



Green Solutions for Heavy Metal Pollution in the Aquatic Environment of the Nile Islands: Cues from some Submerged and Emergent Macrophytes

Abdel Rahman Nadi[✉] · Elsayed Mohamed[✉] · Ahmed M. M. A. Kasem[✉] ·
Abd El-Mageed F. M. Ghanem[✉] · Mohamed O. Badry[✉]

Received: 4 December 2024 / Accepted: 30 March 2025 / Published online: 30 April 2025
© The Author(s) 2025

Abstract The study evaluates the phytoremediation potential of five wild macrophytes—*Setaria geminata* (Forssk.) Veldkamp, *Ceratophyllum demersum* L., *Myriophyllum spicatum* L., *Persicaria senegalensis* (Meisn.) Soják, and *Ludwigia adscendens* subsp. *diffusa* (Forssk.) P.H. Raven—for iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) on the shore of two islands in Luxor governorate, Egypt: Armant (sites 1 and 2) and Aqalata (site 3). The study aimed to assess

how site, season, and species influence heavy metal accumulation in plant organs, chlorophyll content, and antioxidant compounds; to evaluate phytoremediation efficiency using bioaccumulation factors; and to explore the relationship between heavy metals concentrations in shoots and the behavior of chlorophyll and antioxidants. Heavy metal concentrations in water at all three sites fell within the safe irrigation limits. However, Cu and Mn levels in sediments exceeded global freshwater recommendations during summer. Fe and Mn levels in submerged species (*C. demersum* and *M. spicatum*) and emergent species' belowground tissues (*S. geminata*, *P. senegalensis*, and *L. adscendens*) surpassed the permissible limits in most seasons. In contrast, Zn levels in all studied species remained within the acceptable limits, while Cu levels in *S. geminata* and *P. senegalensis* roots exceeded the permissible limits during spring and summer, respectively. The bioaccumulation factors (BAFs) for submerged species exceeded one for all metals, whereas emergent species showed BAFs greater than one only for Mn. Translocation factors (TFs) for all metals were less than one, except for Zn in *P. senegalensis* and *L. adscendens*. Chlorophyll pigments in *S. geminata*, *M. spicatum* and *L. adscendens* negatively correlated with most heavy metals in shoots, while a positive correlation was observed in *C. demersum*. Also, heavy metals in shoots negatively correlated with total phenolics and flavonoids, carotenoids and phenolics, and phenolics in *C. demersum*, *M. spicatum* and *S. geminata*, respectively. In contrast, *L.*

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11270-025-07966-4>.

A. R. Nadi
Department of Aquatic Environment, Faculty of Fish & Fisheries Technology, Aswan University, Aswan 81528, Egypt
e-mail: abdelrahmannadi@gmail.com

E. Mohamed (✉) · A. M. M. A. Kasem ·
A. E.-M. F. M. Ghanem
Botany and Microbiology Department, Faculty of Science,
Al-Azhar University, Assiut 71524, Egypt
e-mail: sayedmohamed@azhar.edu.eg

A. M. M. A. Kasem
e-mail: amkasem@azhar.edu.eg

A. E.-M. F. M. Ghanem
e-mail: abdEl-MageedEldeeb.42@azhar.edu.eg

M. O. Badry
Botany and Microbiology Department, Faculty of Science,
South Valley University, Qena 83523, Egypt
e-mail: mohamedowis@svu.edu.eg

adscendens exhibited a positive correlation between most of these elements and antioxidant compounds. The differential relationships between the studied heavy metals in shoots and chlorophyll/antioxidant compounds suggest species-specific energy allocation strategies. Our results highlight the potential of these species for phytoremediation in contaminated aquatic ecosystems, and indicate that submerged species are suitable for hyperaccumulation, while emergent macrophytes function as accumulators for Mn and excluders for Fe, Cu, and Zn.

Keywords Biomonitoring · Phytoremediation · Macrophytes · Heavy Metals · Water pollution · Antioxidant compounds · Nile Islands

1 Introduction

The Nile River represents Egypt's lifeline; the physical, biological, and chemical qualities of Nile water have changed since the construction of the Aswan High Dam. Another factor contributing to the decline in water quality is the discharge of various anthropogenic activities into the Nile, such as domestic wastewater, agricultural runoff containing chemical fertilizers and herbicides, industrial wastes, and river ship waste (Abdel-Satar et al., 2017; Al-Afify et al., 2018). Heavy metal contamination of aquatic ecosystems is a major global environmental issue. Due to their solubility and mobility, heavy metals can accumulate from polluted water and sediments at various stages of the food chain, resulting in many ecological and health problems (Yan et al., 2010). Heavy metals such as Fe, Mn, Zn, and Cu are essential micronutrients for plant and animal growth but are harmful at high concentrations. Other heavy elements, such as Cd, Pb, As, and Hg, are nonessential and toxic to plants, even at low concentrations (Alloway, 2013). In Egypt, laws have been issued to reduce industrial wastewater discharge to the Nile. However, pollution of the Nile and water scarcity are two major problems due to population increase, industrial development, and the construction of dams on the Nile River course in neighboring countries. Therefore, there is an urgent need for smart methods of managing available water and the remediation of contaminated water (Abdelaal et al., 2021; Abdelhafez et al., 2020; EEAA, 2002; Fawzy et al., 2012).

Phytoremediation provides a cost-effective, efficient, and environmentally friendly approach to restore contaminated water bodies, compared to physical and chemical methods, which are often associated with high operating costs, complex processes, low efficiency, sludge production, and the risk of secondary pollution (Vardhan et al., 2019; Liu et al., 2020, 2024). Phytoremediation utilizes plants to absorb, accumulate, and transform contaminants into less harmful forms (Ansari et al., 2020) which not only restores contaminated ecosystems, but also enables resource recovery. Phytoremediation encompasses several strategies, including phytostabilization, rhizofiltration, phytoextraction, phytodegradation, and phytovolatilization. Among these, phytostabilization and phytoextraction are the most widely used methods. In phytostabilization, plants reduce the mobility and bioavailability of pollutants through mechanisms, such as adsorption, chelation, complex formation with root exudates, accumulation in root tissue, and immobilization in the rhizosphere zone (Liu et al., 2024; Sharma et al., 2023). Root exudates, such as amino acids, organic acids, enzymes, and polysaccharides, play a vital role in this strategy. They trap heavy metals in the root zone or enhance the concentration of some minerals that form complexes with heavy metals. Additionally, some exudates provide nutrients to rhizosphere microorganisms, promoting their growth and further enhancing the mobility of heavy metals in the environment (Barra Caracciolo & Terenzi, 2021; He et al., 2024; Zhu et al., 2024).

In phytoextraction, plants uptake contaminants from water and sediments through their roots and transport them to their aboveground tissues (Rulkens et al., 1998). This process involves metal-chelation, binding of metal to pectin in the cell wall, and interactions with the negative charge of plasma membrane. Additionally, heavy metals form stable complexes with metal-binding peptides such as phytochelatins and metallothionein, followed by sequestration in vacuoles or apoplast space (Sabir et al., 2015; Sarker et al., 2023; Sarwar et al., 2017). The specific mechanisms of phytoextraction vary depending on plant species and environmental conditions. The ideal plants for phytoextraction are characterized by rapid growth and extensive biomass structures, making this strategy one of the most efficient and promising approaches for heavy metal removal from

contaminated areas (Sarker et al., 2023; Shen et al., 2022; Suman et al., 2018).

Aquatic phytoremediation is an emerging technology that utilizes freshwater-adapted flowering plants, pteridophytes, and mosses in floating, submerged, and emergent forms to remove and degrade pollutants from sediment and water columns (Fletcher et al., 2020). The effectiveness of this approach depends on several factors, including physical and chemical properties of water, the physiological status of the plants, sediment geochemistry, plant genotype, and the nature of the pollutant (Prasad, 2006). The most effective macrophytes for phytoremediation are characterized by a wide ecological amplitude, rapid growth, nativeness, the ability to absorb and tolerate high concentrations of heavy metals, and the capacity to transport metals from roots to aboveground tissues (Ali et al., 2020; Cunningham & Ow, 1996; Eid et al., 2020). However, heavy metals can negatively impact macrophytes by reducing chlorophyll contents, photosynthetic efficiency, and overall growth. Macrophytes activate antioxidant enzymes and produce non-enzymatic antioxidant compounds that participate in heavy metal tolerance in these plants (Radić et al., 2010; Ansari et al., 2020). Common aquatic macrophytes used in phytoremediation technology include members of Ceratophyllaceae, Haloragaceae, Potamogetonaceae, Typhaceae, Polygonaceae, Onagraceae, Cyperaceae, Hydrocharitaceae, and Araceae families (Fletcher et al., 2020; Prasad, 2006). Beyond their role in phytoremediation, these aquatic macrophytes are valuable as raw material for biofuel production, medicinal application, and paper pulp manufacturing (Haroön, 2022).

The Nile River has 144 islands between Aswan and the Mediterranean Sea. The Nile Islands are regarded as the most fertile soil, a unique source of biodiversity and natural heritage, and a breathing area for its surrounding cities. The ecosystems of the Nile islands are threatened by several factors, including pollution from sewage, agricultural waste, and trash (Abdel-Satar et al., 2024; Esmail et al., 2023; Taha, 2014). Two main islands (Armant and Aqalta) in Luxor governorate are associated with severe pollution from agriculture runoff, tourism ships, sewage, and industrial and urban runoff. To our knowledge, macrophytes' pollution status and phytoremediation potential in these islands remain unexplored in scientific research. To evaluate the

phytoremediation potential of macrophytes in these two islands, we selected three emergent (*Setaria geminata*, *Persicaria senegalensis*, and *Ludwigia adscendens*) and two submerged macrophytes (*Ceratophyllum demersum* and *Myriophyllum spicatum*) for this purpose. Although some studies have demonstrated the phytoremediation potential of these macrophytes species for heavy metals in aquatic environment across Egypt, Ethiopia, India, China and Turkey (Fitamo & Leta, 2010; Ahmad et al., 2016; Kassaye et al., 2016; Abdelaal et al., 2021; Topaldemir et al., 2023), there is still a significant gap in understanding the seasonal variations of chlorophyll and antioxidant compounds in response to heavy metal phytoremediation in these plants. We hypothesized that the selected macrophytes can absorb and accumulate heavy metals (Fe, Cu, Mn, and Zn) in their tissue. The current study aimed to: (1) evaluate seasonal and spatial variations in the concentrations of selected heavy metals in water, sediments, and roots and shoots of selected macrophytes from two islands; (2) assess the phytoremediation potential of the studied macrophytes based on bioaccumulation and translocation factors; and (3) investigate the relationship between heavy metal concentrations and the behavior chlorophyll pigments and antioxidant compound (carotenoids, flavonoids and total phenol) in the studied plants.

2 Materials and Methods

2.1 Study Area

The study was conducted on two sedimentary islands located in the southern section of the River Nile in Luxor governorate, Egypt: Armant Island (inhabited) and Jazazirat Al-muz (uninhabited, known as Aqalata). Three sites were selected to represent both islands (Fig. 1). Site 1 (25° 36'.21"N; 32° 32'.27"E) and site 2 (25° 36'.17"N; 32° 32'.26"E) are located on Armant Island, while site 3 (25° 40'.52"N; 32° 37'.15"E) represents Aqalata island.

2.2 Sampling

This study was conducted from April 2022 to January 2023. Seasonal samples of water, sediments, and five macrophytes species (*Setaria geminata* (Forssk.) Veldkamp, *Ceratophyllum demersum* L.,



Fig. 1 Map of the investigated area showing the Armant and Aqalta (Jazirzat Elmuz) islands

Myriophyllum spicatum L., *Persicaria senegalensis* (Meisn.) Soják, and *Ludwigia adscendens* subsp. *diffusa* (Forssk.) P. H. Raven) were collected in triplicate from the three sites. Water samples were collected in plastic bottles from the water surface down to a depth of 30 cm. In situ measurements of water temperature, dissolved oxygen (DO), total dissolved solids (TDS), conductivity (EC), and pH values were taken using a portable pH and conductivity meter.

2.3 Heavy Metals in Water and Sediments

Water samples collected from the sites were acidified with concentrated HNO_3 , filtered using Whatman filters, and refrigerated for heavy metal analysis (Eid & Shaltout, 2014). Sediment samples were collected in airtight polyethylene bags to minimize oxidation, air-dried at room temperature, and sieved through a 2 mm sieves to remove coarse debris and stones. Sediment samples were digested, followed by microwave-assisted acid digestion, as described in the United

States Environmental Protection Agency method 3051 (USEPA, 2007). Briefly, 0.25 g of dried sediment was accurately weighed and dissolved in 10 ml of concentrated nitric acid (HNO_3) and digested using a Milestone ETHOS UP microwave digestion system (Milestone Srl, Sorisole, Italy) under controlled conditions according to the manufacturer's protocols. The digested solution was diluted with deionized water, filtered, and adjusted to a final volume of 50 ml with deionized water. The concentrations of heavy metals (Fe, Mn, Cu, and Zn) in both water and sediments samples were measured using the atomic absorption spectrophotometer (Thermo Scientific iCE 3500, USA).

2.4 Plant Analysis

Plant samples of the available species were collected, washed on-site to remove debris and epiphytes, and transported to the laboratory. In the lab, the plants were thoroughly rinsed with running followed by

distilled water. Each plant was separated into shoots (aerial parts) and roots (underground part), oven-dried at 70 °C until constant weight was achieved, and ground into fine powder using a metal-free plastic mill. For heavy metal analysis, one gram of each plant sample was digested in a 20 ml mixture of HNO₃: H₂SO₄: HClO₄ (5: 1: 1, v/v/v) until a transparent solution was obtained. The digested mixture was then filtered and diluted to a final volume of 25 ml with double deionized water (Eid et al., 2020). Heavy metal concentrations were measured using an atomic absorption spectrophotometer (Thermo Scientific iCE 3500, USA) as described earlier.

Bioaccumulation factor (BF) and translocation factor (TF) were calculated to evaluate the efficiency of heavy metal accumulation in roots and shoots, respectively. These parameters were calculated according to the formulae (Eid et al., 2020):

$$BAF = C_{\text{root}} / C_{\text{sediment/water}}$$

where C_{root} , C_{sediment} , and C_{water} are heavy metal concentrations in roots, sediment, or water, respectively.

$TF = C_{\text{shoot}} / C_{\text{root}}$ C_{shoot} refers to metal concentration in the shoot or aerial parts.

2.5 Biochemical Parameters

For biochemical analyses, three samples from the collected plants for each species were used. The following procedure was used to determine chlorophyll and carotenoid contents. A 0.1 g sample of plant tissue was extracted in 10 ml of 80% acetone and centrifuged at 5000 rpm for 15 min. The absorbance of the supernatant was measured at 645 and 663 nm for Chl *a* and *b*, and at 480 and 510 nm for carotenoids. Calculations were performed using the method described by MacLachlan and Zalik (1963).

The total phenol was determined using the Bray and Thorpe (1954) method. A 0.25 g shoot sample was extracted in 25 ml of 80% ethanol and centrifuged at 5000 rpm for 10 min. To 1 ml of supernatant, 1 ml of Folin-Ciocalteu reagent (FCR) and 2 ml of 15% sodium carbonate were added and the absorbance was measured at 650 nm.

Also, the total flavonoids were quantified using the method described by Miliauskas et al. (2004). 2.5 ml of AlCl₃ in 90% ethanol (20.0 mg/ml) were added to 1 ml of the extract. The mixtures were incubated for

40 min. at room temperature, and the absorbance was measured at 415 nm.

All absorbances were measured using a Jenway 7315 spectrophotometer (Jenway Scientific Instrumental Company, UK).

2.6 Data Analysis

All data were presented as means of three replicates with standard error. Levene's test was used to assess the homogeneity of variances. A two-way analysis of variance ANOVA was used to evaluate the effects of site, season, and their interactions on the physicochemical properties of water, and heavy metal concentrations in water and sediments. Additionally, a three-way ANOVA was used to examine the effects of site, season, species, and their interactions on heavy metal concentrations in plant tissues, and biochemical parameters of the studied macrophytes. Tukey HSD tests ($P < 0.05$) were applied to analyze the significant differences in the studied parameters across sites and seasons. Principal component analysis (PCA) was performed to investigate the correlations between studied parameters for each plant species. All statistical analyses were performed using SPSS 16.0 statistical software (SPSS Inc. version 16.0, IBM Corp., Armonk, NY). Values denoted by the same letter were considered not significantly different.

3 Results

3.1 Physicochemical Parameters of Water

Two-way ANOVA revealed that both season and site significantly influenced all water physicochemical parameters (temperature, pH, electrical conductivity [EC], total dissolved salts [TDS], and dissolved oxygen [DO]). However, their interaction had significant influences on EC, TDS, and DO only (Table 1). Regarding seasons, the highest pH, EC, and TDS values in all sites were recorded in autumn, while the maximum values of temperature and DO were recorded in summer and winter, respectively. Among the sites, Site 2 recorded the highest maximum temperature compared to the other sites. Site 1 exhibited the highest EC and TDS values during spring, while Site 3 had the highest DO and pH values in winter and autumn, respectively (Table 2).

Table 1 Two-way ANOVA showing F and the significant levels of the effect of site, season and their interaction on water physicochemical properties in the studied sites

Parameters	Season	Sites	Season*Sites
Water temperature	574.3***	3.7*	1.35 ^{ns}
pH	3.85*	0.29 ^{ns}	1.43 ^{ns}
EC	20.4***	16.3***	16.2***
TDS	235.2***	191.8***	192.8***
DO	59.2***	6.1***	4.1***

ns: not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3.2 Sediment and Water Heavy Metals

Heavy metal concentrations (Fe, Mn, Cu, and Zn) in sediments varied significantly across the three studied sites. The two-way ANOVA showed a significant effect of season on Cu and Zn concentrations, but the interaction between sites and seasons significantly influenced Cu concentrations only (Table 3). While Fe concentrations remained relatively constant in all studied sites and seasons, the highest concentrations of Cu and Zn were recorded in site 2, and of Mn in site 3 during summer (Fig. 2). In water, ANOVA showed significant influence of season on all studied heavy metals, and non-significant effect of their interaction with site on all studied heavy metals except Cu, and significant effect of site on Zn and Cu concentrations (Table 4). The highest concentrations of Fe and Mn were recorded in site 3 and site 1 in autumn, respectively. Site 2 had the highest concentrations of Zn in summer, and site 3 had the highest level of Cu during spring (Fig. 2).

Table 2 Water physicochemical properties of the three studied sites during different seasons. Values represent means of three replicates $\pm$ standard error

Seasons	Site	Temperature	pH	EC (μ S/cm)	TDS	DO
Winter	I	16.6 $\pm$ 0.33 d	7.59 $\pm$ 0.1a	260.6 $\pm$ 1.7b	130.3 $\pm$ 0.87bcd	8.4 $\pm$ 0.18ab
	II	17 $\pm$ 0.51 d	7.69 $\pm$ 0.06a	260.6 $\pm$ 4.2b	130.3 $\pm$ 2.1bcd	8.7 $\pm$ 0.17a
	III	16.3 $\pm$ 0.33 d	8.02 $\pm$ 0.03a	269.3 $\pm$ 1.8abc	134.6 $\pm$ 0.92abc	8.7 $\pm$ 0.38a
Spring	I	21 $\pm$ 0.0b	8.06 $\pm$ 0.13a	287 $\pm$ 2.5a	143.5 $\pm$ 0.5a	5.1 $\pm$ 0.08 d
	II	21 $\pm$ 0.0b	7.79 $\pm$ 0.34a	252 $\pm$ 1.6cd	126.2 $\pm$ 0.8cd	6.4 $\pm$ 0.4c
	III	21 $\pm$ 0.0b	7.82 $\pm$ 0.1a	225 $\pm$ 1.4e	112.5 $\pm$ 1.2e	6.8 $\pm$ 0.14c
Summer	I	26 $\pm$ 0.0a	7.9 $\pm$ 0.0a	253 $\pm$ 1.8cd	126.5 $\pm$ 2.5cd	6.8 $\pm$ 0.12c
	II	26 $\pm$ 0.0a	7.97 $\pm$ 0.03a	241.6 $\pm$ 1.3 de	121.5 $\pm$ 1.1 de	7.4 $\pm$ 0.1bc
	III	26 $\pm$ 0.0a	7.8 $\pm$ 0.0a	247 $\pm$ 1.0 d	123.5 $\pm$ 1.4 d	6.5 $\pm$ 0.13c
Autumn	I	20 $\pm$ 0.6bc	8 $\pm$ 0.13a	271.3 $\pm$ 2.8abc	135.6 $\pm$ 2.4abc	6.9 $\pm$ 0.47c
	II	20 $\pm$ 0.0bc	8.1 $\pm$ 0.13a	274.3 $\pm$ 11.9ab	137.2 $\pm$ 6ab	7.03 $\pm$ 0.06c
	III	19 $\pm$ 0.0c	8.17 $\pm$ 0.03a	267.6 $\pm$ 2.6abc	133.8 $\pm$ 1.3abc	7.03 $\pm$ 0.21c

Table 3 Two-way ANOVA showing F and the significant levels of the effect of site, season and their interactions on heavy metal concentrations in sediments

Parameters	Season	Sites	Season * Sites
Fe	507 ^{ns}	8.77**	0.259 ^{ns}
Mn	0.500 ^{ns}	9.21**	1.80 ^{ns}
Cu	30.69***	51.36***	32.39***
Zn	8.54***	7.81**	1.23 ^{ns}

ns: not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3.3 Plant Heavy Metals

The results of three-way ANOVA showed that sites, species, seasons, and their interactions had significant effects on all the studied heavy metals (Table 5). *P. senegalensis* roots accumulated higher Fe and Mn concentrations (2066 and 819 mg kg⁻¹, respectively) than other species in the summer season, while their lowest concentrations (31.2 and 44.8 mg kg⁻¹, respectively) were noticed in *S. geminata* shoots in autumn and summer (Figs. 3 and 4). In spring, the highest concentrations of Cu and Zn (36.2 and 32.3 mg kg⁻¹, respectively) were recorded in *S. geminata* roots, while their lowest concentrations (1.36 and 3.1 mg kg⁻¹, respectively) were recorded in *S. geminata* shoots and *L. adscendens* roots in spring and autumn respectively (Figs. 5 and 6). The heavy metal concentrations in the studied species were arranged in the order of Fe > Mn > Cu > Zn; their levels could be arranged based on the pattern: *S. geminata* > *P. senegalensis* > *L. adscendens* > *C. demersum* > *M. spicatum*, and they accumulated higher levels of all heavy metals in root than in shoot tissues, except for Zn in *P. senegalensis* and *L. adscendens*.

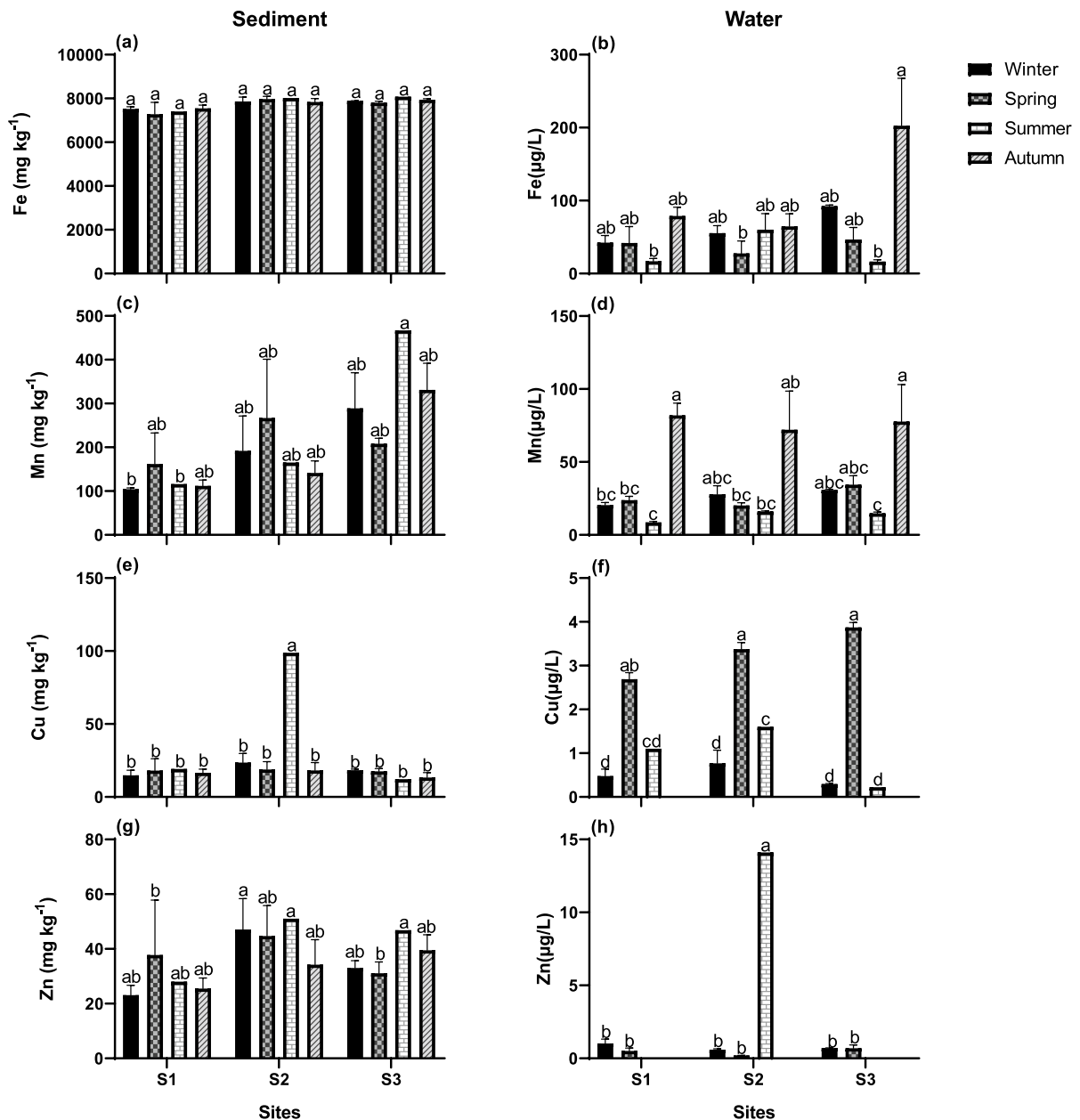


Fig. 2 Heavy metal concentrations in sediments; (a) Fe, (c) Mn, (e) Cu, and (g) Zn, and in water; (b) Fe, (d) Mn, (f) Cu, and (h) Zn from the three selected sites during different sea-

sons. Values represent means of three replicates $\pm$ standard error. Different letters indicated significant differences among seasons and sites (Tukey's HSD, $P < 0.05$)

3.4 Bioaccumulation and Translocation Factors

The three studied emergent species (*S. geminata*, *P. senegalensis*, and *L. adscendens*) had bioaccumulation factors (BFs) lower than one for Fe, Cu, and Zn, but not for Mn (3.1, 4.3, and 3.6, respectively).

Also, the three species had translocation factors (TF) lower than one except for Zn in *P. senegalensis* and *L. adscendens*, and these values showed the sequence $\text{Zn} > \text{Cu} > \text{Mn} > \text{Fe}$. On the other hand, submerged macrophytes (*C. demersum* and *M. spicatum*) showed remarkably high BF values for all studied heavy

Table 4 Two-way ANOVA showing F and the significant levels of the effect of site, season and their interaction on heavy metal concentrations in water

Parameters	Season	Sites	Season*Sites
Fe	4.03*	2.2 ^{ns}	1.69 ^{ns}
Mn	19.7***	0.381 ^{ns}	0.224 ^{ns}
Cu	252.7***	8.5**	12.3***
Zn	3.3***	4.3*	1.7 ^{ns}

ns: not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

metals. These BF_s are arranged in the order Zn > Mn > Fe > Cu for *C. demersum* and as Cu > Zn > Mn > Fe for *M. spicatum* (Table 6).

3.5 Biochemical Parameters

Three-way ANOVA confirmed significant effects of site, season, species, and their interactions on photosynthetic pigments, except for carotenoids, which were not significantly influenced by season or the interaction of site, season, and species (Table 5). For all pigments, the maximum pigment levels were observed in spring in *S. geminata* and *L. adscendens* at site 2, in *C. demersum* and *M. spicatum* at site 1, and in winter in *P. senegalensis* at site 1. Whereas their minimum pigment values were recorded in spring at site 3 for *S. geminata* and in winter at site 2 and site 3 for *C. demersum* and *M. spicatum* respectively. Also, in winter, *P. senegalensis* had the lowest value at site 1, and *L. adscendens* accumulated the minimum pigment contents in summer season at site 2 (Fig. S1). The three-way ANOVA results showed that flavonoids and total phenolics varied significantly within sites, seasons, species, the interaction between

seasons and species, and the interaction between sites and species (Table 5). Maximum total phenolics were detected during winter in *L. adscendens* and *C. demersum* at site 2 and in *P. senegalensis* at site 1. *S. geminata* and *M. spicatum* showed significant promotions of phenolic biosynthesis during summer and spring, respectively. In winter, the highest flavonoid contents were at site 2 in *S. geminata* and *L. adscendens* and at site 3 in *M. spicatum*. The highest flavonoid contents were recorded in summer at site 1 and in autumn at site 3 in *P. senegalensis* and *C. demersum*, respectively (Fig. S2 and S3).

3.6 Principal Component Analysis

Principal component analysis showed PC1 described 59.6%, 95%, 79.4%, 98.5, and 65.2 of the variances for the studied parameters for *S. geminata*, *C. demersum*, *M. spicatum*, *P. senegalensis*, and *L. adscendens*, respectively. For the same preceding arrangement, the second component (PC2) was described as 31%, 3.4%, 18.9%, 1.4%, and 24.4%. For *S. geminata*, three groups were predicted from this analysis: Fe, Mn, and Zn in shoots, Fe and Mn in water, Cu and Zn in sediments, and carotenoids and flavonoids formed the first group; Cu in shoots, Cu and Mn in roots, Fe and Mn in sediments, Cu and Zn in water, chlorophyll pigments (Chl *a* and Chl *b*), and total phenolics constructed the second group; and Fe in roots formed the third group. *C. demersum* also showed three groups from this analysis: all heavy metals in shoots (Fe, Mn, Cu, and Zn), Chl *a*, Chl *b*, and carotenoids and Cu in water represented the first group; phenolics, flavonoids, Mn and Fe in water formed the second group, while Zn in water formed the third group. For *M. spicatum*, three groups were also

Table 5 Three-way ANOVA showing F and the significant levels of the effect of site, species, season and their interactions on heavy metal concentrations, Chl *a*, Chl *b*, carotenoids, phenol, and flavonoids of the studied plants

Variables	Fe	Mn	Cu	Zn	Chl <i>a</i>	Chl <i>b</i>	Caro	Phenol	Flav
Site	52.55***	47.46***	23.77***	6.81**	4.9*	7.9**	10.3***	11.03***	48.4***
Season	40.84***	39.25***	7.68***	518.8***	8.2***	11.7***	0.34 ^{ns}	51.8***	95.2***
Species	534.47***	2.24***	14.37***	83.32***	337.1***	115.3***	186.9***	909.3***	969.02***
Season * Site	8.212***	5.30***	3.71**	17.23***	10.3***	30.5***	9.1***	1.62 ^{ns}	1.88 ^{ns}
Season * Species	34.15***	14.98***	14.53***	117.36***	4.5***	10.5***	7.8***	44.7***	108.1***
Site * Species	83.51***	11.37***	28.55***	23.41***	10.3***	12.6***	9.9***	22.01***	13.3***
Season * Site * Species	36.43***	14.31***	14.32***	7.12***	0.056**	0.00	1.3 ^{ns}	0.06 ^{ns}	0.893 ^{ns}

ns: not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

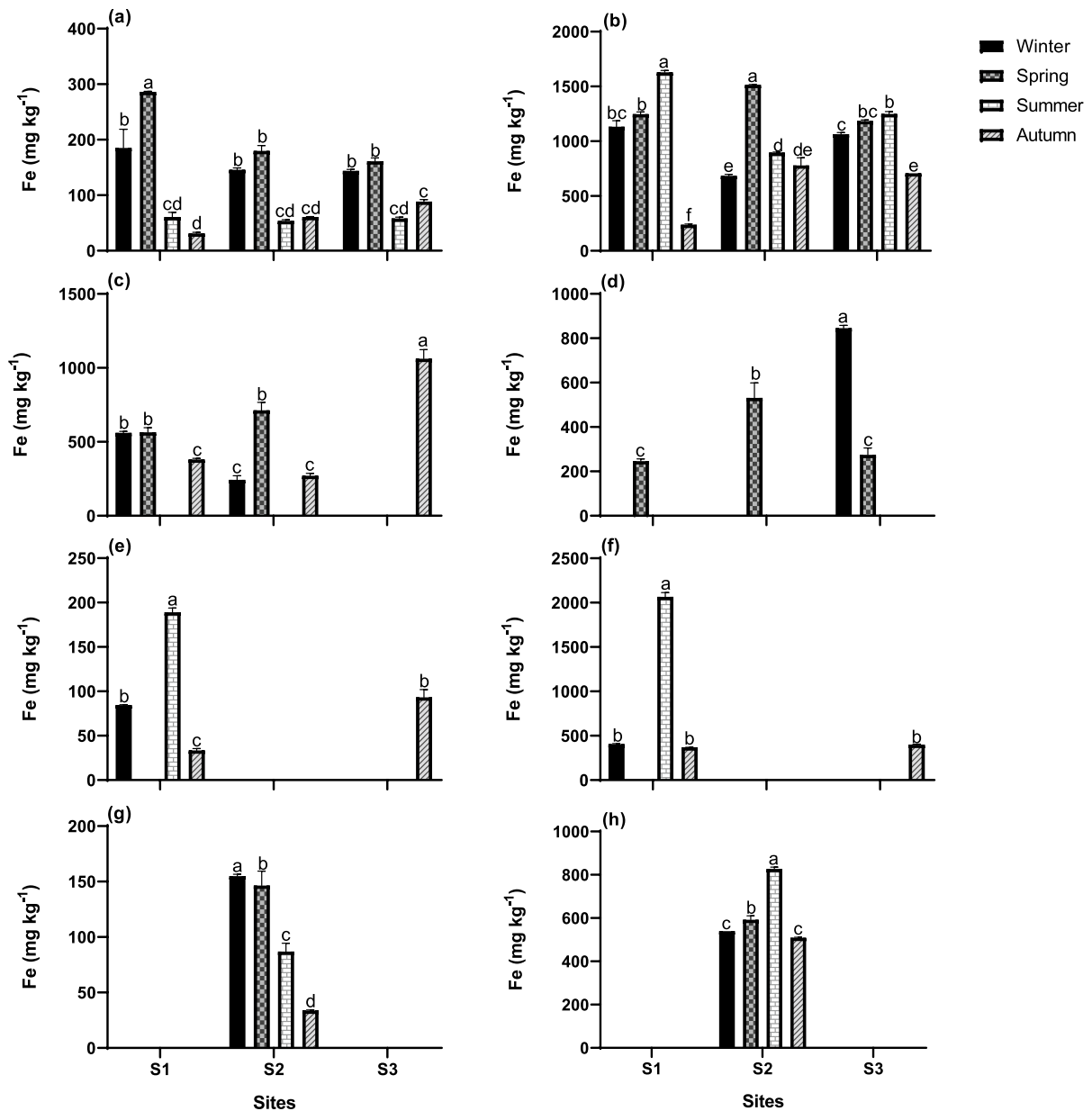


Fig. 3 Fe concentrations in the studied species (a) *Setaria geminata* shoot, (b) *S. geminata* root, (c) *Ceratophyllum demersum*, (d) *Myriophyllum spicatum*, (e) *Perscaria senegalensis* shoot, (f) *P. senegalensis* root, (g) *Ludwigia adscendens*

shoot, and (h) *L. adscendens* root from the three selected sites during different seasons. Data are means of three replicates $\pm$ SD. Different letters indicated significant differences among seasons and sites (Tukey's HSD, $P < 0.05$)

observed: chlorophylls, carotenoids, total phenolics, and Cu in water represented the first group; All heavy metals in shoots, Zn and Mn in water, Fe in sediments, and flavonoids constructed the second group; while Fe in water, Zn and Cu in sediments constructed the third group. Three groups were also visualized in *P.*

senegalensis: Cu and Zn in shoots, Fe and Mn in water, Fe in sediments and phenolics formed the first group; Fe and Mn in shoots, Zn and Cu in water, Mn and Cu in sediments, chlorophylls, carotenoids, and flavonoids constructed the second group, while Zn in sediments represents the third group. Three groups were

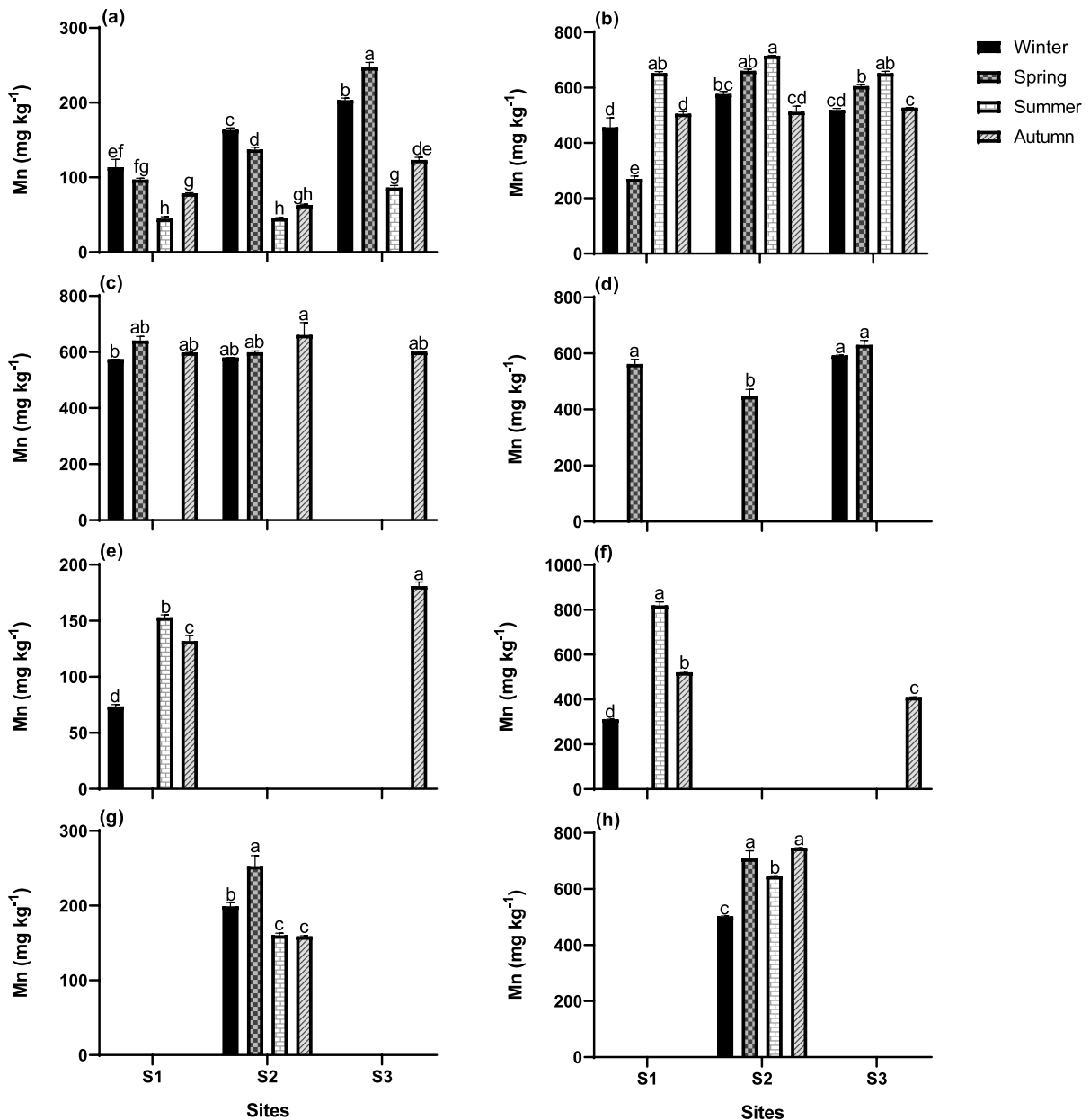


Fig. 4 Mn concentrations in the studied species (a) *Setaria geminata* shoot, (b) *Setaria geminata* root, (c) *Ceratophyllum demersum*, (d) *Myriophyllum spicatum*, (e) *Persicaria senegalensis* shoot, (f) *Persicaria senegalensis* root, (g) *Ludwigia adscendens* shoot, and (h) *Ludwigia adscendens* root from the

three selected sites during different seasons. Values represent means of three replicates $\pm$ standard error. Different letters indicated significant differences among seasons and sites (Tukey's HSD, $P < 0.05$)

also noticed from *L. adscendens*: Most heavy metals in shoots (Fe, Zn, and Cu), phenolics and flavonoids, Zn and Cu in sediments and Zn in roots and water constructed the first group; Chlorophylls, most heavy

metals in roots (Fe, Mn, and Cu), Fe in water, Mn in shoots and sediments constructed the second group; while carotenoids, Fe in sediments and Mn in water formed the third group (Fig. 7).

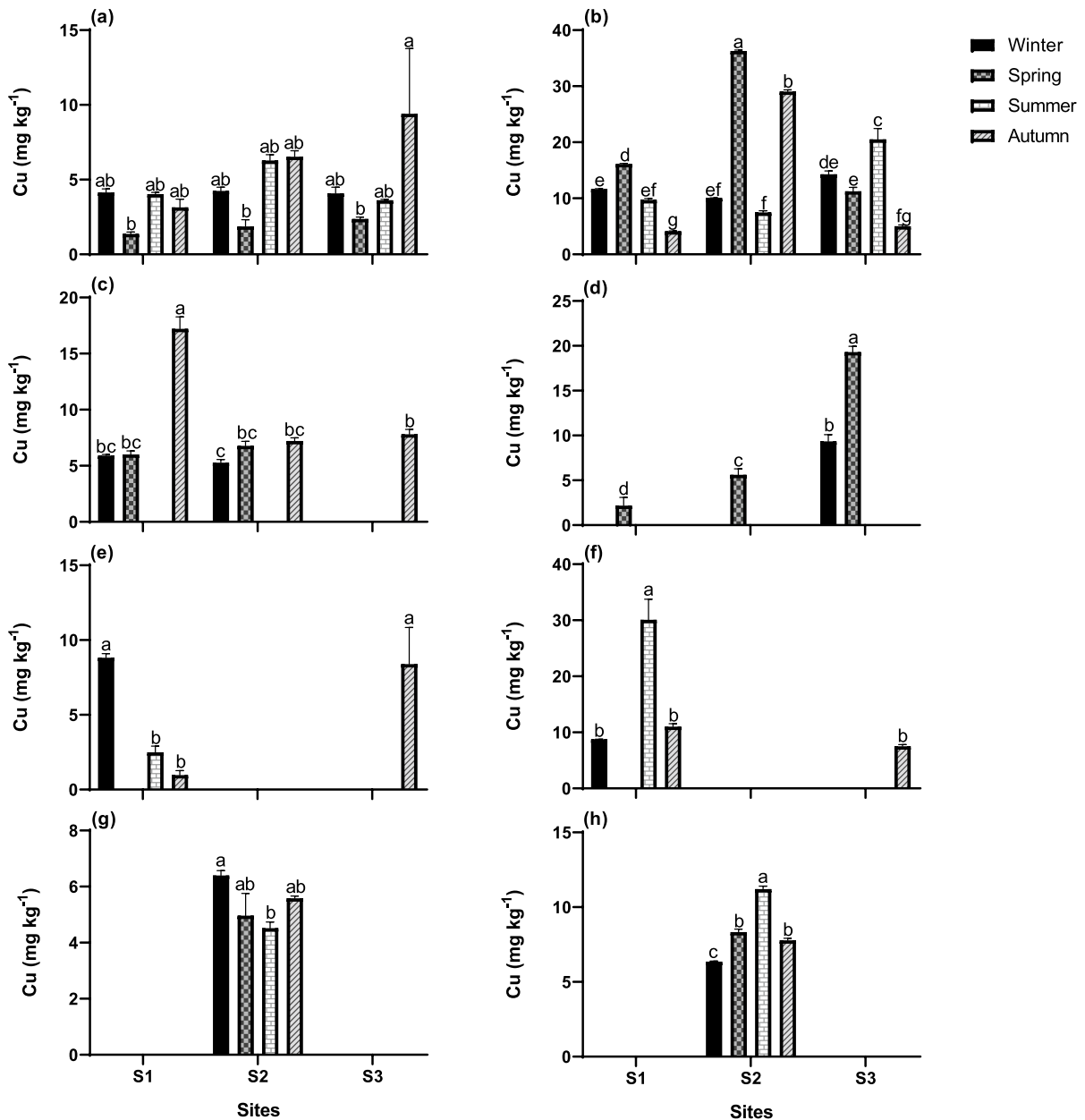


Fig. 5 Cu concentrations in the studied species (a) *Setaria geminata* shoot, (b) *Setaria geminata* root, (c) *Ceratophyllum demersum*, (d) *Myriophyllum spicatum*, (e) *Persicaria senegalensis* shoot, (f) *Persicaria senegalensis* root, (g) *L. adscendens* shoot, and (h) *Ludwigia adscendens* root from the three

selected sites during different seasons. Values represent means of three replicates $\pm$ standard error. Different letters indicated significant differences among seasons and sites (Tukey's HSD, $P < 0.05$)

4 Discussion

Exploring the potential for heavy metal accumulation in aquatic macrophytes is crucial for environmental impact assessment. Phytoremediation efficacy of

macrophytes depends on factors such as plant species, research area, seasonality, plant organ, water pH, light, and pollutant type (Abdelaal et al., 2021; Ansari et al., 2014; Farahat et al., 2021; Fawzy et al., 2012). Floating and emergent hydrophytes primarily rely on

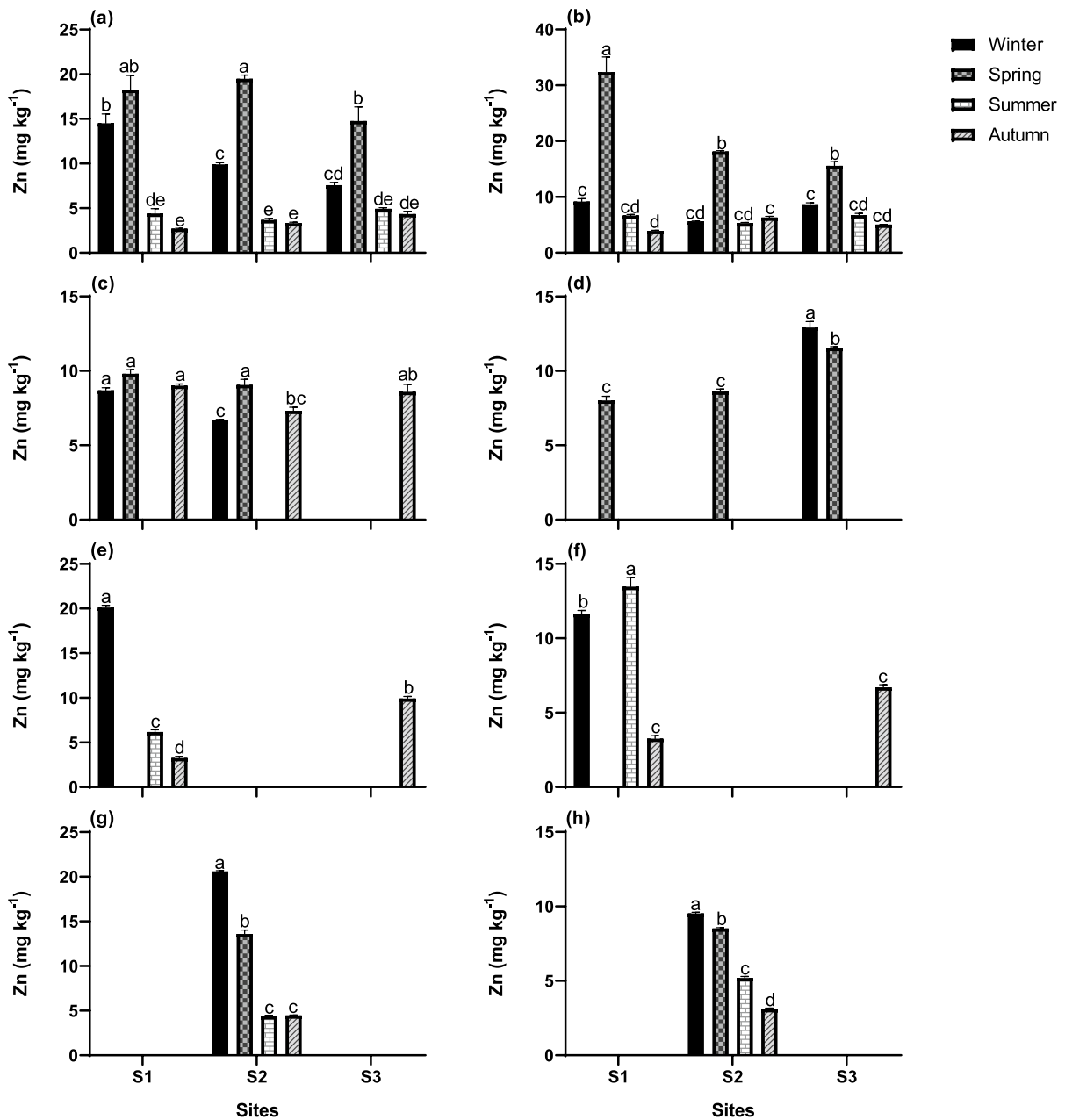


Fig. 6 Zn concentrations in the studied species (a) *Setaria geminata* shoot, (b) *Setaria geminata* root, (c) *C. demersum*, (d) *Myriophyllum spicatum*, (e) *Persicaria senegalensis* shoot, (f) *Persicaria senegalensis* root, (g) *Ludwigia adscendens* shoot, and (h) *Ludwigia adscendens* root from the three

selected sites during different seasons. Values represent means of three replicates $\pm$ standard error. Different letters indicated significant differences among seasons and sites (Tukey's HSD, $P < 0.05$)

their root systems to remove heavy metals from sediments or water columns, whereas submerged macrophyte utilize their stems for contaminants uptake from the water column (Dhote & Dixit, 2009; Fletcher

et al., 2020). Heavy metals include both essential and nonessential elements. Iron (Fe), one of these essential micronutrients, is essential for chlorophyll synthesis, DNA production, and hormone regulation.

Table 6 Bioaccumulation factors (BF) from sediments to roots in *Setaria geminata*, *Persicaria senegalensis*, *Ludwigia adscendens*, and from water to shoots in *Ceratophyllum demersum* and *Myriophyllum spicatum*. Translocation factor (TF) from the roots to shoots in *Setaria geminata*, *Persicaria senegalensis*, *Ludwigia adscendens*

sum and *Myriophyllum spicatum*. Translocation factor (TF) from the roots to shoots in *Setaria geminata*, *Persicaria senegalensis*, *Ludwigia adscendens*

Heavy metals	Fe		Mn		Cu		Zn	
Species	BF	TF	BF	TF	BF	TF	BF	TF
<i>S. geminata</i>	0.13 ± 0.02	0.12 ± 0.02	3.1 ± 0.29	0.22 ± 0.05	0.82 ± 0.1	0.35 ± 0.1	0.29 ± 0.1	0.91 ± 0.16
<i>C. demersum</i>	10739 ± 4175		20219.5 ± 6255.3		5648.9 ± 3528.7		21409.4 ± 11527	
<i>M. spicatum</i>	9373 ± 227.6		20485.2 ± 1231		31880.6 ± 14598.7		21906.9 ± 5138	
<i>P. senegalensis</i>	0.12 ± 0.07	0.15 ± 0.03	4.3 ± 2.40	0.25 ± 0.04	0.92 ± 0.32	0.51 ± 0.26	0.39 ± 0.1	1.07 ± 0.36
<i>L. adscendens</i>	0.07 ± 0.00	0.17 ± 0.05	3.6 ± 0.62	0.29 ± 0.04	0.313 ± 0.07	0.65 ± 0.13	0.14 ± 0.02	1.4 ± 0.27

Values are expressed as mean ± SE

However, excessive Fe concentrations are potentially toxic to plants (Coelho et al., 2023; Rout & Sahoo, 2015). In the present study, Fe concentrations in water and sediments at the three sites were below both WHO/FAO (2007) irrigation water guidelines (5 mg/l) and EPA (2006) benchmarks for freshwater sediment (20 mg/kg). However, concentrations in submerged macrophytes and emergent plant roots exceed the upper limit of 500 mg/kg, as defined by Kabata-Pendias (2011). Similar findings were reported by Harguinteguy et al. (2016) in the Ctalamochita River, Argentina, where Fe concentrations in water were within the permissible irrigation limits, but sediments and submerged macrophytes (*Myriophyllum aquaticum* and *Potamogeton pusillus*) Fe levels exceeded guideline values for sediments and plants. Comparable Fe accumulation patterns were observed in other hydrophytes (*Eichhirnia crassipes*, *Pistia stratiotes* and *Jussiaea repens*) in floating island system near riversides in China (Zhao et al., 2012).

Interestingly, the maximum Fe concentration was recorded in the roots of the studied species during summer, the high root-zone temperature enhances iron and nutrient uptake (Baghour et al., 2016; Falah et al., 2005). A number of studies had been published about the presence of iron plaque around the roots of many hydrophytes (Eid & Shaltout, 2014; Farahat et al., 2021; Wang & Peverly, 1996). These findings suggest that iron accumulation in the root system may be attributed to iron aggregation around the root surface of the studied macrophytes, together with high root temperatures during the summer. Another interesting finding is that the submerged hydrophytes

C. demersum and *M. spicatum* have higher concentrations of Fe in their tissues than the emergent macrophytes' shoots (*S. geminata*, *P. senegalensis*, and *L. adscendens*). Many submerged macrophytes, such as *C. demersum* and *Rotala rotundifolia* (Buch.-Ham. ex Roxb.) Koehne exhibited the same heavy metal accumulation trend compared to the emergent hydrophyte *Bacopa monnieri* (L.) Wettst., as well as *C. demersum* and *M. spicatum* compared to *Phragmites australis* (Cav.) Trin. ex Steud. (Dogan et al., 2015; Fawzy et al., 2012). The submerged macrophytes' efficiency may be attributed to their high surface area to biomass ratio (Xing et al., 2013).

Manganese (Mn) is an essential micronutrient for plant development and growth due to its vital role in photosynthesis, respiration, antioxidant enzymes, hormone signaling, and pathogen defense. Manganese is a cofactor in the oxygen-evolving complex, MnSOD enzymes, and isoprenoid biosynthesis (Alejandro et al., 2020). However, excessive Mn levels inhibit plant growth and development. The present study showed that Mn concentrations in the water from all three sites were below the WHO acceptable limit for irrigation water (200 µg/L), and Mn levels in the sediment are within the EPA's safe limit (400 µg/g) except for site 3 during the summer. However, Mn levels in submerged macrophytes and emergent plant roots exceed the maximum limit of 400 mg/kg established by Kabata-Pendias (2011). Similarly, Mn concentrations in water and macrophytes (*Echinochloa stagnina*, *Paspalidium geminatum* and *Nymphaea nouchalli*) were below acceptable limits in Ethiopian lakes (Koka, Ziway, and Awassa), but its

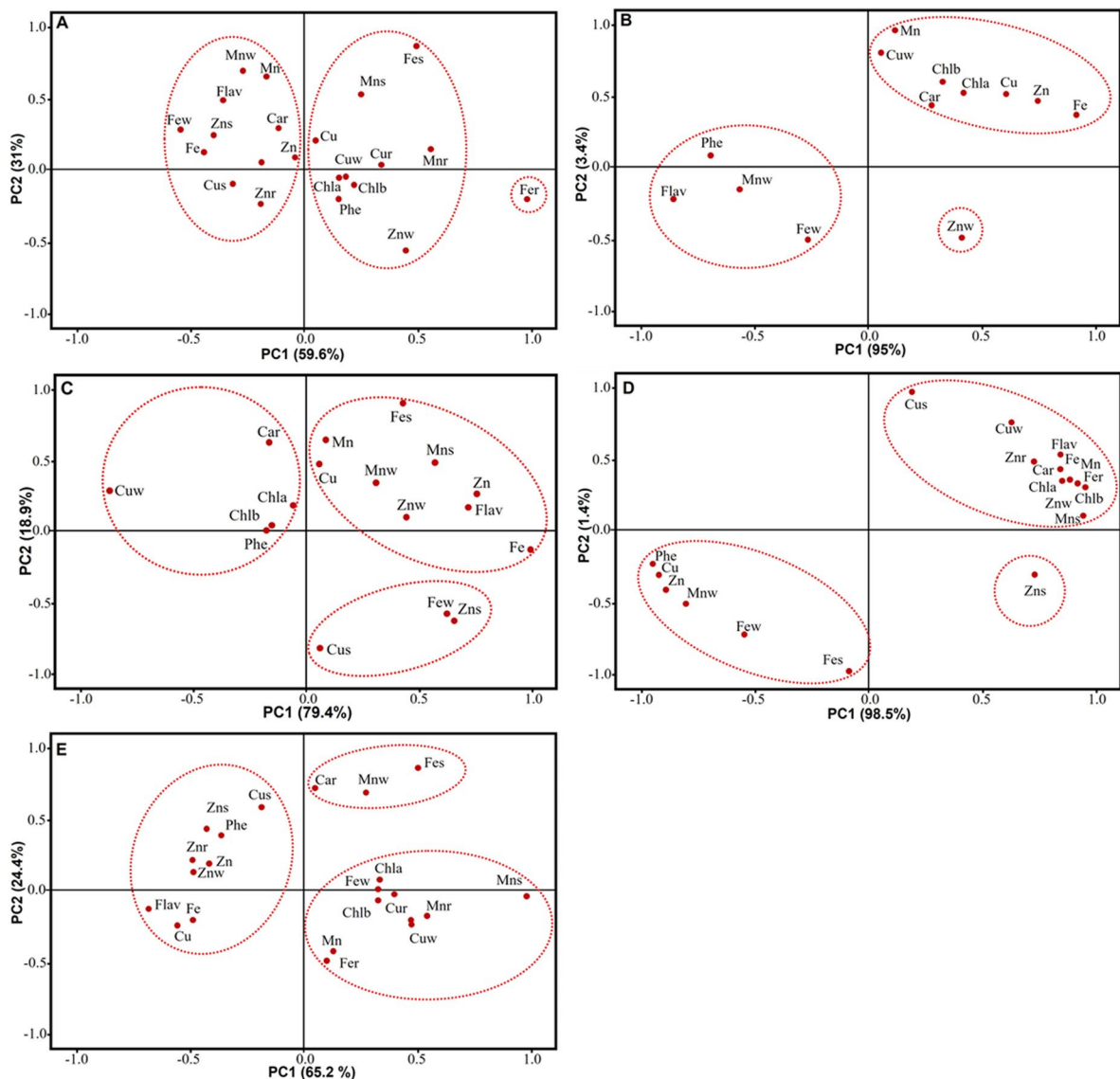


Fig. 7 Biplot of Principal components 1 and 2 in the studied species (**A:** *Setaria geminata*, **B:** *Ceratophyllum demersum*, **C:** *Myriophyllum spicatum*, **D:** *Persicaria senegalensis* and **E:** *Ludwigia adscendens* from the three selected sites during different seasons. Fe: Fe in the shoot, Mn: Mn in the shoot, Cu: Cu in the shoot, Zn: Zn in the shoot, Fer: Fe in the root, Mnr:

Mn in the root, Cur: Cu in the root, Few: Fe in water, Mnr: Mn in water, Cuw: Cu in water, Znw: Zn in water, Fes, Fe in sediments, Mns: Mn in sediments, Cus: Cu in sediments, Zns: Zn in sediments, Chl a: chlorophyll a, Chl b: chlorophyll b, Car: carotenoids, Flav: Flavonoids; Phe: total phenol

concentrations in sediments surpassed the permitted limits at some sites (Kassaye et al., 2016). Also, Sojitra et al. (2024) reported that Mn concentrations in sediments and plants (*Paspallidium geminatum* and *Typha angustata*) of the Uben River in India exceeded the permitted limits. Even many anthropogenic sources of manganese exist, such as mining, industrial

wastes, fertilizers, fungicides, and antiknock compounds in petrol (Gerber et al., 2002; Huang et al., 2021), considerable amounts of Mn in sediments at site 3 during the summer may be attributed to wastewater and agricultural discharges from nearby settlements and farmland, and the elevated Mn concentration in the water at the three sites during autumn

could attributed to fall turnover. Mn concentrations increased remarkably during summer in *S. geminata* roots, and in *P. senegalensis* shoots and roots. But during spring, it increased in *S. geminata* shoot, and in *C. demersum*, *M. spicatum*, and *L. adscendens* shoots and roots. These increases may be due to dissolved oxygen depletion during both seasons and low pH levels in the summer. It is well-known that Mn^{2+} is the available form of manganese for plants, and this Mn species is the dominating form in low pH and anoxic conditions (Huang et al., 2021; Johansson, 2005).

Copper toxicity is an environmental pollutant that deleteriously impacts chlorophyll synthesis, photosynthesis, electron transport system, and plant development and growth (Hossain et al., 2020; Li et al., 2023). The Cu concentrations at the three sites were within the WHO/FAO (2007) limit for irrigation water (0.2 mg/L). The results suggest that Cu increase may result from Cu release under low pH in sites 2 and 3 during spring and under elevated temperature at site 2 during summer (Hong et al., 2010; Li et al., 2013). Site 2 had the highest Cu concentrations in sediment during the summer, exceeding the EPA (2006) guideline of (31.6 $\mu\text{g/g}$). This could be due to the extensive agricultural drainage from nearby corn farms (Fawzy et al., 2012). The Cu concentrations in the examined macrophytes varied according to plant species and tissues. The Cu concentrations in *S. geminata* roots in spring at site 2 and *P. senegalensis* roots in summer at site 1 exceeded Alloway's (2012) safe range for Cu in plants (4 to 20 mg/kg). This behavior may respond to considerable amounts of soluble copper, such as free cupric ions, in water at the same sites and seasons. Globally, Martinez and Shu-Nyamboli (2011) reported that Cu concentrations exceeded the permissible limits in sediments and macrophytes (*Elodea*, *Potamogeton*, and *Fontinalis*) at some sites along the Gallinas River, USA. In contrast, Cu concentrations were within the safe limit in water and macrophytes (*Paspalidium geminatum* and *Phragmites karka*) in Lake Koka, Ethiopia (Kassaye et al., 2016).

Zinc is a trace element required for plant growth, and it is crucial for ion homeostasis, enzyme activity, and plant physiological and metabolic processes. However, zinc toxicity disrupts other nutrient absorption, and high zinc concentrations decrease photosynthetic activity, gas exchange, and plant development

(Bankaji et al., 2019; Chakraborty & Mishra, 2020; Hamzah Saleem et al., 2022). Zn concentrations in water and sediments of the three locations were within the permissible limits (2 mg/L for irrigation water and 121 mg/kg for sediments), according to WHO/FAO (2007) and EPA (2006) Benchmarks, respectively. Also, Zn concentrations in the studied species were within the safe concentrations in plants (30 to 100 $\mu\text{g/g}$ dry weight). Similarly, Zn concentrations in water and macrophytes remained within permissible limits, however, its levels in sediments exceeded permissible limits in the Hokersar Wetland, Kashmir Himalaya, India (Ahmad et al., 2016). Also, Zn level in water remained within acceptable limits in the Oued Fez River, Morocco, while its concentrations in macrophytes *Pistia stratiotes* exceeded the permissible levels in some sites (Chedadi et al., 2024). On the other hand, Fe and Zn had a mutual antagonistic relationship due to the similarity of their basic transporter proteins (IRT1 and IRT2) and divalent cations. High available iron concentrations inhibit zinc uptake in many plants (Rai et al., 2021; Ray et al., 2014; Saenchai et al., 2016; Sinclair & Krämer, 2012). This explains the low Zn levels in the investigated plants, given the high iron concentrations in both water and sediments.

We also used the translocation factor (TF) and the bioconcentration factor (BCF) to evaluate the phytoremediation capacity of the examined species. Based on the bioconcentration factor (BCF), plant species are classified into three categories: excluder or indicator ($BCF < 1$), accumulator ($1 < BCF < 10$), and hyperaccumulator ($BCF \geq 10$) plants (Lam et al., 2023). Perelman (1966) proposed a different scheme that classified plant species into five categories: very weak absorption ($0.001 < BAC < 0.01$), weak absorption ($0.01 < BAC < 0.1$), intermediate absorption ($0.1 < BAC < 1$), strong absorption ($1 < BAC < 10$), and intensive absorption ($10 < BAC < 100$) species. However, plant species are classified into two categories according to their translocation factor: effective translocation ($TF > 1$) and ineffective translocation ($TF < 1$) species (Mocek-Plóćiniak et al., 2023). Nouri et al. (2011) reported that species with a high BAF and low TF may be suitable for phytostabilization. Meanwhile, species with TF and BAF greater than 1 indicate they are suited for phytoextraction. In the current study, the BAF and TF values for *S. geminata*, *P. senegalensis*, and *L. adscendens* were less

than one for Fe, Cu, and Zn, except the TF of *P. senegalensis* and *L. adscendens* for Zn. While the BAFs were greater than one for these species for Mn. The limited translocation of Fe, Mn and Cu may result from their sequestration of these elements in the root cortex outside the endodermis layer, while the high translocation of Zn to shoots in *P. senegalensis* and *L. adscendens* likely reflects its essential role in metabolic activities of these plants (Klink, 2017; Marchand et al., 2014). Based on the preceding classification, these results suggest that the three species have intermediate absorption for Fe, Cu, and Zn, fall within the excluder category, and are suitable for bio-monitoring and phytostabilization of these elements. However, the same species had strong absorption and might be considered an accumulator for Mn. Heavy metals sequestration in plant roots may be caused by the expression of many vacuolar transporters in the root's cortex and epidermis layers, implying that this process occurs in outer cell layers (Giehl et al., 2023). In contrast, the submerged macrophytes *C. demersum* and *M. spicatum* had the highest BF for all metals, thus indicating their potential role as hyperaccumulators. These results may be attributed to the dissected leaves of both species, which increase their surface area. Submerged macrophytes absorb heavy metals through their entire body, particularly their leaves, via passive movement followed by active transport into the vacuoles (Dhir et al., 2009; Rahman & Hasegawa, 2011). Additionally, phytoremediation using macrophytes not only cleans up the contaminated sites but also contributes to carbon dioxide sequestration and mitigating climate change, reducing energy consumption, and enhancing local biodiversity and ecosystem health by improving water quality (Guidi Nissim et al., 2023; Pandey et al., 2022). Also, macrophytes promote biodiversity by increasing animal assemblage and biodiversity due to their role in providing stable habitats, shelter, and feeding sites for aquatic organisms (Thomaz & Cunha, 2010; Bendary et al., 2023). Therefore, macrophytes play an important role in the stability and functioning of aquatic Ecosystem (Manca et al., 2022).

PCA analyses were performed for the studied species. For *S. geminata*, PCA revealed that chlorophyll and total phenolic contents were associated with the positive X-axis. However, in shoots, flavonoids, carotenoids, Fe, Zn, and Mn correlated with the negative X-axis. In *C. demersum*, chlorophyll and heavy

metals in the shoot were shown to be associated with the positive X-axis, while antioxidant compounds were associated with the negative X-axis. However, in *L. adscendens*, most heavy metals in shoots and antioxidant compounds (phenolics and flavonoids) were grouped on the negative X-axis, and photosynthetic pigments and most heavy metals in water were grouped on the positive X-axis. For *M. spicatum*, the group of heavy metals in shoot, sediment, and water were negatively correlated with chlorophyll, carotenoids, and phenolic, but in *P. senegalensis*, chlorophyll, flavonoids, Fe, and Mn in shoots were grouped on the positive X-axis. In contrast, total phenolics, Cu, and Zn in shoots were observed on the opposite negative axis. These results suggest four differential strategies: (1) the phytoremediation potential of *C. demersum* due to the investment of energy in the maintenance of chlorophyll content rather than using it in the biosynthesis of antioxidant compounds; (2) the phytoremediation potential of *L. adscendens* concurrent with an investment of energy in antioxidant compound biosynthesis; and (3) the phytoremediation potential of *M. spicatum* adversely correlated with chlorophyll, carotenoids, and phenolic compounds. Also, *S. geminata* showed a similar trend in the relation between most heavy metals in the shoot with chlorophyll and phenolic contents. (4) The behavior of chlorophyll and antioxidant compounds in *P. senegalensis* based on the type of heavy metals. In the present study, non-enzymatic antioxidant responses differed between the studied plants. According to Bhaduri and Fulekar (2012), antioxidant enzymes play a significant role in phytoremediation; hence, more research is needed to determine their role in macrophytes' tolerance under heavy metal stress conditions.

Although phytoremediation offers an environmentally friendly approach to pollutant removal from the aquatic environment, it faces several limitations concerning time consumption, specificity, and contaminated biomass disposal. Phytoremediation is time consuming process, and it can take several years, especially in highly contaminated areas due to the slow growth of such plants. Also, the process has high specificity, i.e., it depends on plant species, contaminant type, site physiochemical properties, and plant-microbe interactions in rhizosphere area. On the other hand, proper disposal methods of plants with high contaminant levels at the end of the process

must be carefully selected. These challenges can be addressed through proper design, plant species selection, and advanced techniques (Aryal, 2024; Kafle et al., 2022). For example, in the present study, exploration of cosmopolitan species, such as *C. demersum* and *M. spicatum* is crucial for global application. Also, perennial species with creeping rhizomes, such as *S. geminata*, offer a continuous phytoremediation system and sufficient biomass for analysis.

Understanding phytoremediation mechanisms can aid genetic engineering to enhance plant resilience, growth rate, and pollutant tolerance and accumulation under varying climatic conditions. Also, investigating associated microorganisms is very important as they promote plant growth, nutrient uptake, and stress tolerance, thereby enhancing phytoremediation efficiency (Sarker et al., 2023; Yan et al., 2020). Long-term field studies on macrophytes biodiversity, phytoremediation potential, and associated microorganisms will provide insights into unique information about the recovery period of these plants under contaminated areas and identify plant species suitable for water quality restoration systems such as ecological floating bed and constructed wetland. Contaminated plant biomass can be managed through incinerations or pyrolysis, with potential recovery of useful chemicals (Jaramillo et al., 2019; Liu et al., 2024; Shen et al., 2022). Finally, phytoremediation holds a promising solution for restoring heavy metal-polluted aquatic system in the Nile. However, extensive long-term studies are needed to enhance its efficiency, elucidate molecular mechanism, and explore the relationship between the remediation efficiency and biodiversity in these ecosystems.

In conclusion, we confirm that the selected macrophytes have phytoremediation potential for the heavy metals investigated in the Nile River islands ecosystem, and except for Zn, emergent macrophytes (*S. geminata*, *P. senegalensis*, and *L. adscendens*) accumulated higher concentrations of all studied heavy metals in their root tissues than in aboveground tissues. Furthermore, these species accumulated larger quantities of Mn in their belowground tissues than in sediments. Therefore, based on the type of heavy metals, these emergent macrophytes are suitable for biomonitoring and phytostabilization. Submerged

macrophytes are ideal for accumulation and phyto-extraction. The results suggest a dynamic interaction between heavy metals in shoots, chlorophyll, and antioxidant compounds. There are species-specific differences in the energy allocation behavior between heavy metals and biochemical parameters. Our results suggest that the selected species can be used as a unique green solution for removing heavy metals from polluted islands.

Author Contributions Abdel Rahman Nadi: Formal analysis, Investigation and Writing; Elsayed Mohamed: Supervision, Conceptualization, Writing, review and editing, Project administration; Ahmed M. M. A. Kasem: Supervision, review and editing; Abd El-Mageed F. M. Ghanem: Supervision and Methodology; Mohamed O. Badry: Supervision, Conceptualization, review and editing.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors declare that no funds, grants, or other support were received.

Data Availability All data supporting the findings of this study are included within this paper and its Supplementary Information files.

Declarations

Ethical Approval Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abdelaal, M., Mashaly, I. A., Srour, D. S., Dakhil, M. A., El-Liethy, M. A., El-Keblawy, A., El-Barougy, R. F., Halmy, M. W. A., & El-Sherbeny, G. A. (2021). Phytoremediation perspectives of seven aquatic macrophytes for removal of heavy metals from polluted drains in the Nile Delta of Egypt. *Biology*, 10(6), 560. <https://doi.org/10.3390/biology10060560>
- Abdelhafez, A. A., Metwalley, S. M., & Abbas, H. H. (2020). Irrigation: Water Resources, Types and Common Problems in Egypt. *Technological and modern irrigation environment in Egypt: best management practices & evaluation*; Springer: Berlin/Heidelberg, Germany, pp. 15–34.
- Abdel-Satar, A. M., Ali, M. H., & Goher, M. E. (2017). Indices of water quality and metal pollution of Nile River, Egypt. *Egyptian Journal of Aquatic Research*, 43, 21–29.
- Abdel-Satar, A. M., Abdo, M. H., Othman, A. A., & Al-Afify, A. D. (2024). Assessment of water quality in the shores of the Nile River islands, Egypt: Chemical and microbiological analysis. *Ecological Frontiers*.
- Ahmad, S. S., Reshi, Z. A., Shah, M. A., Rashid, I., Ara, R., & Andrabi, S. M. (2016). Heavy metal accumulation in the leaves of *Potamogeton natans* and *Ceratophyllum demersum* in a Himalayan RAMSAR site: Management implications. *Wetlands Ecology and Management*, 24, 469–475.
- Al-Afify, A. D. G., Othman, A. A., & Ramadan, M. A. (2018). Characterization of chemical and microbiological quality of Nile River surface water at Cairo (Egypt). *Rendiconti Lincei. Scienze Fisiche e Naturali*, 29, 725–736.
- Alejandro, S., Höller, S., Meier, B., & Peiter, E. (2020). Manganese in plants: From acquisition to subcellular allocation. *Frontiers in Plant Science*, 11, 300.
- Ali, S., Abbas, Z., Rizwan, M., Zaheer, I. E., Yavaş, İ., Ünay, A., Abdel-DAIM, M. M., Bin-Jumah, M., Hasanuzzaman, M., & Kalderis, D. (2020). Application of Floating Aquatic Plants in Phytoremediation of Heavy Metals Polluted Water: A Review. *Sustainability*, 12(5), 1927.
- Alloway, B. J. (Ed.). (2012). *Heavy metals in soils: trace metals and metalloids in soils and their bioavailability* (Vol. 22). Springer Science & Business Media.
- Alloway, B. J. (2013). Heavy metals and metalloids as micronutrients for plants and animals. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability*, 195–209.
- Ansari, A. A., Gill, S. S., Khan, F. A., & Naeem, M. (2014). Phytoremediation systems for the recovery of nutrients from eutrophic waters. *Eutrophication: Causes, consequences, and control*. Springer, Dordrecht, 2, 239–248.
- Ansari, A. A., Naeem, M., Gill, S. S., & AlZuaibr, F. M. (2020). Phytoremediation of contaminated waters: An eco-friendly technology based on aquatic macrophytes application. *The Egyptian Journal of Aquatic Research*, 46(4), 371–376.
- Aryal, M. (2024). Phytoremediation strategies for mitigating environmental toxicants. *Heliyon*, 10(19).
- Baghour, M., Ben Chekroun, K., Manuel Ruiz Sáez, J., & Romero, L. (2016). Root-zone temperature affects the phytoextraction of iron in contaminated soil. *Journal of Plant Nutrition*, 39(1), 51–58.
- Bankaji, I., Pérez-Clemente, R., Caçador, I., & Sleimi, N. (2019). Accumulation potential of *Atriplex halimus* to zinc and lead combined with NaCl: Effects on physiological parameters and antioxidant enzymes activities. *South African Journal of Botany*, 123, 51–61. <https://doi.org/10.1016/j.sajb.2019.02.011>
- Barra Caracciolo, A., & Terenzi, V. (2021). Rhizosphere microbial communities and heavy metals. *Microorganisms*, 9(7), 1462.
- Bendary, R. E., Goher, M. E., & El-Shamy, A. S. (2023). Taxonomic and functional diversity of macroinvertebrates in sediment and macrophyte habitats: A case study, the Ibrahimia Canal, Nile River, Egypt. *The Egyptian Journal of Aquatic Research*, 49(2), 129–135.
- Bhaduri, A. M., & Fulekar, M. H. (2012). Antioxidant enzyme responses of plants to heavy metal stress. *Reviews in Environmental Science and Bio/technology*, 11, 55–69.
- Bray, H. G., & Thorpe, W. V. (1954). Analysis of phenolic compounds of interest in metabolism. *Methods of Biochemical Analysis*, 1, 27–52. <https://doi.org/10.1002/9780470110171.ch2>
- Chakraborty, S., & Mishra, A. K. (2020). Mitigation of zinc toxicity through differential strategies in two species of the *Cyanobacterium anabaena* isolated from zinc polluted paddy field. *Environmental Pollution*, 263, 114375. <https://doi.org/10.1016/j.envpol.2020.114375>
- Chedadi, M., Moussaoui, A. E., Bassouya, M., Zoufri, I., Barnossi, A. E., Asmi, H. E., ... & Bari, A. (2024). Capacity of an aquatic macrophyte, *Pistia stratiotes* L., for removing heavy metals from water in the Oued Fez River and their accumulation in its tissues. *Environmental Monitoring and Assessment*, 196(11), 1–12.
- Coelho, D. G., da Silva, V. M., Gomes Filho, A. A. P., Oliveira, L. A., de Araújo, H. H., dos Santos Farnese, F., Araújo, W. L., & de Oliveira, J. A. (2023). Bioaccumulation and physiological traits qualify *Pistia stratiotes* as a suitable species for phytoremediation and bioindication of iron-contaminated water. *Journal of Hazardous Materials*, 446, 130701.
- Cunningham, S. D., & Ow, D. W. (1996). Promises and prospects of phytoremediation. *Plant Physiology*, 110(3), 715.
- Dhir, B., Sharmila, P., & Saradhi, P. P. (2009). Potential of aquatic macrophytes for removing contaminants from the environment. *Critical Reviews in Environmental Science and Technology*, 39(9), 754–781.
- Dhote, S., & Dixit, S. (2009). Water quality improvement through macrophytes — a review. *Environmental Monitoring and Assessment*, 152, 149–153.
- Dogan, M., Akgul, H., Inan, O. G., & Zeren, H. (2015). Determination of cadmium accumulation capabilities of aquatic macrophytes *Ceratophyllum demersum*, *Bacopa monnieri* and *Rotala rotundifolia*. *Iranian Journal of Fisheries Sciences*, 14(4), 1010–1017.
- EEAA (2002). Egyptian Pollution Abatement Project, Hazardous Waste Management Manual for Industries. *Egyptian Environmental Affairs Agency. Annual Report*, p. 14
- Eid, E. M., & Shaltout, K. H. (2014). Monthly variations of trace elements accumulation and distribution in above-and belowground biomass of *Phragmites australis* (Cav.) Trin. ex Steudel in Lake Burullus (Egypt): A biomonitoring application. *Ecological Engineering*, 73, 17–25.

- Eid, E. M., Galal, T. M., Sewelam, N. A., Talha, N. I., & Abdallah, S. M. (2020). Phytoremediation of heavy metals by four aquatic macrophytes and their potential use as contamination indicators: A comparative assessment. *Environmental Science and Pollution Research*, 27, 12138–12151.
- EPA (Environmental Protection Agency), (2006). Region III BTAG freshwater sediment screening benchmarks 8/2006.
- Esmail, E. A., Yousry, A., Qutb, S. M., & Abdelrahman, A. (2023). Sustainability Assessment Scale for the Nile Islands (SASNI) as a guideline to determine sustainable urban development policies. *Environmental Research, Engineering and Management*, 79(3), 7–23.
- Falah, M. A. F., Wajima, T., Yasutake, D., Hidaka, K., & Kitano, M. (2005). High temperature affects root absorption. *Journal of Agricultural Meteorology*, 60(5), 809–812.
- Farahat, E. A., Mahmoud, W. F., & Fahmy, G. M. (2021). Seasonal variations of heavy metals in water, sediment, and organs of *Vossia cuspidata* (Roxb.) Griff. in River Nile ecosystem: Implication for phytoremediation. *Environmental Science and Pollution Research*, 28, 32626–32633.
- Fawzy, M. A., Badr, N. E. S., El-Khatib, A., & Abo-El-Kassem, A. (2012). Heavy metal biomonitoring and phytoremediation potentialities of aquatic macrophytes in River Nile. *Environmental Monitoring and Assessment*, 184, 1753–1771.
- Fitamo, D., & Leta, S. (2010). Assessment of plants growing on gold mine wastes for their potential to remove heavy metals from contaminated soils. *International Journal of Environmental Studies*, 67(5), 705–724.
- Fletcher, J., Willby, N., Oliver, D. M., & Spampson, R. S. (2020). Phytoremediation using aquatic plants. Phytoremediation: *in-situ applications*, 205–260.
- Gerber, G. B., Leonard, A., & Hantson, P. H. (2002). Carcinogenicity, mutagenicity, and teratogenicity of manganese compounds. *Critical Reviews in Oncology/Hematology*, 42(1), 25–34.
- Giehl, R. F., Flis, P., Fuchs, J., Gao, Y., Salt, D. E., & Von Wirén, N. (2023). Cell type-specific mapping of ion distribution in *Arabidopsis thaliana* roots. *Nature Communications*, 14(1), 3351.
- Guidi Nissim, W., Castiglione, S., Guarino, F., Pastore, M. C., & Labra, M. (2023). Beyond cleansing: Ecosystem services related to phytoremediation. *Plants*, 12(5), 1031.
- Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Al-safran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science*, 13, 1033092.
- Harguinteguy, C. A., Cofré, M. N., Fernández-Cirelli, A., & Pignata, M. L. (2016). The macrophytes *Potamogeton pusillus* L. and *Myriophyllum aquaticum* (Vell.) Verdc. as potential bioindicators of a river contaminated by heavy metals. *Microchemical Journal*, 124, 228–234.
- Haroon, A. M. (2022). Review on aquatic macrophytes in Lake Manzala. *Egypt. Egyptian Journal of Aquatic Research*, 48(1), 1–12.
- He, M., Yin, H., Liu, Z., Luo, F., Zhao, X., Li, H., & Song, X. (2024). Root exudate-assisted phytoremediation of copper and lead contamination using *Rumex acetosa* L. and *Rumex K-I*. *Ecotoxicology and Environmental Safety*, 284, 117036.
- Hong, J. H., Duncan, S. E., & Dietrich, A. M. (2010). Effect of copper speciation at different pH on temporal sensory attributes of copper. *Food Quality and Preference*, 21(1), 132–139.
- Hossain, M. S., Abdelrahman, M., Tran, C. D., Nguyen, K. H., Chu, H. D., Watanabe, Y., Hasanuzzaman, M., Mohsin, S. M., Fujita, M., & Tran, L. S. P. (2020). Insights into acetate-mediated copper homeostasis and antioxidant defense in lentil under excessive copper stress. *Environmental Pollution*, 258, 113544.
- Huang, C. W., Yen, P. L., How, C. M., Chai, Z. Y., & Liao, V. H. C. (2021). Levels of bioavailable manganese in river sediment may elevate reproductive risk in model organism *Caenorhabditis elegans*. *Aquatic Toxicology*, 239, 105958.
- Jaramillo, E., Duarte, C., Labra, F. A., Lagos, N. A., Peruzzo, B., Silva, R., ... & Melnick, D. (2019). Resilience of an aquatic macrophyte to an anthropogenically induced environmental stressor in a Ramsar wetland of southern Chile. *Ambio*, 48, 304–312.
- Johansson, J. (2005). Manganese solubility due to compaction in soils under corn and soybean. Dissertation, *Lantbruks Universitet Sverige*, pp. 2–20.
- Kabata-Pendias, A. (2011). *Trace Elements in Soils and Plants*, 4th ed.; CRC Press/ Taylor & Francis Group: Boca Raton, FL, USA.
- Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, 8, 100203.
- Kassaye, Y. A., Skipperud, L., Einset, J., & Salbu, B. (2016). Aquatic macrophytes in Ethiopian Rift Valley lakes; their trace elements concentration and use as pollution indicators. *Aquatic Botany*, 134, 18–25.
- Klink, A. (2017). A comparison of trace metal bioaccumulation and distribution in *Typha latifolia* and *Phragmites australis*: Implication for phytoremediation. *Environmental Science and Pollution Research*, 24, 3843–3852.
- Lam, E. J., Keith, B. F., Bech, J., Alvarez, F. A., Zetola, V., Pereira, L. H., & Montofré, Í. L. (2023). Characteristic curve modeling of plant species behavior in soils with heavy metals. *Environmental Geochemistry and Health*, 45(12), 8867–8880.
- Li, H., Shi, A., Li, M., & Zhang, X. (2013). Effect of pH, temperature, dissolved oxygen, and flow rate of overlying water on heavy metals release from storm sewer sediments. *Journal of Chemistry*, 2013(1), 434012.
- Li, Y., Shi, S., Zhang, Y., Zhang, A., Wang, Z., & Yang, Y. (2023). Copper stress-induced phytotoxicity associated with photosynthetic characteristics and lignin metabolism in wheat seedlings. *Ecotoxicology and Environmental Safety*, 254, 114739.
- Liu, Z. et al., (2020). A review on phytoremediation of mercury contaminated soils. *Journal of Hazardous Materials*, 400. <https://doi.org/10.1016/j.jhazmat.2020.123138>.
- Liu, N., Zhao, J., Du, J., Hou, C., Zhou, X., Chen, J., & Zhang, Y. (2024). Non-phytoremediation and phytoremediation technologies of integrated remediation for water and soil heavy metal pollution: A comprehensive review. *Science of The Total Environment*, 174237.

- MacLachlan, S., & Zalík, S. (1963). Plastid structure, chlorophyll concentration, and free amino acid composition of a chlorophyll mutant of barley. *Canadian Journal of Botany*, 41, 1053–1062. [10.1139/b63-088](https://doi.org/10.1139/b63-088).
- Manca, F., Mulà, C., Gustafsson, C., Mauri, A., Roslin, T., Thomas, D. N., ... & Strona, G. (2022). Unveiling the complexity and ecological function of aquatic macrophyte–animal networks in coastal ecosystems. *Biological Reviews*, 97(4), 1306–1324.
- Marchand, L., Nsanganwimana, F., Cook, B. J., Vystavna, Y., Huneau, F., Le Coustumer, P., ... & Mench, M. (2014). Trace element transfer from soil to leaves of macrophytes along the Jalle d'Eysines River, France, and their potential use as contamination biomonitors. *Ecological Indicators*, 46, 425–437.
- Martinez, E. A., & Shu-Nyamboli, C. (2011). Determination of selected heavy metal concentrations and distribution in a southwestern stream using macrophytes. *Ecotoxicology and Environmental Safety*, 74(6), 1504–1511.
- Miliauskas, G., Venskutonis, P. R., & Van Beek, T. A. (2004). Screening of radical scavenging activity of some medicinal and aromatic plant extracts. *Food Chemistry*, 85, 231–237. <https://doi.org/10.1016/j.foodchem.2003.05.007>
- Moczek-Plóćiniak, A., Mencel, J., Zakrzewski, W., & Roszkowski, S. (2023). Phytoremediation as an effective remedy for removing trace elements from ecosystems. *Plants*, 2023(12), 1653. <https://doi.org/10.3390/plants12081653>
- Nouri, J., Lorestani, B., Yousefi, N., Khorasani, N., Hasani, A. H., Seif, F., & Cheraghi, M. (2011). Phytoremediation potential of native plants grown in the vicinity of Ahangaran lead–zinc mine (Hamedan, Iran). *Environmental Earth Sciences*, 62, 639–644.
- Pandey, C. V., Gajić, G., Sharma, P., & Roy, M. (2022). Adaptive phytoremediation practices: *Resilience to climate change* (pp. 1–352). Elsevier.
- Perelman, A. I. (1966). *The geochemistry of land areas in Russian*. Izd Vish Shk.
- Prasad, M. N. V. (2006). Aquatic plants for phytotechnology. In: S. N. Singh, S.N., & R. D. Tripathi, R. D. (Eds.), *Environmental bioremediation technologies*. Springer, Berlin, Heidelberg, pp. 259–274.
- Radić, S., Babić, M., Škobić, D., Roje, V., & Pevalek-Kozlina, B. (2010). Ecotoxicological effects of aluminum and zinc on growth and antioxidants in *Lemna minor* L. *Ecotoxicology and Environmental Safety*, 73(3), 336–342.
- Rahman, M. A., & Hasegawa, H. (2011). Aquatic arsenic: Phytoremediation using floating macrophytes. *Chemosphere*, 83(5), 633–646.
- Rai, S., Singh, P. K., Mankotia, S., Swain, J., & Satbhai, S. B. (2021). Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese. *Plant Stress*, 1, 100008.
- Ray, H., Bett, K., Tar'an, B., Vandenberg, A., Thavarajah, D., & Warkentin, T. (2014). Mineral micronutrient content of cultivars of field pea, chickpea, common bean, and lentil grown in Saskatchewan, Canada. *Crop Science*, 54(4), 1698–1708.
- Rout, G. R., & Sahoo, S. (2015). Role of iron in plant growth and metabolism. *Reviews in Agricultural Science*, 3, 1–24.
- Rulkens, W. H., Tichy, R., & Grotenhuis, J. T. C. (1998). Remediation of polluted soil and sediment: Perspectives and failures. *Water Science and Technology*, 37, 27–35.
- Sabir, M., Waraich, E. A., Hakeem, K. R., Oztürk, M., Ahmad, H. R., & Shahid, M. (2015). *Phytoremediation*. Elsevier Inc. [10.1016/B978-0-12-799937-1.00004-8](https://doi.org/10.1016/B978-0-12-799937-1.00004-8)
- Saenchai, C., Bouain, N., Kisko, M., Prom-U-Thai, C., Doumas, P., & Rouached, H. (2016). The involvement of OsPHO1; 1 in the regulation of iron transport through integration of phosphate and zinc deficiency signaling. *Frontiers in Plant Science*, 7, 396.
- Sarker, A., Al Masud, M. A., Deepo, D. M., Das, K., Nandi, R., Ansary, M. W. R., ... & Islam, T. (2023). Biological and green remediation of heavy metal contaminated water and soils: A state-of-the-art review. *Chemosphere*, 332, 138861.
- Sarwar, N., Imran, M., Shaheen, M. R., Ishaque, W., Kamran, M. A., Matloob, A., Rehman, A., & Hussain, S. (2017). Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere*, 171, 710–721.
- Sharma, J. K., Kumar, N., Singh, N. P., & Santal, A. R. (2023). Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Frontiers in Plant Science*, 14, 1076876.
- Shen, X., Dai, M., Yang, J., Sun, L., Tan, X., Peng, C., Ali, I., & Naz, I. (2022). A critical review on the phytoremediation of heavy metals from environment: Performance and challenges. *Chemosphere*, 291, 132979.
- Sinclair, S. A., & Krämer, U. (2012). The zinc homeostasis network of land plants. *Biochimica et Biophysica Acta (BBA)-Molecular Cell Research*, 123(9), 1553–1567.
- Sojitra, R., Gadhvi, K., Gamit, S., Dudhagara, D., & Vyas, S. (2024). Phytoremediation potential of monocotyledonous plants in the sediments of the Uben River, Gujarat, India. *Scientific Reports*, 14(1), 16938.
- Suman, J., Uhlik, O., Viktorova, J., Macek, T. (2018). Phytoextraction of heavy metals: a promising tool for clean-up of polluted environment?. *Frontiers in Plant Science*, 9.
- Taha, L. G. E. D. (2014). Assessment of urbanization encroachment over Al-Monib Island using fuzzy post classification comparison and urbanization metrics. *The Egyptian Journal of Remote Sensing and Space Science*, 17(2), 135–147.
- Thomaz, S. M., & Cunha, E. R. D. (2010). The role of macrophytes in habitat structuring in aquatic ecosystems: Methods of measurement, causes and consequences on animal assemblages' composition and biodiversity. *Acta Limnologica Brasiliensia*, 22, 218–236.
- Topaldemir, H., Taş, B., Yüksel, B., & Ustaoglu, F. (2023). Potentially hazardous elements in sediments and *Ceratophyllum demersum*: An ecotoxicological risk assessment in Miliç Wetland, Samsun, Türkiye. *Environmental Science and Pollution Research*, 30(10), 26397–26416.
- US-EPA Method 3051A. (2007). Microwave assisted acid digestion of sediment, sludges, soils, and oils. *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods*.

- Vardhan, K.H., Kumar, P.S., & Panda, R.C. (2019). A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. *Journal of Molecular Liquids*, 290.
- Wang, T., & Peverly, J. H. (1996). Oxidation states and fractionation of plaque iron on roots of common reeds. *Soil Science Society of America Journal*, 60(1), 323–329.
- WHO/FAO, (2007). Joint FAO/WHO Food Standard Programme Codex Alimentarius Commission 13th Session. Report of the Thirty-Eight Session of the Codex Committee on Food Hygiene, Houston, United States of America, ALINORM 07/30/13.
- Xing, W., Wu, H., Hao, B., Huang, W., & Liu, G. (2013). Bioaccumulation of heavy metals by submerged macrophytes: Looking for hyperaccumulators in eutrophic lakes. *Environmental Science and Technology*, 47, 4695–4703.
- Yan, C., Li, G., Xue, P., Wei, Q., & Li, Q. (2010). Competitive effect of Cu (II) and Zn (II) on the biosorption of lead (II) by *Myriophyllum spicatum*. *Journal of Hazardous Materials*, 179, 721–728.
- Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land. *Frontiers in Plant Science*, 11, 359.
- Zhao, F., Xi, S., Yang, X., Yang, W., Li, J., Gu, B., & He, Z. (2012). Purifying eutrophic river waters with integrated floating island systems. *Ecological Engineering*, 40, 53–60.
- Zhu, Y., Gu, H., Li, H., Lam, S. S., Verma, M., Ng, H. S., Sonne, C., Liew, R., & Peng, W. K. (2024). Phytoremediation of contaminants in urban soils: A review. *Environmental Chemistry Letters*, 22(1), 355–371.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.