however, the differences were not significant across all species.

4 Discussion

The high sediment As concentration at the Emmaboda site is likely the result of past glasswork activities in that region. Sulfate reduction plays a vital role in the bioavailability of As, with the low sediment pH playing an important role in the gradual oxidation of sulfide, especially in mining areas where a positive correlation is found between sulfide and As content (Alonso et al., 2020; Culioli et al., 2009). The relationship between pH and As species mobility in streams is already well documented, as heavy precipitation may reduce stream water pH levels, which, in

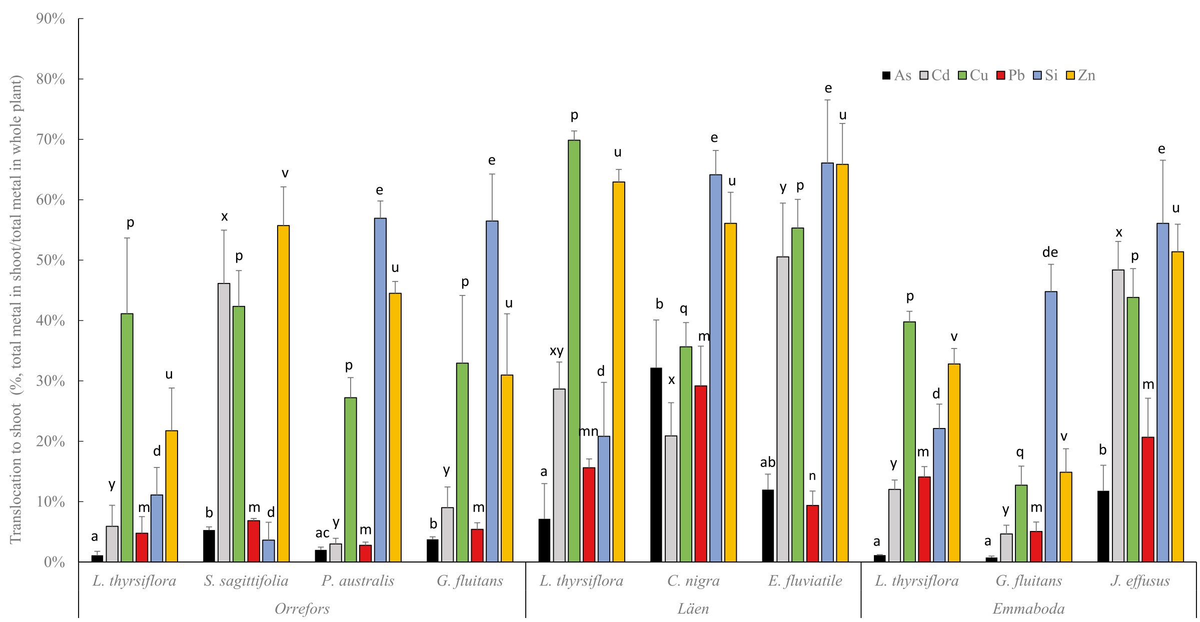

Fig. 2 Translocation to shoot (%) of As, Cd, Cu, Pb, Si, and Zn in the macrophyte species collected from Orrefors, Läen and Emmaboda. Different letters indicate significant differences between the plant species from the same site and for the same element (P <0.05, n = 3 ± SE)

turn, may increase As mobility in aquatic media (Park et al., 2023). In our study, low sediment pH may have increased As mobility in aquatic media. Generally, heavy metal concentrations are higher in the sediments of contaminated sites than in the water column above, as the sediments work as metal sinks (Greger, 2004; Sandhi et al., 2023). Therefore, the heavy metal concentrations in the sediments likely determine the heavy metal accumulation in the macrophyte species collected in this study. The high heavy metal and metalloid concentration in the water at the Emmaboda site was probably a consequence of heavy metals resuspended from the sediment sink. Most macrophytes investigated in our study belonged to the hydrohalophyte category (air–water plant or semi-aquatic plant species) (Petrov et al., 2023). Therefore, we assumed that heavy metal concentrations in sediments influenced the species-specific heavy metal accumulation patterns in macrophytes.

Accumulated heavy metals not only affect the physiological processes of specific macrophyte species but also have antagonistic effects on the uptake of other heavy metals in macrophytes. External medium Zn concentrations can influence Cu and Cd uptake in plant shoots, as shown in previous studies, where high external Zn content reduced Cd and Cu uptake and translocation in *Ceratophyllum demersum* and *Hydrilla verticillata,* respectively (Aravind & Prasad, 2003; Wang et al., 2009a). Concurrent with the above, the low Zn sediment and Zn water concentrations in Läen may have led to higher Cu and Cd concentrations in plant shoots compared with the other two sites with high external Zn concentrations.

This high As net accumulation in certain macrophyte species from Emmaboda could be due to the development of As tolerance mechanisms such as; a) As intercellular compartmentalization and b) extracellular As sequestration. These mechanisms could be similar to those employed by the As hyperaccumulator species *Pteris vittata*, especially when growing at highly contaminated sites (Datta et al., 2017; Sandhi et al., 2018a). Generally, the accumulation patterns of heavy metals in plants are regulated by external factors (e.g., environmental conditions, growing season, pH, sediment characteristics, and organic matter content) and internal physiological factors (e.g. plant type, growth stage, element-based absorption, accumulation, and translocation) (Greger, 2004; Núñez et al., 2011; Petrov et al., 2023).

Plants depend on certain essential trace metals for growth and development. For example, Zn, Cu, and Si play important roles in various essential biological and metabolic processes such as protein synthesis, photosynthesis, oxidative stress response, enzyme activation, and carbohydrate metabolism (Hamzah Saleem et al., 2022; Meharg & Meharg, 2015; Sandhi et al., 2023). Several emergent macrophytes possess a unique ability to accumulate heavy metals from water and sediment in their roots (Tan et al., 2023) (Fig. 3). The relatively high Si accumulation in plant roots may be explained by the role of Si in plant's biotic and abiotic stress tolerance. Si affects various physiological processes in aquatic plants, including hydrodynamic stress, light interception, and herbivore protection (Schoelynck & Struyf, 2016). The benefits of Si in plant stress management (both biotic and abiotic) are extensive, and include the reduction in heavy metal uptake in plants (Meharg & Meharg, 2015). In addition to Si, Zn also plays an important role for plant nutrition, and enzymatic activities. Zn concentration is relatively higher in the leaves compared to root (Hossain et al., 2021). That could corroborate the high Zn translocation to the aboveground parts of our investigated macrophytes.

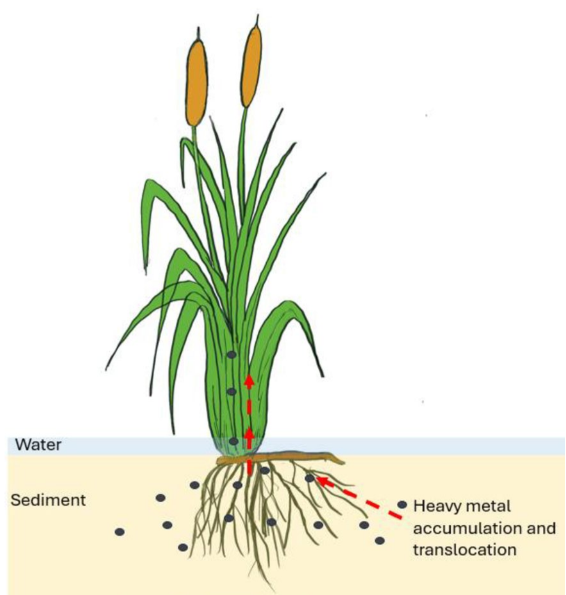

Fig. 3 Schematic diagram for heavy metal and metalloid uptake and translocation process in emergent macrophyte species. The black dots represent the heavy metals and metalloids while red arrows indicate their translocation pathways (illustration courtesy: A. Sandhi)

However, the relatively high translocation factors for Cd and As in *J. effusus* compared to other emergent macrophyte species from the same site could be attributed to its developed tolerance mechanisms. Yang et al. (2020) reported that translocation values are inversely proportional to their concentrations, particularly for non-essential trace elements, such as Cd and Pb. A previous study has found that *J. effusus* can regulate Cd bioavailability at the water-root interface by releasing strong organic ligands around the root zone (Najeeb et al., 2011). Additionally, recent research has highlighted the strong potential for As phytostabilization in a closely related halophytic macrophyte species, *Juncus acutus*, where root As concentration was found to correlate with sediment As levels (Alam et al., 2022). According to Hossain et al. (2021), interactions arising from both dissention and synergistic processes among elements can influence the metabolism of these elements within the plant body. This, in turn, may affect metal translocation in macrophytes independently of their availability in the sediment, potentially explaining the variation observed in heavy metal translocation within the macrophytes studied.

The much higher heavy metal concentration in plant roots compared to sediments from the Emmaboda site could be explained by sediment being the main metal sink in aquatic environments, and the sediment mass being higher than the plant biomass (Núñez et al., 2011). Moreover, the accumulation of heavy metals in macrophytes from sediment could also depend on the presence or absence of other metals, as well as on local sediment characteristics (Cardwell et al., 2002). Therefore, our study revealed that the net accumulation of heavy metals in plants depends on the heavy metal concentration of the sediment at specific sites. In contrast, heavy metal translocation in plant shoots is related to the beneficial or essential roles of these elements in plant growth and development.

Our study revealed that the perennial emergent macrophyte *L. thyrsiflora* is an excellent As accumulator species at both Orrefors and Emmaboda sites. The low translocation of As to the aboveground plant parts further confirms the potential of *L. thrysiflora* as an As phytostabilizer candidate. Wang et al. (2009b) reported that *Lysimachia deltoides* could be an excellent Cd hyperaccumulator in contaminated soils (52 mg/kg Cd) under favourable hot and humid climatic conditions. In northern temperate conditions, a recent study also confirmed that *L. thyrsiflora* (collected in Sweden) demonstrated excellent heavy metal (Cd, Cu, Zn and Pb) removal capacity in a five-day laboratory trial (Schück & Greger, 2020). Overall, the low translocation of toxic heavy metals in the emergent macrophyte species investigated may be explained by the fact that most accumulated heavy metals are stored or stabilized in the root parts. This could be due to 1) a developed tolerance mechanism, or 2) a defence mechanism or protection of photosynthetic cells in aboveground plant parts, including leaves, in the studied macrophyte species (Abdelaal et al., 2021; Rascio & Navari-Izzo, 2011). In addition, the compartmentalization of heavy metals in the below-ground parts of wetland macrophytes—such as their storage capacity within intercellular air spaces like the cortex parenchyma—may play a significant role in reducing the translocation of heavy metals to above-ground tissues (Bonanno et al., 2017).

5 Limitations

This study acknowledges the limitation of lacking an experimental design to evaluate the effects of seasonal changes on heavy metal loading in sediments and their uptake by emergent macrophytes. Addressing this aspect could have enhanced the comparisons and strengthened the study's conclusions. The primary aim of this investigation was to provide preliminary insights into industrial contamination at the glassworks site and its impact on adjacent aquatic systems, including sediment–water-emergent macrophyte species. Furthermore, analyses of organic matter content and cation exchange capacity in sediment samples—which are critical for understanding contamination dynamics—could not be included due to time and resource constraints. Future research should incorporate these components to facilitate a more comprehensive assessment of contaminated wetland management at the glassworks site.

6 Conclusion

Investigations of emergent macrophytes from contaminated glasswork sites demonstrate their ability to accumulate high levels of heavy metals from heavily contaminated sediments. Our study also revealed that for most of the investigated heavy metals and metalloids, translocation to the shoot/aerial parts of these emergent macrophyte species was limited. This suggests that these macrophytes are not suitable for phytoextraction, where aerial plant parts with high heavy metal contents are removed, as a remediation strategy for contaminated sites.

In conclusion, *L. thyrsiflora* and *J. effusus* exhibit strong potential as multi-metal phytostabilizers in Swedish and other temperate regions, making them promising candidates for phytoremediation applications such as constructed floating wetland systems. However, before deploying these emergent macrophytes as nature-based solutions for aquatic ecosystem management, further research is required to assess the long-term leaching dynamics and seasonal bioavailability of leached heavy metals from these species.

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Data Availability All the data used for this work will be made available on request.

Declarations

Ethical Approval N/A.

Informed Consent N/A

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Conflict of interest The authors declare that they have no conflicts of interest.

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