J Soils Sediments (2017) 17:1310–1320
DOI 10.1007/s11368-015-1260-x

Accumulation and phytoremediation of Pb, Zn, and Ag by plants growing on Koshk lead–zinc mining area, Iran

Kobra Mahdavian[1] · **Seyed Majid Ghaderian**[1] · **Masoud Torkzadeh-Mahani**[2]

Received: 22 May 2015 / Accepted: 4 September 2015 / Published online: 15 September 2015

Abstract
Purpose This study investigated the extent of metal accumulation by plants colonizing a mining area in Yazd Province in Central Iran. It also investigated the suitability of these plants for phytoextraction and phytostabilization as two potential phytoremediation strategies.
Materials and methods Plants with a high bioconcentration factor (BCF) and low translocation factor (TF) have the potential for phytostabilization, whereas plants with both BCFs and TFs >1 may be appropriate for phytoextraction. In this study, both shoots and roots of 40 plant species and associated soil samples were collected and analyzed for total concentrations of trace elements (Pb, Zn, and Ag). BCFs and TFs were calculated for each element.
Results and discussion *Nonnea persica*, *Achillea wilhelmsii*, *Erodium cicutarium*, and *Mentha longifolia* were found to be the most suitable species for phytostabilization of Pb and Zn. *Colchicum schimperi*, *Londesia eriantha*, *Lallemantia royleana*, *Bromus tectorum*, *Hordeum glaucum*, and *Thuspeinantha persica* are the most promising species for element phytoextraction in sites slightly enriched by Ag. *Ferula assa-foetida* is the most suitable species for phytostabilization of the three studied metals. *C. schimperi*, *L. eriantha*, *L. royleana*, *B. tectorum*, *M. longifolia*, and *T. persica* accumulated Ag, albeit at low level.
Conclusions Our preliminary study shows that some native plant species growing on this contaminated site may have potential for phytoremediation.

Keywords Bioconcentration factor · Lead–zinc mine · Native plants · Phytoremediation · Translocation factor

Responsible editor: Maria Manuela Abreu

✉ Seyed Majid Ghaderian
ghaderian@sci.ui.ac.ir

[1] Department of Biology, Faculty of Sciences, University of Isfahan, Isfahan 81746-73441, Iran

[2] Biotechnology Department, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran

1 Introduction

Heavy metals and metalloids are currently of much environmental concern. They can be harmful to humans and animals and tend to bioaccumulate in the food chain. Activities such as mining and smelting of metal ores, industrial emissions, and applications of insecticides and fertilizers have all contributed to elevated levels of metals and metalloids in the environment (Alloway 1994). Several technologies are available to remediate soils contaminated by metals and metalloids. However, many of these technologies are costly, e.g., excavation of contaminated material and chemical/physical treatment or do not achieve a long-term nor aesthetic solution (Mulligan et al. 2001; Cao et al. 2002). Phytoremediation can provide a cost-effective, long-lasting, and aesthetic solution for the remediation of contaminated sites (Ma et al. 2001). It has been suggested as an inexpensive and sustainable in situ biotechnological approach to assist in the restoration of soils contaminated by metals and metalloids without destructive effects on soil properties (Salt et al. 1998; McGrath et al. 2002; Pilon-Smits 2005). *Typha latifolia* L. and *Phragmites australis* (Cav.) Trin. Ex. Steudel have been successfully used for phytoremediation of Pb/Zn mines in southern China (Ye et al. 1997a, b; Srivastava et al. 2014). Remediation of soils contaminated by potentially hazardous elements by plant species can be considered in three groups:

(1) phytoextraction, in which metal-accumulating plants are planted in contaminated soil and later harvested in order to remove metals from the soil; (2) rhizofiltration, where the roots of metal-accumulating plants absorb metals from polluted sediments or effluent streams and are later harvested to diminish the metal loading; and (3) phytostabilization, in which metal-tolerant plants are used to reduce the mobility of metals, thus stabilizing them in the substrate (Salt et al. 1995; Abdel-Ghani et al. 2007).

More than 500 plant species called hyperaccumulators are able to accumulate high amounts of these metals (Reeves and Baker 2000). Different concentration limits have been set for defining hyperaccumulation of different metals (Van der Ent et al. 2013). For Zn, the threshold for hyperaccumulation in plant dry matter is 3000 mg kg^{-1}; for Co, Cu, and Cr, 300 mg kg^{-1}; for As, Ni, and Pb, 1000 mg kg^{-1}; and for Ag, tentatively 1 mg kg^{-1}. Both bioconcentration factor (BCF) and translocation factor (TF) can be used to estimate a plant's potential for phytoremediation purposes. The ability of a plant to accumulate metals from soils can be estimated using the BCF, which is defined as the quotient of the metal concentration in the roots to that in soil. The ability to translocate metals from the roots to the shoots is measured using the TF, which is defined as the quotient of the metal concentration in the shoots to the roots. Effective phytoextraction requires the translocation of heavy metals and metalloids to the easily harvestable plant parts, i.e., shoots. By comparing the BCF and TF, we can compare the ability of different plants in taking up metals from soils and translocating them to the shoots. Tolerant plants tend to restrict soil–root and root–shoot transfers and therefore have much less accumulation in their biomass, while accumulators actively take up and translocate metals into their above-ground biomass. Plants exhibiting a TF and particularly BCF values <1 are unsuitable for phytoextraction (Fitz and Wenzel 2002). Plants with both BCF and TF >1 have a potential to be used in phytoextraction; those with both a BCF and TF <1 are more suitable for phytostabilization (Yoon et al. 2006). There is a continuing interest in searching for native plants that are tolerant to metals and metalloids, and several studies have evaluated the phytoremediation potential of native plants under field conditions (e.g., Shu et al. 2002b; Abioye et al. 2012).

There are about 8000 plant species in Iran, belonging to 150 families. Some 1727 of these are native (Jalili and Jamzad 1999). Due to the shortage of rainfall in Central Iran, most plant species in these areas are herbaceous. There are numerous natural metalliferous and metal-contaminated soils in Iran, but little information is available regarding their flora, the concentration of trace elements in plants, and also any relationships between the concentration of metals in plants and soils (Ghaderian and Baker 2007).

The aims of this research were to (1) identify the plant species growing on mineralized and contaminated soils in the Koshk lead–zinc mining area; (2) determine the concentrations of Pb, Zn, and Ag in plant biomass growing on a contaminated site; (3) compare metal concentrations in the above-ground biomass with those in roots and in soils; and (4) assess the feasibility of using these plants for phytoremediation purposes. Results from this study provide insight into possibilities for using native plants to remediate Iranian metal-contaminated sites.

2 Materials and methods

2.1 Site characterization

The Koshk lead–zinc mining area is located 165 km east of Yazd and 45 km northeast of Bafg in Central Iran in an arid to semi-arid area at 1800 m asl (Fig. 1). Annual rainfall is about 120 mm, mostly in winter and to some extent in autumn and spring. Maximum and minimum temperatures in summer and winter in this area are about 35 and 9 °C, respectively.

Galena, sphalerite, pyrite, and dolomite are main minerals in the ore. There are several Zn and Pb mining sites, mostly exploited as open mines; some have been reopened during the last 60 years. In some areas, the surface soils naturally contain a high background concentration of Pb, Zn, and Ag. Owing to mining activity and the resulting distribution of dust and spoil, soils surrounding the mines have been contaminated by Pb, Zn, and Ag over a vast area. Ore concentration using flotation methods and smelting was carried out close to the mining sites, and so dust and contaminated water cover the surrounding land. In the present study, sampling of soils and plants was carried out at six different sites near Koshk mine: site 1, the area around smelter plant; site 2, wastewater drainage; site 3, the foot of the hill near the wastewater drainage; site 4, the tailings dump; site 5, hole tailing dump; and site 6, an area around Koshk village.

2.2 Plant sampling and analysis

Forty plant species and associated soil samples were collected in the area surrounding Koshk mine from April 2013–October 2014. The species sampled were from 40 genera and 19 families, of which eight species belong to the Asteraceae, forming the most dominant floral component colonizing the metal-polluted sites. Individual plants were placed in plastic bags and transferred to the laboratory where they were separated into roots and shoots. Plant material was carefully washed with tap water and once more with distilled water. Oven-dried (60 °C) plant material was ground, and subsamples of 0.05 g dry weight were digested in a mixture of HNO_3 (65 %), HCl (37 %), and H_2O_2 (30 %) (6:3:1, *v/v/v*) and heated at 120 °C for 1 h. After cooling, digests were made up to 10 ml with deionized water. The solutions were analyzed for Pb, Zn, and Ag by atomic absorption spectrophotometry (AAS; Shimadzu 6200 AA).

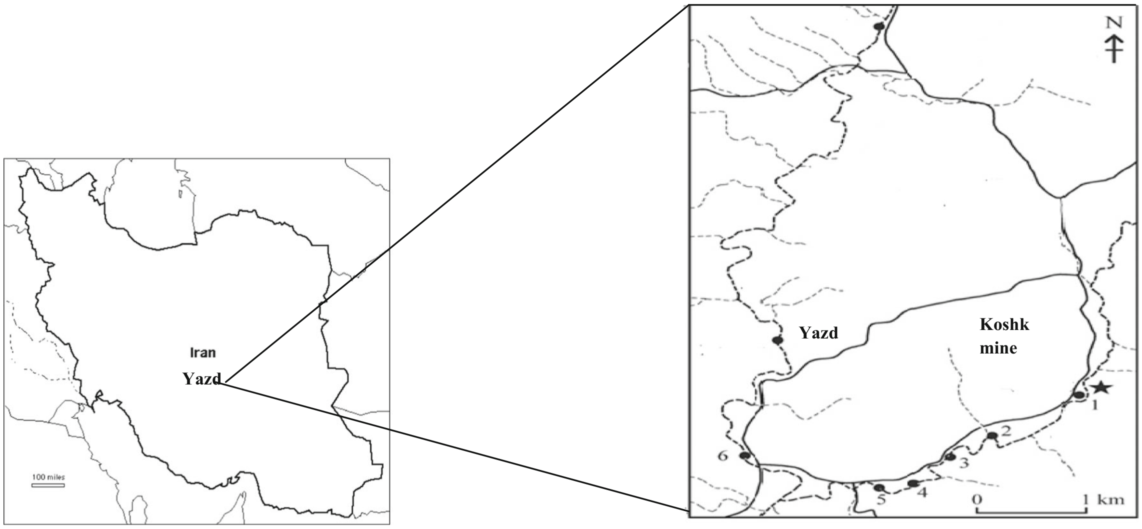

Fig. 1 Location of the study area. Sampling of soils and plants was carried out at six different sites near Koshk mine: site 1, the area around smelter plant; site 2, wastewater drainage; site 3, the foot of the hill near the wastewater drainage; site 4, the tailings dump; site 5, hole tailing dump; and site 6, an area around Koshk village

2.3 Soil sampling and analysis

For each plant sampled, the top 20 cm of soil around the roots was also collected. Subsamples of 4–5 g for chemical analysis were ground and passed through a sieve (<190 μm) and then oven-dried at 70 °C. A further subsample of 0.5 g was transferred to a digestion tube for extraction with 10 ml of an $HClO_4/HNO_3/HCl$ (1:6:3, *v/v/v*) mixture. Tubes were left at room temperature overnight and were then placed in a heating block. Each was covered with an air condenser and refluxed gently at 120 °C for 2 h. After cooling, the digests were filtered through a moistened filter paper into a 50-ml volumetric flask and made up to volume with distilled water. Ten milliliters of the digest was added to 15-ml tubes and analysis for Pb, Zn, and Ag performed by AAS. For the determination of exchangeable elements, 20 g of air-dried soil was placed in 100-ml screw-cap polythene bottles, 50 ml of 1 M NH_4NO_3 was solution added, and the suspension was shaken for 2 h at 20 °C. After shaking, the soil suspensions were left to stand for 10 min and then filtered. The filtrate was then acidified to 0.2 % HNO_3 for analysis of the above elements by AAS (see, e.g., Gryschko et al. 2004). The pH and EC values of soil samples were measured electrometrically after 10 g of soil had been stirred well in 30 ml distilled water in a beaker and allowed to stand for about 30 min.

3 Results

Concentrations of total and exchangeable Pb, Zn, and Ag in the soils at the six sampling sites are given in Table 1. Concentrations of Pb and Zn are both elevated and Ag slightly so. Total Pb concentrations were variable, ranging from 5 mg kg^{-1} at site 6 to 3520 mg kg^{-1} at site 2 (Table 1). These sites also show elevated levels of Zn and Ag, ranging from 124 to 4503 mg kg^{-1} for Zn and from 0.3 to 6.5 mg kg^{-1} for Ag (Table 1). Concentrations of Pb, Zn, and Ag in the exchangeable fractions were 0.5–124.1, 6.1–434.4, and <0.1–0.5 mg kg^{-1}, respectively. The pH of all soil samples was in the range 6.8–8.8 (Table 1).

During the course of this study, 40 species of vascular plants belonging to 40 genera and 19 families were collected from the six sites at the Koshk lead–zinc mining area (Table 2). Concentrations of Pb, Zn, and Ag in plant biomass are summarized in Table 2. Lead concentrations in the roots ranged from 4 to as high as 3074 mg kg^{-1} and shoots from 4 to 361 mg kg^{-1}, with maximum values in the roots of *Nonnea persica* Boiss. and shoots of *Hordeum glaucum* Steud. Zinc concentrations in roots ranged from 43 to 1292 mg kg^{-1} and shoots from 5 to 957 mg kg^{-1}, with the maximum concentrations in the roots of *N. persica* and shoots of *Salsola nitraria* Pall. Silver concentrations in roots were very low, ranging from 0.1 up to 8.3 mg kg^{-1} and shoots from <0.1 to 3.6 mg kg^{-1}, with the highest values in the roots of *Ferula assa-foetida* L. and shoots of *Thuspeinantha persica* (Boiss.) Briq.

4 Discussion

The soils of all sites studied were found to contain predictably high concentrations of Pb, Zn, and moderate concentrations of Ag typical of this area. This is due to weathering of the ore-bearing parent rocks and to contamination by mining and smelting activities over the last 60 years. There are considerable variations in the element concentrations both within and

Table 1 Selected properties (mean and minimum–maximum) of soil samples from the contaminated site in the Koshk mining area

Site #	No. of samples	Soil pH	EC (ms cm^{-1})	Total Pb (mg kg^{-1})	Exchangeable Pb (mg kg^{-1})	Total Zn (mg kg^{-1})	Exchangeable Zn (mg kg^{-1})	Total Ag (mg kg^{-1})	Exchangeable Ag (mg kg^{-1})
1	10	7.5±0.5	2.3±1.1	273.8±100.2	13.3±4.2	1232.2±676.1	147.2±56.6	1.3±1.1	<0.1
		7.1–8.3	1.1–3.4	154.7–375.1	7.7–18.8	400.2–2027.0	36.0–186.2	0.3–2.9	
2	10	7.0±0.1	8.2±0.1	2831.4±551.8	88.2±14.5	3442.1±877.5	328.4±81.7	1.6±0.5	<0.1
		7.0–7.1	8.1–8.3	2113.3–3520.0	74.5–124.0	2354.1–4503.2	227.6–434.0	0.3–1.7	
3	5	6.8±0.3	8.6±0.4	825.2±309.2	8.9±4.1	1856.8±1060.7	129.3±75.1	3.4±1.1	0.3±0.1
		6.8–7.1	8.2–9.0	377.2–1250.3	4.7–15.6	345.1–3345.0	24.5–237.0	1.6–4.3	0.2–0.4
4	5	7.1±0.3	8.7±0.5	1698.2±429.9	10.8±3.3	2075.5±54.7	224.4±5.6	1.4±0.3	0.1±0.1
		6.9–7.5	8.2–9.2	1022.1–2200.4	6.2–15.3	2011.0–2160.4	217.5–233.0	0.3–1.5	<0.3
5	6	7.7±0.1	3.9±0.1	89.3±46.3	8.6±5.9	488.2±454.2	34.4±19.6	4.5±2.4	0.3±0.1
		7.7–7.8	3.8–4.0	20.3–166.2	1.5–16.1	124.0–1367.5	6.1–67.7	0.6–6.3	<0.5
6	10	8.8±0.2	1.1±0.1	34.2±22.1	3.4±2.2	497.3±260.9	18.8±9.4	5.8±1.6	0.4±0.2
		8.6–8.8	1.1–1.2	5.0–63.1	0.5–6.2	144.0–678.1	7.0–33.0	1.0–6.5	0.1–0.5

between sites pointing to the heterogeneous dispersion of individual minerals in the mine wastes (Wenzel and Jockwer 1999; Dahmani-Muller et al. 2000; Ghaderian et al. 2007). Global background values for total Ag in uncontaminated soils range from <0.01 to 5 mg kg^{-1}, with an average of 0.1 mg kg^{-1} (Boyle 1968) and for Zn 80–120 mg kg^{-1}; higher concentrations can be considered as enrichment or contamination (Alloway 1995). The global baseline for Pb in uncontaminated soils is given as 20 mg kg^{-1} (Kabata-Pendias 2011). In our study, the Pb, Zn, and Ag concentrations in the Koshk mining area greatly exceed these baseline values with the exception of site 6. The 40 plant species growing in the most heavily contaminated sites might be expected to exhibit high metal tolerances. Heavy metals and metalloids in insoluble form are not immediately bioavailable to plants, and therefore, they are not all directly toxic. However, those present in soluble and exchangeable forms may be directly accessible to organisms in the soil (Lorenz et al. 1997; Pollard et al. 2002). Our analyses demonstrated that the highest exchangeable concentrations of Pb, Zn, and Ag were 124 mg kg^{-1} at site 2, 434 mg kg^{-1} at site 2, and 0.5 mg kg^{-1} at site 6, respectively. Although these values suggest significantly increased bioavailability, the toxicity of an element to a specific organism cannot simply be evaluated by the concentration of that element in the soluble or exchangeable fractions alone (Otero et al. 2012). The pH of most of soils sampled were neutral to alkaline. In this pH range, the availability of most heavy metals is low compared to more acidic soils (Harris et al. 1996; Wong 2003).

Metal and metalloid concentrations in plants vary between plant species (Alloway et al. 1990; Quezada-Hinojosa et al. 2015). Plant uptake of metals and metalloids from soil occurs either passively in the mass flow of water into the roots or through active transport across of the plasma membrane of root epidermal cells. Under normal growing conditions, plants can potentially accumulate certain metallic ions with an order of magnitude greater than in the surrounding medium (Kim et al. 2003). The bioavailability of metals and metalloids to plants is ultimately controlled by their total concentrations in the soil and by their chemical forms (Thornton 1999). Kabata-Pendias (2011) reported 0.01–18.8 Pb mg kg^{-1}, 6–126 Zn mg kg^{-1}, and 0.03–0.5 Ag mg kg^{-1} in plants growing in uncontaminated soils. Lead is neither essential nor beneficial in plant nutrition and is generally present at about 1–10 mg kg^{-1} in plant tissues (Ghaderian et al. 2007). In our study, none of the plant species accumulated Pb >1000 mg kg^{-1} in their shoots, the notional criterion for Pb hyperaccumulator (Van der Ent et al. 2013). Moreover, in 95 % of the plant samples, the root Pb concentrations were much greater than those in the shoots, indicating little translocation of Pb from the roots to the shoots and immobilization in the roots. Lead concentrations in plants in this study ranged from 4 to as high as 3074 mg kg^{-1} in the roots and shoots from 4 to 361 mg kg^{-1}, with maximum values in the roots of *N. persica* and shoots of *H. glaucum*. There have been many reports of Pb concentrations in plants growing on mine-impacted soils and tailings. For example, research conducted by Yoon et al. (2006) reported Pb concentrations were in the range of non-detectable to 491 mg kg^{-1}, the maximum value in the shoot of *Gentiana pennelliana* Fern., and those given by Pitchtel et al. (2000) showed similar Pb concentrations in plant roots (from non-detectable to 1800 mg kg^{-1}). Stoltz and Greger (2002) reported a range of 3.4–920 mg kg^{-1} of Pb concentrations in the roots of different wetland plant species collected from mine tailings.

Zinc is an essential element for plants and is normally present at concentrations of 10–200 mg kg^{-1} (Ghaderian and Ghotbi Ravandi 2012). Zinc concentrations in the plant shoots in this study ranged from 5 to 957 mg kg^{-1}; the maximum value was found in *S. nitraria.* However, none of the plant species sampled accumulated Zn >3000 mg kg^{-1} in their shoots, the notional criterion for Zn hyperaccumulation (Van der Ent et al. 2013). As for Pb, Zn concentrations were greater in the roots than in the shoots. There have been many

Table 2 Mean and range (below) of total Pb, Zn, and Ag concentrations in soils and in plants (shoots and roots) (mg kg^{-1} dry matter) collected in the Koshk mining area

Species	No. of sample	Site	Pb			Zn			Ag		
			Roots	Shoots	Soil	Roots	Shoots	Soil	Roots	Shoots	Soil
Apiaceae											
Dorema ammoniacum D. Don	3	3	987.2–1208.9 1107.9±112.1	52.1–69.2 66.0±12.3	385.2–423.3 390.0±30.9	143.1–172.3 162.2±16.4	112.7–154.2 144.6±28.3	3023.4–3325.3 3273.0±227.4	0.9–1.8 1.7±0.7	0.4–0.6 0.5±0.1	3.2–4.8 4.0±0.8
Ducrosia anethifolia (DC.) Boiss.	5	3, 6	24.8–1570.4 597.4±360.3	3.0–125.0 53.7±44.8	27.0–765.0 287.5±158.8	81.06–530.2 234.7±174.5	42.0–449.5 231.8±162.9	160.0–1395.0 534.8±489.7	0.5–0.6 0.5±0.1	0.5–0.9 0.7±0.1	2.5–4.7 3.6±0.8
Eryngium billardieri Delile	3	6	5.7–7.3 6.1±1.1	4.0–4.5 4.1±0.3	52.6–71.2 63.0±9.4	73.2–89.4 84.3±9.2	28.4–35.3 31.0±3.6	144.0–146.3 144.0±1.3	0.3–0.4 0.3±0.1	0.1–0.2 0.2±0.1	1.1–1.2 1.1±0.1
Ferula assa-foetida L.	3	6	46.6–1175.9 407.5±388.6	14.2–100.0 43.2±49.1	32.1–63.0 42.3±17.8	103.9–159.9 124.3±30.8	27.0–150.5 73.2±67.3	132.0–144.0 135.3±7.5	8.0–8.5 8.3±0.2	0.8–1.0 0.9±0.1	5.6–6.4 6.1±0.4
Asteraceae											
Achillea wilhelmsii C. Koch	5	1, 5	789.2–1448.0 1041.2±355.6	45.0–90.0 65.3±22.8	166.1–179.0 170.5±7.3	209.0–255.0 227.2±24.4	184.4–213.0 195.3±15.4	182.0–192.0 188.0±5.2	0.7–1.1 0.9±0.2	0.1–0.4 0.2±0.1	5.3–6.4 6.1±0.4
Anthemis odontostephana Boiss.	4	1, 5	35.2–55.3 38.4±6.9	108.0–354.3 165.4±115.0	166.2–373.0 245.3±91.1	96.3–117.1 104.2±9.2	78.0–96.1 86.2±7.4	411.1–2022.0 985.1±734.6	0.2–0.3 0.2±0.1	0.1–0.2 0.2±0.1	1.1–1.2 1.1±0.1
Artemisia sieberi Besser	5	1, 6	135.6–1012.7 345.2±375.2	46.6–214.0 106.2±64.0	63.1–207.0 127.4±52.5	75.4–224.3 128.6±56.6	46.2–280.3 154.2±83.9	144.2–1678.0 723.4±574.2	1.2–1.6 1.4±0.1	0.5–0.6 0.5±0.1	1.3–4.0 2.1±1.1
Filago arvensis L.	5	5, 6	4.0–5.6 4.6±0.6	87.0–111.3 92.1±10.5	63.2–166.0 104.5±37.9	96.3–131.3 104.2±15.8	53.0–77.2 62.5±9.3	144.0–411.0 258.4±98.2	0.3–0.4 0.3±0.1	0.2–0.3 0.2±0.1	0.7–1.3 1.0±0.2
Lactuca glaucifolia Boiss.	4	1, 5	145.2–186.4 155.6±21.6	24.0–38.0 31.4±5.7	166.2–373.0 253.1±87.5	183.0–234.8 206.3±21.0	154.0–197.0 172.8±17.9	256.0–2022.0 956.3±765.8	0.2–0.3 0.2±0.1	0.1–0.2 0.1±0.1	0.6–0.7 0.6±0.1
Scariola orientalis (Boiss.) Soják	5	1, 5	12.2–14.2 13.4±0.8	56.0–119.4 78.5±23.9	166.0–373.0 247.6±76.4	85.5–100.7 90.5±5.7	97.3–104.6 98.4±3.1	2022.1–2160.0 2085.3±49.1	0.1–0.2 0.2±0.1	<0.1	0.5–1.1 0.8±0.2
Scorzonera mucida Rech. F., Aellen & Esfand.	5	1, 6	30.4–1107.9 468.3±400.1	15.0–337.0 164.6±114.4	63.1–268.0 154.3±73.3	99.3–320.2 189.1±81.2	32.3–542.2 243.7±184.9	144.2–1817.0 865.1±614.0	0.1–0.6 0.3±0.1	0.8–0.9 0.8±0.1	1.1–4.1 2.6±1.1
Senecio glaucus L.	3	3	1023.4–1156.6 1148.8±122.6	240.2–256.3 248.0±8.0	521.4–567.3 559.0±34.6	474.2–487.3 480.2±6.5	468.3–476.2 471.8±4.0	1687.5–1743.2 1704.0±33.8	1.4–1.7 1.6±0.2	0.1–0.2 0.2±0.1	2.0–2.2 2.1±0.1
Boraginaceae											
Arnebia decumbens (Vent.) Coss. & Kralik	4	1, 5	550.2–2866.7 1407.3±1012.5	38.0–139.0 76.4±44.5	148.3–186.0 154.8±23.3	339.1–742.2 452.7±193.9	47.7–444.4 216.5±167.1	1270.0–1572.0 1378.5±137.0	0.5–1.2 0.8±0.3	0.1–0.2 0.2±0.1	1.1–4.1 2.6±1.2
Nonnea persica Boiss.	5	1, 5, 6	522.5–3074.5 2563.2±1140.7	22.3–743.0 354.2±260.4	63.1–373.0 192.7±113.3	127.8–1292.3 698.4±412.1	41.5–186.1 103.8±53.4	144.0–2022.0 895.7±690.1	0.4–0.5 0.4±0.1	0.4–0.9 0.6±0.1	2.1–2.6 2.3±0.2
Onosma stenosiphon Boiss.	5	1, 5	27.8–46.6 32.4±7.7	23.0–30.4 24.5±3.1	166.3–373.0 248.9±76.1	87.0–106.0 92.6±7.8	45.0–58.7 49.2±5.5	411.0–2022.0 987.6±613.9	0.9–1.2 1.1±0.1	0.8–0.9 0.8±0.1	1.4–2.1 1.7±0.3
Paracaryum strictum Boiss.	3	3	1234.2–1387.4 1339.2±91.4	175.2–194.3 184.0±9.7	673.5–934.2 801.0±130.5	211.4–245.3 238.2±17.1	200.6–235.4 230.8±27.9	1410.6–1749.7 1658.0±194.6	0.2–0.4 0.3±0.1	0.2–0.3 0.3±0.1	1.0–1.3 1.1±0.1
Brassicaceae											
Fortuynia bungei Boiss.	3	5	1634.2–1768.4 1720.1±74.7	68.4–75.4 73.0±4.0	112.4–134.3 127.0±12.7	423.4–463.2 451.4±24.4	398.5–410.3 409.2±11.02	1284.3–1299.8 1292.0±7.4	0.5–0.7 0.6±0.1	0.3–0.5 0.4±0.1	1.2–1.4 1.3±0.1
Malcolmia africana (L.) R. Br.	4	1, 6	75.2–1434.4 554.3±601.0	70.8–100.1 74.5±17.9	63.1–191.0 126.4±52.2	166.0–388.3 214.6±120.5	178.4–369.3 256.1±81.6	654.0–1230.0 794.1±282.6	1.8–2.1 1.9±0.1	0.7–0.8 0.7±0.1	2.1–6.1 4.1±1.6
Capparidaceae											
Cleome coluteoides Boiss.	5	1, 5	70.8–258.9 154.2±77.7	70.8–78.9 72.3±5.1	166.1–373.0 252.1±88.0	60.5–111.7 84.7±20.9	38.0–113.1 68.3±32.2	411.2–2022.0 934.1±769.6	0.1–0.3 0.2±0.1	<0.1	0.6–0.9 0.7±0.1

Table 2 (continued)

Species	No. of sample	Site	Pb			Zn			Ag		
			Roots	Shoots	Soil	Roots	Shoots	Soil	Roots	Shoots	Soil
Caryophyllaceae											
Acanthophyllum bracteatum Boiss.	5	1, 5	43.2–78.9 50.3±15.9	53.0–143.6 86.5±34.5	166.2–373.0 243.1±82.0	43.8–88.6 62.6±16.6	5.3–9.2 6.8±1.5	411.1–2022.0 892.7±654.1	0.3–0.4 0.3±0.1	0.2–0.3 0.2±0.1	0.7–0.8 0.7±0.1
Chenopodiaceae											
Londesia eriantha Fisch. & C.A. Mey.	4	5, 6	21.9–35.7 24.1±5.1	2.0–5.3 3.2±1.4	63.2–166.0 98.4±46.2	114.0–341.8 212.5±95.0	54.2–74.7 58.3±8.5	144.1–411.0 256.5±116.9	0.2–0.3 0.2±0.1	0.5–0.9 0.7±0.2	0.2–0.4 0.3±0.1
Salsola nitraria Pall.	5	1, 4	78.9–1053.5 435.2±371.9	48.0–201.5 98.6±61.1	113.1–2184.0 985.2±751.2	155.1–300.7 225.4±61.3	228.4–957.0 573.5±258.4	416.0–2160.0 1145.3±642.0	0.8–1.3 1.1±0.2	0.1–0.2 0.2±0.1	1.2–4.2 2.7±1.1
Colchicaceae											
Colchicum schimperi Janka ex Stef.	3	1	118.4–124.5 119.4±2.2	98.4–116.8 115.9±17.7	356.8–386.2 373.0±15.3	113.4–128.5 123.0±8.4	13.8–14.3 13.9±0.3	1946.3–2134.6 2022.0±99.0	1.0–1.2 1.1±0.1	1.4–1.7 1.6±0.1	0.6–0.9 0.8±0.1
Euphorbiaceae											
Euphorbia gedrosiaca Rech. F., Aellen & Esfand.	4	1, 4	254.0–434.5 332.1±92.3	45.6–67.6 52.1±11.3	375.1–1022.0 564.9±328.2	457.0–788.1 512.4±94.9	70.4–90.1 73.4±5.7	2011.0–2022.0 2014.7±6.3	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.4–0.7 0.5±0.1
Fabaceae											
Astragalus durandianus Aitch. & Baker	3	1	1145.2–1212.3 1189.5±38.6	121.4–146.8 137.0±13.8	212.8–256.7 241.0±25.1	244.6–274.5 265.1±17.2	342.4–368.2 357.8±13.7	1256.8–1321.4 1296.0±35.2	2.2–2.6 2.5±0.2	0.4–0.6 0.5±0.1	2.6–3.1 2.9±0.2
Geraniaceae											
Erodium cicutarium (L.) L Her.	3	3	1334.2–1628.4 1516.0±159.2	98.2–120.5 110.4±11.1	610.2–653.8 637.0±23.4	321.7–367.6 348.1±24.0	310.1–316.3 314.2±3.5	318.4–362.1 344.0±23.0	0.5–0.8 0.7±0.2	0.3–0.4 0.4±0.1	4.0–4.2 4.1±0.1
Lamiaceae											
Lallemantia royleana (Benth.) Benth.	5	1, 4	234.7–303.8 254.5±29.7	156.0–232.5 193.3±26.8	373.0–2184.0 567.4±433.0	189.0–255.0 203.8±31.7	42.5–63.2 51.7±7.7	2022.0–2160.0 2086.3±50.3	0.4–0.5 0.4±0.1	0.7–2.1 1.4±0.4	0.4–0.6 0.5±0.1
Mentha longifolia L.	3	6	2011.3–2276.3 2168.9±139.6	120.1–127.2 125.0±4.0	56.2–59.6 58.0±1.5	413.5–429.3 424.5±9.4	185.4–201.9 196.2±9.7	135.3–154.2 147.0±10.4	5.6–5.8 5.7±0.1	3.1–3.4 3.2±0.1	5.8–6.1 6.0±0.1
Thuspeinantha persica (Boiss.) Briq.	3	1	132.4–157.3 146.0±12.7	112.5–134.3 123.7±11.06	356.8–386.2 373.0±15.3	144.2–167.4 157.3±12.0	109.7–124.5 119.4±8.6	1964.2–2126.4 2022.0±90.2	1.1–1.3 1.2±0.1	3.4–3.8 3.6±0.2	0.3–0.4 0.4±0.1
Liliaceae											
Allium umbilicatum Boiss.	3	6	1234.2–1278.3 1257.6±22.1	75.4–84.3 80.0±4.5	23.1–26.8 25.0±1.7	309.2–324.1 318.4±8.2	254.8–293.1 283.2±17.3	1070.4–1089.3 1081.0±9.8	0.2–0.4 0.3±0.1	0.1–0.2 0.2±0.1	1.1–1.4 1.3±0.1
Papaveraceae											
Fumaria parviflora L.	5	2, 4	123.0–259.5 191.0±68.0	10.0–14.2 11.8±2.0	2184.0–3511.0 2546.7±576.3	95.3–132.2 112.8±18.5	24.2–36.3 28.4±6.5	2160.0–2354.0 2210.4±87.1	0.2–0.3 0.2±0.1	0.1–0.2 0.2±0.1	0.3–0.4 0.3±0.1
Glaucium elegans Fisch. & Mey.	4	1, 5	21.9–155.4 79.3±68.6	46.6–233.1 128.4±95.4	166.3–373.0 213.5±82.5	60.8–243.2 147.4±91.7	32.0–104.2 59.2±39.1	411.0–2022.0 1095.8±832.2	1.0–1.1 1.1±0.1	0.1–0.2 0.2±0.1	1.3–1.7 1.5±0.2
Onobrychis aucheri Boiss.	4	5	226.5–1611.2 719.3±611.6	45.4–100.1 68.4±23.2	91.2–166.0 128.7±30.6	351.7–541.3 432.1±79.9	76.0–272.5 153.7±84.7	371.0–1121.0 564.3±371.3	0.2–0.4 0.3±0.1	0.1–0.2 0.2±0.1	1.3–1.4 1.4±0.1
Papaver dubium L.	5	1, 3	1064.0–1075.2 1069.4±4.0	110.0–200.2 147.4±33.0	248.4–855.0 432.5±249.6	256.0–296.6 268.2±16.9	230.0–251.2 237.4±8.2	1254.0–1471.0 1234.4±140.1	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	1.1–1.7 1.4±0.2
Poaceae											
Bromus tectorum L.	5	1, 4	102.6–182.3 134.2±29.8	23.7–37.2 28.3±5.3	373.1–2184.0 985.6±734.1	145.8–268.1 198.4±44.3	32.0–40.9 34.8±3.0	2022.1–2160.0 2083.6±49.6	0.4–0.6 0.5±0.1	0.9–1.3 1.1±0.1	0.3–0.4 0.3±0.1

Table 2 (continued)

Species	No. of sample	Site	Pb Roots	Pb Shoots	Pb Soil	Zn Roots	Zn Shoots	Zn Soil	Ag Roots	Ag Shoots	Ag Soil
Hordeum glaucum Steud.	5	1, 6	45.0–66.1 47.8±5.2	132.0–361.3 308.3±99.0	63.1–373.0 195.3±112.8	243.1–262.2 251.3±6.8	127.3–186.4 148.9±22.4	144.1–2022.0 989.8±673.6	0.3–0.4 0.3±0.1	0.5–0.8 0.6±0.1	0.3–0.6 0.4±0.1
Polygonaceae											
Rheum ribes L.	3	6	12.1–15.2 14.3±1.1	50.3–56.3 54.7±2.3	61.2–65.8 63.0±2.0	62.5–68.9 66.5±2.8	21.7–32.1 29.2±5.1	131.5–156.2 144.0±12.5	0.2–0.4 0.2±0.1	0.1–0.2 0.2±0.1	1.0–1.2 1.1±0.1
Resedaceae											
Reseda lutea L.	3	1, 5	112.2–135.6 123.5±11.5	14.2–19.2 15.8±2.8	166.4–373.0 243.6±112.7	65.0–86.1 71.7±12.1	15.3–19.7 16.8±2.0	411.3–2022.0 1034.6±864.6	0.2–0.3 0.2±0.1	0.1–0.2 0.2±0.1	0.4–0.6 0.5±0.1
Solanaceae											
Hyoscyamus senecionis Willd.	4	5, 6	54.6–78.5 65.7±12.0	4.0–7.2 5.3±1.6	63.1–166.0 103.8±54.6	116.0–133.1 122.8±9.1	95.0–103.2 98.6±4.0	144.0–411.0 205.7±106.5	0.5–0.7 0.6±0.1	0.1–0.2 0.2±0.1	0.6–1.2 0.9±0.3
Zygophyllaceae											
Peganum harmala L.	5	1, 2, 5, 6	87.0–1801.6 734.5±636.7	6.1–171.0 76.4±60.1	63.2–3511.0 1345.3±1297.1	73.6–353.0 165.1±108.2	8.9–318.8 127.4±114.3	144.2–4415.0 1893.5±1558.5	0.1–0.6 0.3±0.1	0.2–0.3 0.2±0.1	1.0–3.7 2.3±0.9

reports of Zn concentrations in plants growing on mine-impacted soils and tailings. For example, research conducted by Stoltz and Greger (2002) reported Zn concentrations of 68–1630 mg kg^{-1} in plant biomass and those given by Shu et al. (2002a) showed 66–7607 mg kg^{-1} in plant biomass sampled from metalliferous mine sites in China.

Silver is one of the most toxic metals and its concentration in plant tissues is usually <0.01 mg kg^{-1} (Kabata-Pendias 2011), although it can be higher in plants from regions of Pb and Ag mining. As shown in Table 2, among the sampled plants, *Colchicum schimperi*, *Londesia eriantha*, *Lallemantia royleana*, *Bromus tectorum*, *Mentha longifolia*, and *T. persica* accumulated slightly elevated concentrations of Ag. In the absence of definitive information, the hyperaccumulation threshold for Ag has provisionally been set at the very low value of 1 mg kg^{-1} (Baker et al. 2000).

Issues of metals and metalloids toxicity do not generally arise in the case of populations of native species colonizing metalliferous mine wastes as these plants often become adapted over time (by natural selection of tolerant individuals) to the locally elevated metals and/or metalloid concentrations (Varun et al. 2012; D'Souza et al. 2013). These species may be more suitable for use as phytoremediators of wastelands than introduced metal hyperaccumulators such as *Noccaea* (*Thlaspi*) *caerulescens* and *Alyssum bertolonii Desv.* because the latter have generally slowly grown with shallow root systems and have a low biomass (Saraswat and Rai 2009; D'Souza et al. 2010; Varun et al. 2011).

Plants exhibiting TF and particularly BCF values >1 are suitable for phytoextraction and may have some potential for phytoextraction, whereas plants with a BCF >1 and a TF <1 could have use in phytostabilization (Yoon et al. 2006). Thus, from Table 3 data, some of the sampled plant species could be suitable for phytoextraction or phytostabilization of Pb, Zn, and Ag. *N. persica*, *Achillea wilhelmsii*, *Erodium cicutarium*, and *M. longifolia* were the most suitable for phytostabilization of Pb and Zn. Whereas *C. schimperi*, *L. eriantha*, *L. royleana*, *B. tectorum*, *H. glaucum*, and *T. persica* are considered the most promising species for phytoextraction of Ag-enriched sites and *F. assa-foetida* the most efficient in the phytostabilization of Pb, Zn, and Ag. Almost all the plant species collected showed metal concentrations higher than the normal or even reported phytotoxic levels. These results may indicate that plant species growing on this site contaminated with Pb, Zn, and Ag are tolerant of these metals. Restriction of upward movement of metals/metalloids from roots into shoots can be considered as one of the tolerance mechanisms operated by plants (Verkleij and Schat 1990). Phytostabilization can therefore be used to minimize migration of contaminants in soils and subsequently into the food chain (Susarla et al. 2002). In South China, pioneer species such as the grasses *Cynodon dactylon* L., *Imperata cylindrica* var. *major*, *Paspalum notatum* Flügge, *Vetiveria zizanioides*

Table 3 Mean and range of the bioaccumulation factor (BCF) and the translocation factor (TF) of Pb, Zn, and Ag of the plants collected in the Koshk mining area

Species	No. of sample	Site	Bioconcentration factor (BCF)			Translocation factor (TF)		
			Pb	Zn	Ag	Pb	Zn	Ag
Apiaceae								
Dorema ammoniacum D. Don	3	3	*2.6–2.9*	0.1–0.2	0.4–0.5	0.1–0.2	0.8–0.9	0.3–0.4
			2.8±0.2	0.2±0.1	0.4±0.1	0.2±0.1	0.8±0.1	0.3±0.1
Ducrosia anethifolia (DC.) Boiss.	5	3, 6	*0.9–2.1*	0.2–0.5	0.1–0.2	0.1–0.2	0.3–0.8	*1.0–1.5*
			1.9±0.5	0.3±0.1	0.2±0.1	0.2±0.1	0.5±0.2	*1.2±0.1*
Eryngium billardieri Delile	3	6	0.1–0.2	0.5–0.6	0.2–0.3	0.6–0.7	0.3–0.4	0.3–0.5
			0.2±0.1	0.5±0.1	0.3±0.1	0.6±0.1	0.3±0.1	0.4±0.1
Ferula assa-foetida L.	3	6	*1.4–1.6*	*1.0–1.2*	*1.3–1.4*	0.1–0.3	0.2–0.9	0.1–0.2
			1.4±0.1	*1.2±0.1*	*1.3±0.1*	0.2±0.1	0.5±0.4	0.2±0.1
Asteraceae								
Achillea wilhelmsii C. Koch	5	1, 5	*7.4–8.1*	*0.8–1.1*	0.1–0.2	0.1–0.2	0.8–0.9	0.1–0.4
			7.7±0.3	*1.0±0.1*	0.2±0.1	0.2±0.1	0.8±0.1	0.2±0.1
Anthemis odontostephana Boiss.	4	1, 5	0.1–0.2	0.1–0.2	0.2–0.3	*5.0–6.4*	0.7–0.8	0.1–0.2
			0.2±0.1	0.2±0.1	0.2±0.1	*5.7±0.5*	0.8±0.1	0.2±0.1
Artemisia sieberi Besser	5	1, 6	*2.1–4.8*	0.1–0.8	0.4–0.9	0.2–0.3	0.6–*1.2*	0.3–0.4
			3.4±1.0	0.4±0.3	0.6±0.2	0.2±0.1	*1.1±0.3*	0.3±0.1
Filago arvensis L.	5	5, 6	0.1–0.2	0.2–0.9	0.3–0.4	*19.6–21.7*	0.5–0.6	0.7–0.8
			0.2±0.1	0.5±0.3	0.3±0.1	*20.6±0.9*	0.5±0.1	0.7±0.1
Lactuca glaucifolia Boiss.	4	1, 5	0.4–0.8	0.1–0.7	0.3–0.4	0.1–0.2	0.7–0.8	0.5–0.6
			0.6±0.2	0.4±0.3	0.3±0.1	0.2±0.1	0.8±0.1	0.5±0.1
Scariola orientalis (Boiss.) Soják	5	1, 5	0.1–0.2	0.1–0.2	0.1–0.2	*4.5–8.3*	*1.0–1.1*	0.2–0.3
			0.2±0.1	0.2±0.1	0.2±0.1	*7.4±1.6*	*1.1±0.1*	0.2±0.1
Scorzonera mucida Rech. F., Aellen & Esfand.	5	1, 6	0.4–*4.1*	0.1–0.6	0.1–0.2	0.3–0.4	0.4–*1.6*	*1.5–8.0*
			3.2±1.5	0.3±0.2	0.2±0.1	0.3±0.1	*1.2±0.5*	*4.7±2.3*
Senecio glaucus L.	3	3	*1.9–2.0*	0.2–0.3	0.7–0.8	0.2–0.5	0.8–0.9	0.1–0.2
			2.0±0.1	0.2±0.1	0.7±0.1	0.5±0.2	0.9±0.1	0.2±0.1
Boraginaceae								
Arnebia decumbens (Vent.) Coss. & Kralik	4	1, 5	*3.7–15.4*	0.2–0.3	0.3–0.4	0.1–0.2	0.1–0.9	0.1–0.3
			10.5±4.9	0.2±0.1	0.3±0.1	0.2±0.1	0.5±0.3	0.2±0.1
Nonnea persica Boiss.	5	1, 5, 6	*6.0–8.2*	0.1–*1.3*	0.1–0.2	0.2–0.5	0.1–0.9	*1.0–1.8*
			6.4±1.0	*1.1±0.5*	0.2±0.1	0.3±0.1	0.5±0.3	*1.4±0.3*
Onosma stenosiphon Boiss.	5	1, 5	0.1–0.2	0.1–0.2	0.5–0.6	0.6–0.7	0.5–0.6	0.7–0.8
			0.2±0.1	0.2±0.1	0.5±0.1	0.6±0.1	0.5±0.1	0.7±0.1
Paracaryum strictum Boiss.	3	3	*1.4–1.8*	0.1–0.2	0.2–0.3	0.1–0.2	0.8–0.9	*0.7–1.0*
			1.6±0.2	0.2±0.1	0.2±0.1	0.2±0.1	0.9±0.1	*1.0±0.2*
Brassicaceae								
Fortuynia bungei Boiss.	3	5	*13.5–14.5*	0.3–0.4	0.4–0.5	0.1–0.2	0.8–0.9	0.6–0.7
			13.5±1.0	0.3±0.1	0.4±0.1	0.2±0.1	0.9±0.1	0.6±0.1
Malcolmia africana (L.) R. Br.	4	1, 6	*0.3–7.5*	0.2–0.3	0.3–0.8	0.1–0.9	*0.4–2.2*	0.3–0.4
			5.9±2.5	0.2±0.1	0.5±0.2	0.5±0.3	*1.8±0.9*	0.3±0.1
Capparidaceae								
Cleome coluteoides Boiss.	5	1, 5	0.4–0.6	0.1–0.2	0.2–0.3	0.3–*1.0*	0.3–*1.8*	0.2–0.3
			0.5±0.1	0.2±0.1	0.2±0.1	*1.0±0.1*	*1.1±0.5*	0.2±0.1
Caryophyllaceae								
Acanthophyllum bracteatum Boiss.	5	1, 5	0.2–0.3	0.1–0.2	0.4–0.5	*1.2–1.8*	0.1–0.2	0.7–0.8
			0.2±0.1	0.2±0.1	0.4±0.1	*1.5±0.2*	0.2±0.1	0.7±0.1
Chenopodiaceae								
Londesia eriantha Fisch. &C.A. Mey.	4	5, 6	0.2–0.3	0.7–0.8	*0.7–1.0*	0.1–0.2	0.2–0.3	*2.5–3.0*
			0.2±0.1	0.7±0.1	*1.0±0.1*	0.2±0.1	0.2±0.1	*2.7±0.2*
Salsola nitraria Pall.	5	1, 4	*0.1–9.3*	0.1–0.6	0.3–0.7	0.1–0.6	*1.4–3.6*	0.1–0.2
			6.7±3.8	0.3±0.2	0.5±0.2	0.3±0.2	*2.9±0.9*	0.2±0.1

Table 3 (continued)

Species	No. of sample	Site	Bioconcentration factor (BCF)			Translocation factor (TF)		
			Pb	Zn	Ag	Pb	Zn	Ag
Colchicaceae								
Colchicum schimperi Janka ex Stef.	3	1	0.2–0.3 0.3±0.1	0.1–0.2 0.2±0.1	*1.3–1.6* *1.3±0.1*	0.8–0.9 0.9±0.1	0.1–0.2 0.2±0.1	*1.3–1.4* *1.4±0.1*
Euphorbiaceae								
Euphorbia gedrosiaca Rech. F., Aellen & Esfand.	4	1, 4	0.4–0.6 0.5±0.1	0.2–0.3 0.2±0.1	0.2–0.3 0.3±0.1	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.5–0.6 0.5±0.1
Fabaceae								
Astragalus durandianus Aitch. & Baker	3	1	*4.7–4.9* *4.9±0.1*	0.1–0.2 0.2±0.1	0.7–0.8 0.8±0.1	0.1–0.2 0.2±0.1	*1.3–1.4* *1.3±0.1*	0.1–0.2 0.2±0.1
Geraniaceae								
Erodium cicutarium (L.) L Her.	3	3	*2.0–2.3* *2.3±0.1*	*1.0–1.1* 1.0±0.1	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.8–0.9 0.9±0.1	0.5–0.6 0.6±0.1
Lamiaceae								
Lallemantia royleana (Benth.) Benth.	5	1, 4	0.1–0.6 0.3±0.2	0.1–0.2 0.2±0.1	0.8–*1.0* *1.0±0.1*	0.6–0.7 0.6±0.1	0.1–0.2 0.2±0.1	*1.7–4.2* *2.9±0.9*
Mentha longifolia L.	3	6	*37.1–37.5* *37.4±0.2*	*2.7–3.0* *2.8±0.2*	0.8–0.9 0.9±0.1	0.1–0.2 0.2±0.1	0.4–0.5 0.4±0.1	0.5–0.6 0.5±0.1
Thuspeinantha persica (Boiss.) Briq.	3	1	0.3–0.4 0.3±0.1	0.1–0.2 0.2±0.1	*3.0–3.1* *3.0±0.1*	0.8–0.9 0.8±0.1	0.7–0.8 0.7±0.1	*2.9–3.1* *3.0±0.1*
Liliaceae								
Allium umbilicatum Boiss.	3	6	*49.8–50.5* *50.3±0.4*	0.2–0.3 0.2±0.1	0.2–0.3 0.2±0.1	0.1–0.3 0.1±0.1	0.8–0.9 0.8±0.1	0.6–0.7 0.7±0.1
Papaveraceae								
Fumaria parviflora L.	3	2, 4	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.7–0.8 0.7±0.1	0.1–0.2 0.2±0.1	0.2–0.3 0.2±0.1	0.5–0.7 0.6±0.1
Glaucium elegans Fisch. & Mey.	4	1, 5	0.1–0.4 0.2±0.1	0.1–0.2 0.2±0.1	0.6–0.7 0.6±0.1	*1.5–2.1* *1.8±0.2*	0.4–0.5 0.4±0.1	0.1–0.2 0.2±0.1
Onobrychis aucheri Boiss.	4	5	*2.4–9.7* *6.1±2.9*	0.4–0.8 0.6±0.2	0.2–0.3 0.2±0.1	0.1–0.2 0.2±0.1	0.2–0.5 0.3±0.2	0.2–0.3 0.3±0.1
Papaver dubium L.	5	1, 3	*1.7–5.0* *4.3±1.5*	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.8–0.9 0.8±0.1	0.4–0.5 0.5±0.1
Poaceae								
Bromus tectorum L.	5	1, 4	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	*1.3–1.4* *1.3±0.1*	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	*2.2–2.3* *2.2±0.1*
Hordeum glaucum Steud.	5	1, 6	0.1–0.7 0.4±0.2	0.1–0.5 0.3±0.1	*0.7–1.0* *1.0±0.1*	*2.9–5.4* *4.1±1.0*	0.5–0.7 0.6±0.1	*1.7–2.0* *1.8±0.1*
Polygonaceae								
Rheum ribes L.	3	6	0.1–0.2 0.2±0.1	0.4–0.5 0.4±0.1	0.2–0.3 0.2±0.1	*3.7–4.1* *3.8±0.2*	0.3–0.5 0.4±0.1	0.4–0.5 0.5±0.1
Resedaceae								
Reseda lutea L.	3	1, 5	0.3–0.6 0.4±0.2	0.1–0.2 0.2±0.1	0.4–0.5 0.5±0.1	0.1–0.2 0.2±0.1	0.2–0.3 0.2±0.1	0.5–0.6 0.5±0.1
Solanaceae								
Hyoscyamus senecionis Willd.	4	5, 6	0.4–0.8 0.6±0.2	0.2–0.9 0.5±0.3	0.6–0.8 0.7±0.1	0.1–0.2 0.2±0.1	0.7–0.8 0.7±0.1	0.1–0.2 0.2±0.1
Zygophyllaceae								
Peganum harmala L.	5	1, 2, 5, 6	0.5–*1.3* *1.1±0.3*	0.1–0.5 0.3±0.2	0.1–0.2 0.2±0.1	0.1–0.2 0.2±0.1	0.1–0.9 0.5±0.3	0.5–*2.0* *1.2±0.5*

BCF and TF values >1 are in italics

L., and the herb *Sesbania rostrata* Bremek. & Oberm. (Wong 2003) have been shown to be suitable for phytoremediation of a Pb/Zn mine. In this study, the Pb concentrations in the plant roots remained higher than the concentrations in the shoots. Some species also showed variable accumulation patterns for metals at different soil concentrations. This difference was also noted between parts of the same plant suggesting that full consideration of plant–soil interactions should be taken into account when selecting plant species for use in phytoremediation.

5 Conclusions

This study was conducted to screen plants growing on a contaminated site to determine their potential for metal accumulation. Only species with both BCFs and TFs >1 have any potential for phytoextraction. Among the 40 species screened, several plants had BCFs or TFs >1. *N. persica*, *A. wilhelmsii*, *E. cicutarium*, and *M. longifolia* were most effective in taking up all three metals, with BCFs ranging from 1 to 37. Among those plant species collected from the contaminated site, *C. schimperi*, *L. eriantha*, *L. royleana*, *B. tectorum*, *H. glaucum*, and *T. persica* are considered the most promising species for phytoextraction in soils with elevated Ag. *Peganum harmala* is suggested as the most effective species in the phytostabilization of soils contaminated with Pb. The phytoremediation potential of all these plant species needs to be further investigated.

Acknowledgments We would like to thank the graduate School of University of Isfahan for providing the research facilities for this study. We also would like to thank from Plant Stress Center of Excellence (University of Isfahan) and also Graduate University of Advanced Technology—Kerman for their support for this study. We thank S. M. Mir Tajadiny for his help in the identification of plant species. Professor A. J. M. Baker (University of Melbourne, Australia) kindly assisted with the final refinement of the paper.

References

Abdel-Ghani NT, Hefny M, El-Chagbaby GAF (2007) Removal of lead from aqueous solution using low cost abundantly available adsorbents. Int J Environ Sci Technol 4(1):67–73

Abioye OP, Agamuthu P, Abdul AA (2012) Phytotreatment of soil contaminated with used lubricating oil using *Hibiscus cannabinus*. Biodegradation 23:277–286

Alloway BJ (ed) (1994) Toxic metals in soil–plant systems. John Wiley and Sons, Chichester

Alloway BJ (ed) (1995) Heavy metals in soils. Edmundsbury Press, London

Alloway BJ, Jackson AP, Morgan H (1990) The accumulation of cadmium by vegetables grown on soils contaminated from a variety of sources. Sci Total Environ 91:223–236

Baker AJM, McGrath SP, Reeves RD, Smith JAC (2000) Metal hyperaccumulator plants: a review of the ecology and physiology of a biological resource for phytoremediation of metal-polluted soils. In: Terry N, Bañuelos G (eds) Phytoremediation of contaminated soil and water. Lewis, Boca Raton, pp 85–107

Boyle RW (1968) The geochemistry of silver and its deposits (Geological Survey of Canada Bulletin No. 160, 264 pp). Department of Energy Mines and Resources, Ottawa

Cao X, Ma LQ, Chen M (2002) Impacts of phosphate amendments on lead biogeochemistry in a contaminated site. Environ Sci Technol 36:5296–5304

D'Souza R, Varun M, Masih J, Paul MS (2010) Identification of *Calotropis procera* L. as a potential phytoaccumulator of heavy metals from contaminated soils in Urban North Central India. J Hazard Mater 184:457–464

D'Souza R, Varun M, Pratas J, Paul MS (2013) Spatial distribution of heavy metals in soil and flora associated with the glass industry in north central India: implications for phytoremediation. Soil Sediment Contam 22:1–20

Dahmani-Muller H, Van Oort F, Gelie B, Balaban M (2000) Strategies of heavy metal uptake by three plant species growing near metal smelter. Environ Pollut 109:231–238

Fitz WJ, Wenzel WW (2002) Arsenic transformation in the soil–rhizosphere-plant system, fundamentals and potential application of phytoremediation. J Biotechnol 99:259–278

Ghaderian SM, Baker AJM (2007) Geobotanical and biogeochemical reconnaissance of the ultramafics of Central Iran. J Geochem Explor 92:34–42

Ghaderian SM, Ghotbi Ravandi AA (2012) Accumulation of copper and other heavy metals by plants growing on Sarcheshmeh copper mining area, Iran. J Geochem Explor 123:25–32

Ghaderian SM, Hemmat GR, Reeves RD, Baker AJM (2007) Accumulation of lead and zinc by plants colonizing a metal mining area in central Iran. J Appl Bot Food Qual 81:145–150

Gryschko R, Kuhnle R, Terytze K, Breuer J, Stahr K (2004) Soil extraction of readily soluble heavy metals and as with 1 M NH_4NO_3-solution. J Soils Sediments 4:1–6

Harris JA, Birch P, Palmer JP (1996) Land restoration and reclamation: principles and practice. Longman, London

Jalili A, Jamzad Z (1999) Red data book of Iran. RIFR, Tehran

Kabata-Pendias A (2011) Trace elements in soils and plants, 4th edn. CRC Press, Boca Raton

Kim IS, Kang HK, Johnson-Green P, Lee EJ (2003) Investigation of heavy metal accumulation in *Polygonum thunbergii* for phytoextraction. Environ Pollut 126:235–243

Lorenz SE, Hamon RE, Holm PE, Domingues HC, Sequeria EM (1997) Cadmium and zinc in plants and H2O-extracts from contaminated soils. Plant Soil 189:21–23

Ma LQ, Komar KM, Tu C, Zhang WA (2001) A fern that hyperaccumulates arsenic. Nature 409:579

McGrath SP, Zhao FJ, Lombi E (2002) Phytoremediation of metals, metalloids, and radionuclides. Adv Agron 75:1–56

Mulligan CN, Yong RN, Gibbs BF (2001) Remediation technologies for metal-contaminated soils and groundwater, an evaluation. Eng Geol 60:193–207

Otero XL, Alvarez E, Fernandez-Sanjurjo MJ, Macias F (2012) Micronutrients and toxic trace metals in the bulk and rhizospheric soil of the spontaneous vegetation at an abandoned copper mine in Galicia (NW Spain). J Geochem Explor 112:84–92

Pilon-Smits E (2005) Phytoremediation. Annu Rev Plant Biol 56:15–39

Pitchtel J, Kuroiwa K, Sawyerr HT (2000) Distribution of Pb, Cd and Ba in soils and plants of two contaminated sites. Environ Pollut 110: 171–178

Pollard AJ, Powell KD, Harper FA, Smith JAC (2002) The genetic basis of metal hyperaccumulation in plants. Crit Rev Plant Sci 21:539–566

Quezada-Hinojosa R, Föllmi KB, Gillet F, Matera V (2015) Cadmium accumulation in six common plant species associated with soils containing high geogenic cadmium concentrations at Le Gurnigel, Swiss Jura Mountains. Catena 124:85–96

Reeves RD, Baker AJM (2000) Metal accumulating plants. In: Raskin I, Ensley BD (eds) Phytoremediation of toxic metals: using plants to clean up the environment. John Wiley and Sons Inc., New York, pp 193–229

Salt DE, Blaylock M, Kumar NPBA, Dushenkov V, Ensley BD, Chet I, Raskin I (1995) Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13:468–474

Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Physiol Plant Mol Biol 49:643–668

Saraswat S, Rai JPN (2009) Phytoextraction potential of six plant species grown in multimetal contaminated soil. Chem Ecol 25:1–11

Shu WS, Xia HP, Zhang ZQ, Lan CY, Wong MH (2002a) Use of vetiver and three other grasses for revegetation of Pb/Zn mine tailings: field experiment. Int J Phytoremediation 4:47–57

Shu WS, Ye ZH, Lan CY, Zhang ZQ, Wong MH (2002b) Lead, zinc and copper accumulation and tolerance in populations of *Paspalum distichum* and *Cynodon dactylon*. Environ Pollut 120:445–453

Srivastava J, Kalra SJS, Naraian R (2014) Environmental perspectives of *Phragmites australis* (Cav.) Trin. Ex. Steudel. Appl Water Sci 4: 193–202

Stoltz E, Greger M (2002) Accumulation properties of As, Cd, Cu, Pb and Zn by four wetland plant species growing on submerged mine tailings. Environ Exp Bot 47:271–280

Susarla S, Medina VF, McCutcheon SC (2002) Phytoremediation, an ecological solution to organic contamination. Ecol Eng 18:647–658

Thornton L (1999) Bioavailability of trace metals in the food chain. The 2nd International Vetiver Conference, Bangkok, Thailand

Van der Ent A, Baker AJM, Reeves RD, Pollard AJ, Schat H (2013) Hyperaccumulators of metal and metalloid elements: facts and fiction. Plant Soil 362:319–334

Varun M, D'Souza R, Kumar D, Paul MS (2011) Bioassay as monitoring system for lead phytoremediation through *Crinum asiaticum* L. Environ Monit Assess 178:373–381

Varun M, D'Souza R, Pratas J, Paul MS (2012) Metal contamination of soils and plants associated with the glass industry in North-central India: prospects of phytoremediation. Environ Sci Pollut Res 19: 269–281

Verkleij JAC, Schat H (1990) Mechanisms of metal tolerance in plants. In: Shaw AJ (ed) Heavy metal tolerance in plants—evolutionary aspects. CRC press, pp 179–93

Wenzel WW, Jockwer F (1999) Accumulations of heavy metals in plants grown on mineralized soils of the Austrian Alps. Environ Pollut 104:145–155

Wong MH (2003) Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. Chemosphere 50:775–780

Ye ZH, Baker AJM, Wong MH, Willis AJ (1997a) Copper and nickel uptake, accumulation and tolerance in populations of *Typha latifolia* L. New Phytol 136:469–480

Ye ZH, Baker AJM, Wong MH, Willis AJ (1997b) Zinc, lead and cadmium tolerance, uptake and accumulation by the common reed, *Phragmites australis* (Cav.) Trin ex Steudel. Ann Bot 80:363–370

Yoon J, Cao X, Zhou O, Ma LQ (2006) Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Sci Total Environ 368:456–464