Phytoremediation potential of plants growing spontaneously on abandoned coal mine wastes

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Abstract

Coal mining activities cause drastic perturbation of vegetation, soil and diffuse heavy metal to environment. Hence, identification of heavy metals tolerant species is essential for ecological restoration of mine impacted lands. This study aimed to assess the concentration of heavy metals in soils and the phytoremediation potential of 13 dominant plants naturally growing on abandoned coal waste dumps in northern Iran. Plant roots and shoots and the corresponding soils were sampled and then prepared, dried and milled in the laboratory. The results showed that metals concentration varied among plants and for each species between root and shoot. Majority of plants accumulated greater metals in aboveground biomass than belowground biomass, which indicates their effective metal translocating capacity. *Artemisia scoparia* and *Capparis spinosa* were contained the highest concentrations of Cu in shoot with 41.06 and 42.48 mg/kg, and TF>1 indicating the capacity for phytoextraction. The accumulation of Arsenic in the shoots and roots of *Sylibum marianum* was higher than normal. *Cynodon dactylon* and *Hordeum vulgare* were the only plants that accumulated >100 mg/kg Zn in the roots and can be recommended for phytostabilization. *S. marianum* and *Chenopodium album* potentially can be considered as Cd-accumulator. *Kochia prostrate* with BCF and TF < 1 for most detected metals is the only excluder species. The only indicator species for Vanadium was *S. marianum* with a transfer factor of 2.01. *S. marianum* and *Glaucium fimbriligerum* showed a tolerance mechanism to Strontium. The findings confirmed the potential of these plants in translocating of metal(loid)s from roots to the aerial parts.

1. Introduction

Coal is one of the most abundant and widespread mineral reserves that plays a major role in the world energy production and economy (Tripathi et al. 2016). Long term and devastating environmental drawbacks are exposed as the coal industry continued to expand (Wang et al. 2014). Some of these negative impacts in the local ecological conditions are soil and air pollution, land subsidence, surface and groundwater contamination, vegetation degradation, loss of biodiversity, and habitat destruction (Fan et al. 2003). Dumping of huge amounts of waste materials is another environmental problem caused by coal mining being heaped and abandoned around the mines without any remediation treatments (Freitas et al. 2004). These are the main sources of toxic elements causing adverse impact on surrounding environment (Finkelman 1994). Coal wastes are often inhospitable to natural plant due to low organic matter contents, acidic pH, nutrient deficiency, high sand content, low water-holding capacity, low microbial activities, and elevated levels of heavy metals (Tripathi et al. 2016). The non-biodegradability and the persistence of heavy metals in the soil allow them to be easily transferred to plant or animal organs and accumulate in human body through food chain (Pérez-López et al. 2014). There are more than twenty metal(loid)s reported in coal regions and surrounding soils in various countries (Finkelman 1994) which most of their average concentrations are higher than their respective values in world background soils (Sahoo et al. 2016). These trace elements can be released into the environment due to coal exploration and mining, as well as other coal processing activities such as transportation, crushing, washing and flotation (Zhang et al. 2016).

The waste management after finishing the mining operations has become an essential issue in ecological restoration (Zhu et al. 2018; Midhat et al. 2019). Different physical, chemical and biological methods have been used for treating heavy metals-contaminated soils (Alaboudi et al. 2018), but most of them are accompanied by costly and occasionally unfavorable effect to surrounding environment (Van der Ent et al. 2012). Phytoremediation is a widely used and cost-effective method known as an eco-friendly approach in reducing the impact of contaminants in the environment and effective factor on improving the soil structure and biodiversity (Ali et al. 2013; SutLohmann et al. 2023). It is based on the plant ability to stabilize, decontaminate and extract pollutants from the soil (McGrath et al. 2002). Since different plant species vary intensively in terms of the ability to accumulate and tolerate metals, a key step in phytoremediation strategy is plant selection (Monei et al. 2021). It is important to use plants from local species pool that can tolerate high concentrations of metal(loid)s and grow well in mine wastes with a potential of phytoremediation (Midhat et al. 2019). These indigenous and spontaneous plant species often act better than non-indigenous ones as they can survive, grow, reproduce under pollutants, and provide long-term sustainability of the landscape (Ameh and Aina 2020). Care must be taken when using exotic species as they may invade surrounding areas of native vegetation, or become a weed for the local agricultural lands (Maiti 2013).

In Iran, the most important coalfield regions based on quantity are in Tabas, Central Alborz, Kerman, and Eastern and Western Alborz (Osanloo 1999). There are several under-ground coal mines in the central Alborz region, which some of them were closed after the end of mine processing. The Hyrcanian forests in this area have been designated a UNESCO World Heritage Site since 2019. Over the last 10 years, several studies were carried out on the Alborz coal mines located in Mazandaran province (Lashgari et al. 2016; Hosseini-Kiasari 2016). In details, these studies highlighted that different autochthonous species are able to grow in these environments (Lashgari et al. 2016). Heavy metals accumulation in native vegetation on mining wastes in Iran has been reported for Cu mine (Alizadeh et al. 2022), Fe mine (Nouri et al. 2009), Lead-Zinc mine (Ghaderian et al. 2007; Lorestani et al. 2012) but little is known about heavy metals concentration in autochthonous plants surrounding coal mining wastes. Therefore, this study was done to evaluate the coal wastes pollution level and phytoremediation potential of selected plant species collected from the abandoned coal mining waste dumps in north of Iran. We aimed to assess the ability of 13 indigenous plant species growing on coal mine wastes to accumulate and translocate some important heavy metals and rare elements, the estimation of metal pollution in coal waste and compare the concentration of metals between the aboveground biomass and those in roots and the soil.

2. Materials and methods

2.1. Study area

This study was carried out in central Alborz coalfield at Karmozd mines in Savadkoh county (52º57'38" to 52º58'12" E and 36º05'57" to 36º06'53" N) and Kiasar mines in Sari county (53º34'36" to 53º35'28" E and 36º15'48" to 36º16'04" N) both located in Mazandaran province (Hyrcanian region). The underground exploitation in Karmozd and Kiasar coal mines started in 1971 and 1983, respectively. In terms of coal classification, the reserves of coal at Karmazd and Kiasar regions are anthracite and cocking coal, respectively (Yazdi 2003). Both sites were affected by coal minerals exploitation with a large volume of coal wastes that have been abandoned. The composition of coal wastes are largely characterized by argillite with a high amount of weathering

(Yazdi 2003). The wastes were spread around the mine and in the surrounding environment without treatment and management plans. The resulting extensive spoil heaps were often left to spontaneous succession. Both sites are characterized by humid cold weather. The mean annual rainfall and temperature in Karmozd are 536.5 mm and 10.9°C and in Kiasar are 520.3 mm and 13.2°C, respectively.

2.2. Plant and soil sampling and analysis

Primary field survey showed natural revegetation on coal waste with a composition of grasses, forbs, sub-shrubs, and shrubs. A total of 13 plant species were collected from dumping sites belonging to seven plant families and a combination of different life forms and life spans (Table 1) which were the most abundant and representative species on waste dump. Plant sampling was performed in April to June 2018 according to the phenological period. For each species three to four specimens were randomly selected and for each sample, one to three individual plants were randomly collected. Plant roots and shoot were sampled separately and kept in polyethylene bags for transport to the laboratory until further analysis. In the laboratory, all plant samples were thoroughly washed once with tap water and then three times with distilled water. The plant samples were oven dried at 70°C for 48 hours and ground to a fine powder for chemical and elemental analysis. For analyzing the metals content in plant organs, one-gram dry weight powdered of shoot and root material of each species were digested with a 4:1 ratio of concentrated nitric acid (HNO_3)/ perchloric acid ($HClO_4$) (Zhu et al., 2018). The obtained extract from digested samples was analyzed for the total content of metals (Al, Fe, Cu, Zn, Mn, Cr, Ni, Co, Sr, Mo, V, Pb, As, and Cd) by an inductively coupled plasma mass spectrometry (Agilent 7900 ICP-MS).

Table 1
Dominant plant species growing on coal waste in Mazandaran Province, Iran

Species	Family	Abbreviation	Life span	Life form
Artemisia absinthium L.	Asteraceae	Ar.ab	Perennial	Chamaephyte
Artemisia aucheri Boiss.	Asteraceae	Ar.au	Perennial	Chamaephyte
Artemisia scoparia Waldst. & Kit.	Asteraceae	Ar.sc	Biennial	Chamaephyte
Capparis spinosa L.	Capparidaceae	Ca.sp	Perennial	Chamaephyte
Chenopodium album L.	Chenopodiaceae	Ch.al	Annual	Therophyte
Cynodon dactylon (L.) Pers.	Poaceae	Cy.da	Perennial	Cryptophyte
Glaucium fimbriligerum Boiss.	Papaveraceae	Gl.fi	Annual	Therophyte
Hordeum vulgare L.	Poaceae	Ho.vu	Annual	Therophyte
Kochia prostrate (L.) Schrad.	Chenopodiaceae	Ko.pr	Perennial	Chamaephyte
Melica persica Kunth	Poaceae	Me.pe	Perennial	Hemicryptophyte
Polygonum aviculare L.	Polygonaceae	Po.av	Annual	Therophyte
Rapistrum rugosum (L.) All	Brassicaceae	Ra.ru	Annual	Therophyte
Sylibum marianum L.	Asteraceae	Sy.ma	Biennial	Hemicryptophyte

Simultaneously, the soils of the sampled plants were also collected at a depth of 0–20 cm. The samples were combined and homogenized, air-dried at room temperature for a week and then sieved through a 2 mm mesh. In order to investigate coal wastes impact, some samples were collected using a stainless steel auger from different parts of mining land. Physical properties of the coal wastes such as soil texture was measured by hydrometric method as described by Bouyoucos (1962). Chemical characteristics of coal waste samples were determined according to the standard procedures of Black et al. (1965). Soil pH was measured by a pH meter in distilled water (pHH_2O) and in KCl solution, 1M (pHKCl) at 1:2.5 soil to liquid ratio, while EC was determined using a conductivity meter. Total organic carbon (TOC) was analyzed by Walkley-Black method, available phosphorus was determined according to the Olsen method, Total Nitrogen (TN) was determined using Kjeldahl method, and available potassium by extracting the soil with 1 N ammonium acetate and estimated by flame photometer. For determination of metal and metalloid concentrations, one gram of the dried soil samples were digested using concentrated HNO3-HClO4-HF with a ratio of 6:2:2 and placed on the hot plate at 80°C for 2 h. The solutions were cooled to room temperature, filtered and transferred to a 100-ml volumetric flask and diluted with distilled water (Zhu et al. 2018). Total concentrations of metals were determined by ICP-MS (Agilent 7900).

2.3. Phytoremediation and pollution indices

Transfer factor (TF) and bioconcentration factor (BCF) are extensively used to evaluate the translocation and efficiency of metal accumulation into the growing plant’s tissues from soil (Ali et al. 2013). Translocation factor (TF) which is defined as the ratio of metal concentration (mg/kg) in plant shoots to the metal concentration in plant roots (Xiao et al. 2017). Bioconcentration factor (BCF) was determined by dividing the metal concentration (mg/kg) in plant root to the metal concentration in soil (Xiao et al. 2017). The contamination factor (CF) was calculated to determine the level of soil contamination with respect to metal accumulation value in reference sites and it is the ratio of metal concentrations in polluted soils to the reference soil of that metal (Barbieri 2016). Reference samples were collected from nearby rangelands. The CF values classified (Hołtra and Zamorska-Wojdyła 2020) as low (< 1), moderate (1 ≤ CF < 3), considerable (3 ≤ CF < 6), and very high contamination (≥ 6). Pollution load index (PLI) was used to investigate the reciprocal contamination effects of the elements at a specific area (Jorfi et al. 2017). It was determined as $PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots \times CF_n)^{1/n}$ where CF is the contamination factor and n is the number of metals assessing. Metal load is near background level when the PLI is close to one, while PLI > 1 represents soil pollution (Liu et al. 2015). The Geo-accumulation index (Igeo) can be calculated as $Igeo = \log_2 (C_n/1.5B_n)$ (Muller 1969). B_n is geochemical background (average content in earth crust) and C_n is the measured concentrations of element n in coal waste sample. 1.5 is the background matrix correction factor due to lithogenic effects. Geo-accumulation index classified into seven classes (Taylor 1964) as a quantitative measure of the pollution intensity (Table 2).

Table 2
Classification of Geo-accumulation index (Muller, 1969)

geoaccumulation value	Igeo class	pollution intensity
5 < Igeo	6	Very strongly polluted
4 < Igeo < 5	5	Strong to very strongly polluted
3 < Igeo < 4	4	Strongly polluted
2 < Igeo < 3	3	Moderately to strongly polluted
1 < Igeo < 2	2	Moderately polluted
0 < Igeo < 1	1	Unpolluted to moderate polluted
Igeo ≤ 0	0	Practically unpolluted

2.4. Data analysis

Metal contents in plants were subjected to one-way ANOVA. This was done separately for root and shoot. For each significant effect means were compared using Duncan test at $P < 0.05$. All analyses were performed in the R statistical environment (3.5.1 version R Core Team 2019).

3. Results

3.1. Coal waste physicochemical characteristics

Coal waste in both sites had sandy texture (Table 3). The samples collected from the Karmozd mine were acidic (4.75 ± 0.42) but the Kiasar coal wastes revealed a near neutral pH (6.98 ± 0.19). The mean value of EC at Karmozd coal wastes (1.15 dS/m) was higher than that in Kiasar (0.6 dS/m). The total mean values of N in coal wastes were generally low, 0.11 and 0.1 percent for Karmozd and Kiasar, respectively (Table 3). There were significantly greater organic carbon and phosphorus contents in coal waste at Karmozd (Table 3). Among all the elements investigated, concentrations of Cu, Zn, Mn, Cr, Ni, Sr, Mo, and V were greater at Karmozd coal wastes whereas higher contents of Co, Ar, and Pb were observed at Kiasar coal wastes (Table 3).

Table 3
Coal waste physico-chemical characteristics and heavy metal concentrations in studied mine sites (the mean values ± standard error)

Property	Value	Karmozd	Kiasar
Sand	%	76.86 ± 7.36	86.25 ± 8.41
Silt	%	12.10 ± 4.51	9.31 ± 7.29
Clay	%	11.04 ± 4.94	4.44 ± 3.52
Total Nitrogen	%	0.11 ± 0.03	0.1 ± 0.02
Total Organic Carbon	%	6.12 ± 0.5	2.60 ± 0.33
pH	-	4.75 ± 0.42	6.98 ± 0.19
Electrical conductivity	ds/m	1.15 ± 0.03	0.6 ± 0.1
Available potassium	mg/kg	227.17 ± 6.29	279.21 ± 2.96
Available phosphorus	mg/kg	6.72 ± 1.34	1.19 ± 0.69
Cu	mg/kg	107.5 ± 30.95	29.33 ± 1.7
Zn	mg/kg	141 ± 18.95	93 ± 11.14
Mn	mg/kg	389.15 ± 37.2	193 ± 9.2
Al	mg/kg	54566 ± 0.97	67133 ± 0.16
Fe	mg/kg	24766 ± 0.17	20933 ± 0.1
Cr	mg/kg	157.16 ± 9.47	74 ± 4.54
Ni	mg/kg	118.18 ± 9.97	40 ± 1.63
Co	mg/kg	13.27 ± 2.37	21.33 ± 1.69
Mo	mg/kg	2.16 ± 1.14	1 ± 0.08
Sr	mg/kg	251.27 ± 33.88	152 ± 32.52
V	mg/kg	238.64 ± 14.49	88.33 ± 5.18
Pb	mg/kg	34 ± 3.74	35.66 ± 5.56
Cd	mg/kg	0.1	0.1>
As	mg/kg	4.66 ± 0.81	14.33 ± 2.05

3.2. Metal concentrations in shoots and roots of plant

The results of ANOVA showed significant differences between the elemental content in the roots and shoots of plant species (Table 4). The highest Cu concentration was observed in the root of *Artemisia scoparia* (averaging 23.91 mg/kg). The aerial parts of *Capparis spinosa* and *A. scoparia* had the highest Cu contents with mean values of 42.48 and 41.6 mg/kg, respectively. The Zn content varied between 8.86 and 121 mg kg^{-1} in roots and 22.56 and 74.14 mg Kg^{-1} in shoots (Table 4). *Cynodon dactylon* and *C. spinosa* had the highest zinc concentrations in roots and aboveground parts, respectively. *Kochia prostrata* accumulated significantly higher Mn (98.55 mg/kg), Fe (176.76 mg/kg), and Ni (5.11 mg/kg) in the roots than other species, while greater Mn (140.06 mg/kg) and Ni (6.45 mg/kg) concentrations were observed in the aboveground parts of *Chenopodium album*. Moreover, *Silybum marianum* showed the greatest content of Ni in the shoot. *S. marianum* was the only plant species that accumulated Vanadium in its root (3.5 mg/kg), while the highest Vanadium content in aboveground parts (6.2 mg/kg) was also recorded in *S. marianum*. *C. dactylon* accumulated significantly greater Cr (2.61 mg/kg in root and 3.4 mg/kg in aboveground parts). Three species had higher lead in their roots including *K. prostrate*, *Polygonum aviculare* and *S. marianum* (0.83 mg/kg, 0.84 mg/kg and 0.77 mg/kg, respectively). Pb accumulation in the aerial parts of *C. spinosa* was greater than the others. The highest As concentration was recorded for *S. marianum* in both aerial and roots. *Artemisia scoparia* accumulated significantly higher Cd in roots (0.77 mg/kg) and aerial parts (0.63 mg/kg) than the other species. Average Co concentrations in *S. marianum* and *P. aviculare* were 3.45 mg/kg and 3.2 mg/kg in underground and aboveground parts, respectively, which were seen to be greater than other species. The higher concentrations of Mo were found in *Glaucium fimbriligerum* (1.35 mg/kg in root and 2.64 mg/kg in aboveground parts). The highest concentrations of Sr were accumulated in *G. fimbriligerum* (145.87 mg/kg in root and 337.11 mg/kg in aerial parts) and *S. marianum* (131.17 mg/kg in root and 276.74 mg/kg in aerial parts).

Table 4
Mean metal(loid)s concentration in roots and aerial parts of dominant plants species growing on coal mine wastes (ND: not detected)

	Ar.ab	Ar.au	Ar.sc	Ca.sp	Ch.al	Cy.da	Gl.fi	Ho.vu	Ko.pr	Me.pe	Po.av	Ra.ru	Sy.ma
Root													
Cu	12.32 ± 3.46^{bcd}	14.65 ± 0.12^{bc}	23.91 ± 8.23^{a}	7.27 ± 0.40^{de}	7.21 ± 1.8^{de}	17.13 ± 1.12^{b}	16.89 ± 5.21^{b}	3.03 ± 2.79^{e}	15.76 ± 1.51^{b}	6.59 ± 2.50^{de}	15.64 ± 5.42^{de}	8.14 ± 1.98^{cde}	17.41 ± 1.12^{b}
Zn	14.65 ± 6.9^{fg}	20.76 ± 1.3^{efg}	26.08 ± 4.2^{def}	58.46 ± 4.1^{c}	19.84 ± 12.3^{efg}	121 ± 10.23^{a}	8.86 ± 2.9^{g}	104.61 ± 7.30^{b}	20.97 ± 5.5^{efg}	40.37 ± 11^{d}	28.4 ± 12.9^{def}	39.38 ± 8.8^{d}	34.99 ± 12.3^{de}
Mn	7.4 ± 1.00^{e}	10.39 ± 1.00^{de}	16.1 ± 10.0^{cde}	26.39 ± 14.00^{bcde}	29.16 ± 12.00^{bcde}	8.06 ± 1.00^{e}	34.3 ± 17.00^{bcd}	29.79 ± 10.00^{bcde}	98.55 ± 21.00^{a}	12.87 ± 6.00^{cde}	36.19 ± 25.00^{bc}	9.67 ± 5.00^{de}	46.76 ± 12.00^{b}
Fe	79.18 ± 9.00^{cd}	38.83 ± 1.00^{de}	74.85 ± 19.0^{cd}	59.12 ± 2.00^{cde}	17.99 ± 6.00^{e}	64.92 ± 15.00^{cd}	56.84 ± 12.00^{cde}	51.76 ± 6.00^{de}	176.76 ± 47.00^{a}	71.34 ± 24.00^{cd}	97.11 ± 38.00^{bc}	56.7 ± 20.00^{cde}	131.31 ± 33.0
Al	47.25 ± 4^{cd}	21.66 ± 1de	35.25 ± 11^{cde}	28.33 ± 7^{cde}	9.00 ± 2^{e}	21.00 ± 1de	38.25 ± 9^{cde}	25.00 ± 4de	102.33 ± 28^{a}	42.6 ± 14^{cd}	56.85 ± 29^{bc}	28.66 ± 15^{cde}	80.33 ± 23^{ab}
Cr	0.84 ± 0.06^{bcdef}	0.42 ± 0.10^{f}	0.81 ± 0.16^{bcdef}	0.8 ± 0.06^{cdef}	0.72 ± 0.10^{def}	2.61 ± 0.53^{a}	0.86 ± 0.12^{bcdef}	0.52 ± 0.39^{ef}	1.19 ± 0.37^{bc}	0.66 ± 0.47^{def}	0.89 ± 0.16^{bcde}	1.26 ± 0.22^{b}	1 ± 0.12^{bc}
Ni	1.41 ± 0.18^{cde}	0.65 ± 0.28^{e}	2.02 ± 0.75^{cde}	1.86 ± 0.41^{cde}	2.65 ± 1.66^{bcd}	2.90 ± 0.82^{bc}	2.29 ± 0.85^{bcde}	0.44 ± 0.24^{e}	5.11 ± 1.72^{a}	0.9 ± 0.83^{de}	3.09 ± 1.47^{bc}	2.28 ± 0.32^{bcde}	3.94 ± 1.07^{ab}
Co	0.3 ± 0.05^{d}	0.3 ± 0.06^{d}	0.69 ± 0.27^{cd}	0.57 ± 0.19^{cd}	2.02 ± 1.56^{abc}	0.53 ± 0.17^{cd}	2.27 ± 0.65^{ab}	0.29 ± 0.02^{d}	2.5 ± 1.31^{ab}	0.3 ± 0.02^{d}	1.92 ± 1.44^{bc}	0.64 ± 0.39^{cd}	3.45 ± 0.6^{a}
Mo	0.69 ± 0.30^{b}	0.25 ± 0.04^{bc}	0.37 ± 0.14^{bc}	0.64 ± 0.32^{bc}	0.32 ± 0.08^{bc}	0.2 ± 0.02^{c}	1.35 ± 0.59^{a}	0.2 ± 0.04^{c}	0.46 ± 0.17^{bc}	0.3 ± 0.09^{bc}	0.44 ± 0.24^{bc}	0.31 ± 0.09^{bc}	0.4 ± 0.16^{bc}
Sr	47.9 ± 11.09^{bc}	47.62 ± 4.1^{bc}	34.76 ± 4.5^{bc}	66.74 ± 38.9^{b}	22.77 ± 4.7^{c}	28.08 ± 5.1^{c}	145.87 ± 35.8^{a}	31.28 ± 15.1^{c}	30.61 ± 1.2^{c}	18.4 ± 1.8^{c}	44.59 ± 21.5^{bc}	39.67 ± 7.8^{bc}	131.17 ± 26.2
V	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.5 ± 2.26
Pb	0.3 ± 0.22^{b}	0.3 ± 0.25^{b}	0.65 ± 0.27^{ab}	0.47 ± 0.25^{ab}	0.3 ± 0.25^{b}	0.3 ± 0.21^{b}	0.68 ± 0.11^{ab}	0.3 ± 0.22^{b}	0.83 ± 0.31^{a}	0.34 ± 0.09^{b}	0.84 ± 0.39^{a}	0.36 ± 0.14^{b}	0.77 ± 0.06^{a}
Cd	0.01 ± 0.17^{bc}	0.11 ± 0.09^{bc}	0.77 ± 0.1^{a}	0.46 ± 0.02^{ab}	0.24 ± 0.09^{bc}	ND	0.24 ± 0.13^{bc}	ND	0.24 ± 0.04^{bc}	0.06 ± 0.08^{c}	0.39 ± 0.45^{bc}	0.08 ± 0.08^{c}	0.14 ± 0.02^{bc}
As	ND	ND	ND	ND	ND	0.72 ± 0.3^{b}	0.33 ± 0.57^{c}	ND	ND	ND	ND	ND	2.01 ± 1.45^{a}
Shoot													
Cu	14.59 ± 3.11^{b}	11.5 ± 0.96^{b}	41.06 ± 20.74^{a}	42.48 ± 47.06^{a}	11.28 ± 2.74^{b}	17.87 ± 12.45^{b}	10.64 ± 1.48^{b}	7.61 ± 3.09^{b}	11.38 ± 1.31^{b}	5.64 ± 2.17^{b}	9.47 ± 4.00^{b}	15.68 ± 2.74^{b}	12.85 ± 1.46^{b}
Zn	22.56 ± 4.95^{d}	27.12 ± 1.7^{d}	32.92 ± 2.77^{cd}	74.14 ± 12.58^{a}	50.26 ± 11.57^{bc}	55.16 ± 1.63^{ab}	25.88 ± 9.36^{d}	23.97 ± 3.62^{d}	28.98 ± 3.31^{d}	26.14 ± 8.32^{d}	33.01 ± 14.68^{cd}	59.33 ± 19.09^{ab}	31.15 ± 14.28^{c}
Mn	14.8 ± 4.35^{e}	14.37 ± 1.12^{e}	23.58 ± 9.26^{de}	55.86 ± 25.75^{cde}	140.06 ± 26.25^{a}	44.79 ± 15.61^{de}	77.62 ± 61.54^{bcd}	69.01 ± 18.39^{bcde}	115.18 ± 36.73^{ab}	18.71 ± 8.5^{de}	64.29 ± 55.34^{bcde}	25.71 ± 10.33^{de}	112.66 ± 23.48^{a}
Fe	201.2 ± 57.09^{ns}	72.41 ± 1.98^{ns}	171.77 ± 62.66^{ns}	81.36 ± 9.93^{ns}	174.71 ± 36.27^{ns}	180.78 ± 157.98^{ns}	206.17 ± 176.25^{ns}	95.58 ± 22.9^{ns}	227.66 ± 63.69^{ns}	101.93 ± 37.09^{ns}	132.04 ± 92.12^{ns}	204.94 ± 36.84^{ns}	201.18 ± 94.67^{n}
Al	125.25 ± 4^{ns}	42 ± 4.08^{ns}	89 ± 26.05^{ns}	51.33 ± 16.76^{ns}	126.5 ± 21.42^{ns}	141 ± 164.84^{ns}	193.25 ± 151.47^{ns}	25 ± 4^{ns}	102.33 ± 28^{ns}	42.6 ± 14^{ns}	56.85 ± 29^{ns}	28.66 ± 15^{ns}	80.33 ± 23^{ns}
Cr	2.29 ± 0.91^{b}	0.25 ± 0.04^{e}	1.42 ± 0.22^{bcd}	1.06 ± 0.01^{cde}	1.37 ± 0.09^{bcd}	3.4 ± 0.77^{a}	1.68 ± 0.63^{bc}	2.16 ± 0.79^{b}	0.61 ± 0.37^{de}	2.24 ± 0.48^{b}	1.33 ± 0.59^{bcd}	1.68 ± 0.12^{bc}	1.88 ± 0.61^{bc}

	Ar.ab	Ar.au	Ar.sc	Ca.sp	Ch.al	Cy.da	Gl.fi	Ho.vu	Ko.pr	Me.pe	Po.av	Ra.ru	Sy.ma
Root													
Ni	1.77 ± 0.24^{bc}	0.3 ± 0.02^{c}	2.96 ± 0.69^{b}	2.2 ± 0.44^{bc}	6.45 ± 2.14^{a}	3.76 ± 0.16^{b}	3.37 ± 0.98^{b}	1.83 ± 0.76^{bc}	2.26 ± 2.71^{bc}	2.31 ± 0.57^{bc}	2.38 ± 0.99^{bc}	3.12 ± 0.78^{b}	7.5 ± 2.33^{a}
Co	0.3 ± 0.07^{c}	0.3 ± 0.05^{c}	0.57 ± 0.11^{c}	0.94 ± 0.23^{bc}	2.89 ± 1.44^{ab}	0.33 ± 0.05^{c}	1.36 ± 0.09^{abc}	0.55 ± 0.26^{c}	1.12 ± 1.1^{abc}	0.28 ± 0.07^{c}	3.2 ± 2.82^{a}	0.74 ± 0.36^{bc}	2.48 ± 0.73^{ab}
Mo	0.59 ± 0.26^{bc}	0.3 ± 0.08^{bc}	0.27 ± 0.08^{c}	1.13 ± 0.7^{b}	0.49 ± 0.17^{bc}	0.83 ± 0.46^{bc}	2.64 ± 1.15^{a}	0.49 ± 0.21^{bc}	0.33 ± 0.09^{bc}	0.36 ± 0.15^{bc}	0.37 ± 0.1^{bc}	0.97 ± 0.37^{bc}	0.52 ± 0.39^{bc}
Sr	67.38 ± 24.65^{b}	52.49 ± 5.69^{b}	37.31 ± 2.89^{b}	102.26 ± 76.56^{b}	50.37 ± 20.75^{b}	43.5 ± 21.05^{b}	337.11 ± 128.73^{a}	18.57 ± 2.16^{b}	28.06 ± 3.07^{b}	20.32 ± 5.87^{b}	54.87 ± 29.16^{b}	72.42 ± 26.65^{b}	276.74 ± 65.87
V	0.52 ± 0.32^{b}	ND	0.14 ± 0.25^{b}	0.24 ± 0.34^{b}	0.3 ± 0.3^{b}	ND	0.41 ± 0.42^{b}	ND	0.19 ± 0.28^{b}	ND	0.16 ± 0.27^{b}	0.17 ± 0.25^{b}	6.20 ± 2.69^{a}
Pb	0.86 ± 0.53^{b}	0.2 ± 0.1^{b}	0.65 ± 0.1^{b}	7.67 ± 4.38^{a}	0.78 ± 0.1^{b}	0.5 ± 0.15^{b}	1.06 ± 0.33^{b}	0.48 ± 0.13^{b}	0.44 ± 0.13^{b}	0.39 ± 0.15^{b}	0.47 ± 0.28^{b}	0.46 ± 0.24^{b}	0.6 ± 0.07^{b}
Cd	0.25 ± 0.3^{bc}	ND	0.63 ± 0.15^{a}	0.41 ± 0.01^{ab}	0.38 ± 0.14^{ab}	ND	0.07 ± 0.07^{c}	ND	0.06 ± 0.08^{c}	0.04 ± 0.04^{c}	0.23 ± 0.25^{bc}	0.22 ± 0.06^{bc}	0.19 ± 0.03^{bc}
As	ND	ND	ND	0.17 ± 0.24^{b}	ND	ND	0.17 ± 0.31^{b}	ND	ND	ND	ND	ND	1.48 ± 1.07^{a}

3.3. Heavy metal accumulation and translocation in plants

Most of the plant species showed TF values greater than one (Table 5) and all had TF > 1 for Al, Fe, and Mn. Among the plant species, the highest TF values for Al (15.5), Fe (10.6), Zn (3.13) and Cd (1.64) were found for *C. album. H. vulgare* had the highest TF values for Cu (10.17), Cr (6.75), Ni (5.7), and Co (1.88). *C. dactylon* revealed the maximum values of TF for Mn (5.55) and Mo (4.15). The majority of plant species had TF > 1 for Sr, except *H. vulgare* and *K. prostrata*. The TF for Pb ranged between 0.57 for *K. prostrata* and 18.29 for *C. spinosa*. Table 6 shows that BCF values of plant species were less than one except for Cd (2.67 to 37.38). The highest BCF value was observed in *A. scoparia* for Cd (37.38). *K. prostrata* showed greater BCF values for Al (0.0015), Fe (0.006), Cu (0.23), Mn (0.21), Ni (0.05), and Pb (0.03). While *C. dactylon* had the highest BCF for Zn and Cr, *G. fimbriligerum* for Sr and Mo, and *S. marianum* for Co (Table 6).

Table 5

Translocation factor (TF) for dominant plants species growing on coal mine wastes

Species	Al	Fe	Cu	Zn	Mn	Cr	Ni	Co	Sr	Mo	V	Pb	As	Cd
Artemisia absinthium	2.61	2.61	1.21	**1.7**	1.95	2.79	1.26	1	1.36	0.86	-	2.87	-	0.49
Artemisia aucheri	1.95	1.86	0.78	1.3	1.38	0.65	0.58	1	1.1	1.23	-	0.66	-	-
Artemisia scoparia	2.7	2.33	1.71	1.29	1.68	1.79	1.64	0.92	1.08	0.83	-	1.26	-	0.83
Capparis spinosa	1.77	1.38	5.52	1.26	2.24	1.33	1.18	1.75	1.38	1.68	-	18.29	-	0.89
Chenopodium album	15.5	10.6	1.58	3.13	5.36	1.94	3	1.72	2.15	1.65	-	2.61	-	1.64
Cynodon dactylon	6.71	2.78	1.04	0.45	5.55	1.3	1.34	0.63	1.55	4.15	-	1.68	-	-
Glaucium fimbriligerum	6.61	4.7	0.66	2.96	2.05	2	1.5	0.66	2.29	2.04	-	1.59	0.13	0.28
Hordeum vulgare	2.71	1.84	10.17	0.23	2.31	6.75	5.7	1.88	0.59	2.46	-	1.58	-	-
Kochia prostrata	1.37	1.28	0.72	1.43	1.14	0.47	0.3	0.36	0.91	0.87	-	0.57	-	0.27
Melica persica	1.44	1.44	1.03	0.66	1.49	4.79	5.22	0.93	1.11	1.44	-	1.24	-	0.17
Polygonum aviculare	1.52	1.29	0.6	1.2	1.72	1.44	0.86	1.39	1.21	1	-	0.6	-	0.33
Rapistrum rugosum	6.69	4.37	1.97	1.5	2.82	1.36	1.4	1.3	1.8	3.18	-	1.4	-	0.77
Sylibum marianum	1.68	1.5	0.74	0.85	2.58	1.84	2.04	0.7	2.21	0.75	2.01	0.77	0.76	1.44

Table 6
Bioconcentration factor (BCF) for dominant plants species growing on coal mine wastes

Species	Al	Fe	Cu	Zn	Mn	Cr	Ni	Co	Sr	Mo	V	Pb	As	Cd
Artemisia absinthium	0.00069	0.003	0.17	0.13	0.02	0.005	0.01	0.03	0.29	0.17	-	0.01	-	4.86
Artemisia aucheri	0.0003	0.002	0.11	0.16	0.05	0.003	0.005	0.03	0.23	0.12	-	0.008	-	3.67
Artemisia scoparia	0.0005	0.003	0.14	0.14	0.03	0.005	0.01	0.04	0.1	0.37	-	0.013	-	37.38
Capparis spinosa	0.00054	0.002	0.05	0.4	0.05	0.005	0.01	0.04	0.29	0.64	-	0.017	-	22.99
Chenopodium album	0.00012	0.0008	0.09	0.12	0.08	0.005	0.023	0.18	0.09	0.32	-	0.008	-	7.44
Cynodon dactylon	0.00047	0.003	0.13	0.87	0.04	0.02	0.03	0.05	0.12	0.05	-	0.007	0.14	-
Glaucium fimbriligerum	0.00056	0.002	0.19	0.07	0.06	0.005	0.02	0.16	0.59	0.68	-	0.02	0.08	5.39
Hordeum vulgare	0.00038	0.002	0.002	0.73	0.16	0.002	0.002	0.02	0.1	0.05	-	0.006	-	-
Kochia prostrata	0.0015	0.006	0.23	0.17	0.21	0.009	0.05	0.23	0.14	0.12	-	0.03	-	10.34
Melica persica	0.0008	0.003	0.09	0.33	0.04	0.004	0.009	0.09	0.08	0.15	-	0.01	-	3.69
Polygonum aviculare	0.00084	0.004	0.18	0.2	0.08	0.006	0.026	0.13	0.19	0.22	-	0.026	-	11.42
Rapistrum rugosum	0.0006	0.003	0.09	0.3	0.02	0.008	0.02	0.04	0.15	0.16	-	0.008	-	2.67
Sylibum marianum	0.0011	0.005	0.17	0.25	0.09	0.006	0.03	0.29	0.46	0.46	0.01	0.02	0.14	8.4

3.4. Pollution indices

Pollution indices including contamination factor (CF), geo-accumulation index (Igeo) and pollution load index (PLI) are summarized in Table 7. Except for Fe, the contamination factor values for other elements were more than one ($1 \leq CF < 3$) and it shows that the coal mine at Karmozd was exposed to moderate contamination. The numerical value of pollution load index was 1.36, which indicates metal contamination of the coal wastes. According to the geo-accumulation classification, Igeo was negative for Sr, Al, Fe, Mn, Co, and Cd that represented practically unpolluted level. Zn, Pb, Cr, and As were categorized as unpolluted to moderately polluted ($0 < Igeo < 1$) and Cu, Ni, and V as moderately polluted ($1 < Igeo < 2$).

Table 7
Pollution indices including contamination factor (CF), geo-accumulation index (Igeo) and pollution load index (PLI)

contamination indices	elements												
	Cu	Zn	Pb	Ni	Sr	Al	Fe	Cr	Mn	Co	As	Cd	V
Igeo	1.51	0.42	0.59	1.98	-0.91	-1.15	-1.6	0.07	-1.47	-0.25	0.78	-0.6	1.4
CF	1.7	1.18	1.24	1.42	1.16	1.03	0.87	1.15	1.58	1.28	2.33	2	1.48
PLI							1.36						

4. Discussion

4.1. Coal waste physicochemical characteristics

Coal wastes of two sites showed slightly different characteristics. The higher electrical conductivity in Karmozd coal wastes could be associated with higher concentration of soluble salts (Raj et al. 2010). There is more vegetation cover in Karmozd waste dumps and subsequent decomposition of plant residues could increase the organic carbon and phosphorus contents at this site (Fettweis et al. 2005; Kumar et al. 2015; Lashgari et al. 2016). Soil organic carbon content is linked to phosphorus uptake (Hou et al. 2014). Generally, nitrogen (N) reserves is low at coal mine wastes (Ahirwal et al. 2017). Coal wastes contained large amounts of sand and silt particles (Borůvka et al. 2012). The major amounts of sand in coal wastes are usually originated from the high content of quartz (Barnhisel and Massey 1969). The mine waste acidity depends on parent materials (Carrillo González and González-Chávez 2006). Solubility of chemical components such as toxic metals and nutrients are associated with pH values and thus affect plant growth (Freitas et al. 2004). The low pH and high EC of Karmozd waste dumps can be from the interactions of sulphide minerals that causes an increase in the concentration of SO_4^{2-} and sulfuric acid formation with the pyrite oxidation (Midhat et al. 2019). Rill and gully erosion are obvious in Karmozd waste dumps which increase the chemical process (oxidation and pyrite hydrolysis) and acid mine drainage when exposed to oxygen and water (Naicker et al. 2003). Higher acidic condition in Karmozd coal wastes decreased the potassium contents as potassium leaching in acidic soils can be accelerated due to the less exchange capacity (Dianjun et al. 2022). Metals concentration in Karmozd coal wastes were: Al > Fe > Mn > Sr > V > Cr > Zn > Ni > Cu > Pb > Co > As > Mo > Cd, whereas a different order was observed for Kiasar coal wastes (Al > Fe > Mn > Sr > Zn > V > Cr > Ni > Pb > Cu > Co > As > Mo > Cd). Different orders of metal concentration are also reported in other coal mines worldwide (Sahoo et al. 2016; Li et al. 2017). The variability of coal waste characteristics and their metals contents at mined sites is probably related to mineral composition, mining operations, and minerals weathering rates (Carrillo González and González-Chávez 2006).

4.2. Metal concentrations in plants

This study showed that heavy metal concentrations were highly variable between plants and also in their roots and aerial parts. Metals uptake by plants from the soil depends on plant species, total metal concentrations and their availability, soil pH, plant physiology, and age of plant (Rascio and Navari-Izzo 2011). The mean concentrations of copper in coal wastes varied between 29.33 mg/kg for Kiasar and 107.5 mg/kg for Karmozd. Similarly, at the coal wastes in Poland (Ciesielczuk et al. 2014), China (Li et al., 2017) and India (Jain et al. 2017) the Cu levels were reported to be 111, 100, and 4 mg/kg, respectively. The normal copper concentrations in plant tissues typically ranges between 3 and 25 mg/kg (Reeves and Baker 2000). In our study the Cu concentration varied between 5.64 and 42.48 mg/kg in aerial parts and 3.03 and 23.91 mg/kg in roots. The levels of Cu in *A. scoparia* (23.91 mg/kg in root and 41.06 mg/kg in in aerial parts) and *C. spinosa* (42.48 mg/kg in in aerial parts) exceeded the normal range. Similar to this finding, Li et al. (2017) at coal wastes of China reported that *A. scoparia* accumulated 37 mg/kg Cu in aerial parts. A copper concentration of 34.01 mg/kg in aerial parts and 15.38 mg/kg in roots was reported for *A. scoparia* in Azerbaijan (Alirzayeva et al. 2006). According to Shah et al. (2013) the copper concentrations in aerial parts and root of *C. spinosa* in Pakistan were 21.61 and 4.93 mg/kg, respectively, which were lower compared with our study. Copper hyperaccumulators are described as plants that accumulate more than 1000 mg/kg Cu in dry weight biomass (Baker and Brooks 1989), so no plant species in present study were considered as Cu hyperaccumulator.

The world average level of Arsenic in soil is 5–20 mg/kg (Kabata-Pendias and Pendias 2001). The mean As concentration in coal wastes varied between 4.66 mg/kg in Karmozd and 14.33 mg/kg in Kiasar, which was within the reported ranges (0.5 to 38.3 mg/kg) in different coal mining areas worldwide (Sahoo et al. 2016). The normal concentrations of As in plants varies between 0.01 and 1 mg/kg (Chaney 1989). *S. marianum* exceeded this limit with 2.01 and 1.48 mg/kg As in root and shoot, respectively. This implies its tolerance to As due to vacuole compartmentalization which cause the prevention of free metal ions in the cytosol and limit them into a spaces where cell division and respiration occur (Singh et al. 2017).

Lead is a non-essential heavy metal for plants and is normally considered at concentrations between 2 and 5 mg/kg in soil (Chaney 1989). In this study, coal wastes contained about 35 mg/kg Pb which was less than some other coal mine areas in Poland (63 mg/kg) and China (91 mg/kg; Ciesielczuk et al. 2014; Li et al. 2017). In the present study, *Capparis spinosa* was the only plant that accumulated Pb about 7 mg/kg in shoot while it was less than 1 mg/kg for other species. In a lead-zinc mine in semi-arid climate in Iran, *C. spinosa* had 45–230 µg/gr Pb in shoot (Ghaderian et al. 2007). None of the plants can be considered as hyperaccumulators of Pb. Normally, roots have high potential to concentrate large amounts of Lead, while limited amounts could transfer to aerial parts (Lane and Martin 1977). In this study plants tendency to high lead accumulation in aerial parts represented their ability to Pb translocation from the roots to aboveground parts.

The mean concentration of Zn in coal wastes ranged between 93 mg/kg for Kiasar and 141 mg/kg for Karmozd. Similarly, in the coal wastes of Silesia (Poland), Henan (China) and Meghalaya (India) the Zn levels were 179, 172.38, and 37 mg/kg, respectively (Ciesielczuk et al. 2014; Li et al. 2017; Jain et al. 2017). The Zn ranging between 15 and 150 mg/kg (Chaney 1989) or concentrations less than 100 mg/kg (van der Ent et al. 2012) are normal for the plant growth. The Zn concentrations for studied plants were within the limits considered as normal values (Kabata-Pendias 2011). Similar to van der Ent et al. (2012) C. *dactylon* had the concentrations of Zn more than 100 mg/kg. Kumar et al. (2015) found that the highest Zn concentrations were in *C. dactylon* at reclaimed mine land. Zinc concentration in other studied plants was similar to reported levels at a contaminated area (Wei et al. 2005).

In current study, the Cr concentrations were not phytotoxic to plant organs and were found to be in the normal range reported for plant species (0.2 to 5 mg/kg, Reeves and Baker 2000). The accumulation of Cr efficiently occurred in *C. dactylon* (2.61 mg/kg in aerial parts and 3.4 mg/kg in root) which represents its high ability compared with other plants. In this regard, Abou-Shanab et al. (2007) reported the Cr content in aerial parts of *C. dactylon* was about 39, 8, 6 and 4 times higher than the shoots of *Helianthus annuus*, *Sorghum bicolor*, *Zea mays* and *Conyza discoridies.* The concentration of Cr in the aerial parts of most plant species were higher than their roots. Thus, they can effectively translocate Cr from root into the aerial parts.

The Cadmium levels in studied coal wastes were low (ranged 0–0.1 mg/kg) and below the range determined for not contaminated soils (5–30 mg/kg, Kabata-Pendias and Pendias 2001). Cd is a non-essential element for plant growth and its normal concentrations is 0.1–3 mg/kg in soil (Baker and Brooks 1989). Cadmium occurs in plant organs due to the unwanted absorption and translocation into the plant organs (Benavides et al. 2005). The content of Cd in this study ranged from 0.01 to 0.77 mg/kg in aerial parts and roots with greatest concentration in *A. scoparia* (0.77 mg/kg in aerial parts and 0.63 mg/kg in root). Li et al. (2017) observed the highest mean concentration of Cd in *A. scoparia* (2.62 mg/kg in aerial parts and 0.46 mg/kg in root) colonized on the coal waste dumps in China. Cadmium accumulated in *A. scoparia* studied by Alirzayeva et al. (2006) varied between 0.97 and 4.02 mg/kg in the roots and aerial parts, respectively and reported to be significantly higher than the other Artemisia species. Generally, in the present study, cadmium concentrations in plants was within the normal range observed in other studies (Wei et al. 2005; Brunetti et al. 2008).

The Sr concentrations for *G. fimbriligerum* (145.87 mg/kg in root and 337.11 mg/kg in aboveground parts) and *S. marianum* (131.17 mg/kg in root and 276.74 mg/kg in aboveground parts) exceeded the phytotoxic level (30 mg/kg; Shacklette et al. 1978), which could be explained by great Sr content of the coal wastes. It seems that these species can be valuable bioaccumulators in their aerial parts for strontium. In accordance with Kabata-Pendias and Pendias (2001), the higher concentrations of Sr were observed in aerial parts of most plant species, despite the strontium translocation from roots into aerial parts of plants is not easily conducted. Generally, Metal uptake by plants occur mainly in two ways: passive transport (apoplastic pathway): water mass flow causing the entrance of metal into roots and active transport (symplastic pathway): ion translocating across the plasma membrane (Shahid et al., 2017). Sasmaz and Sasmaz (2009) indicated that mean Sr values in the aerial parts and roots of plants grown up in mined land were 453 and 243 mg/kg for *Euphorbia macroclada*; 149 and 106 mg/kg for *Verbascum cheiranthifolium*; and 278 and 223 mg/kg for *Astragalus gummifer*, respectively. We also found that Poaceae family accumulated low contents of Strontium in their tissues. Hence, Korobova et al. (1998) have stated that radionuclide absorption by plants decreases in the following order: legumes > herbs > grasses.

The Ni levels in coal waste varied between 40 and 118.18 mg/kg for Kiasar and Karmozd, which were above the range identified for different countries (13–37 mg/kg according to Kabata-Pendias 2011). Jain et al. (2017) has reported the lower content of this metal in Meghalaya (India) coal mine waste (mean value 7 mg/kg). Ni contents of 10 to 100 mg/kg are toxic for different plant species (Brooks 1980). In current study, none of the plants showed Ni concentrations in their tissues that reached the phytotoxic level, except *S. marianum* (11.44 mg/kg, totally). In line with these findings, Zehra et al. (2009) reported that Ni concentration in *S. marianum* (12.33 mg/kg) was above the normally reported values. Similarly, lower Ni accumulation reported in the roots of *S. marianum* than the aerial part (Brunetti et al. 2008).

The average contents of Mn in coal wastes varied between 193 mg/kg and 389.15 mg/kg which was within the normal ranges accepted for worldwide soils (270–525 mg/kg; Kabata-Pendias 2011) and mean concentrations for coal mine areas at different countries (86-3700 mg/kg; Sahoo et al. 2016). All plants had larger concentrations of Mn in their aerial parts, but, none of them reached the toxicity levels considered for plant species (more than 400 mg/kg; Kabata-Pendias 2011). This is because when Mn transfers from roots to shoot by the transpiration flow, it cannot be readily remobilized through phloem to other parts of the plants (Loneragan 1988).

The geochemical characteristics of Vanadium are strongly related to its oxidation states and environmental acidity (Kabata-Pendias 2011; Altaf et al. 2021). The mean concentration of V in coal waste varied between 88.33 and 238.64 mg/kg for Kiasar and Karmozd, respectively, and exceeded the world average soil content (129 mg/kg; Kabata-Pendias 2011). Altaf et al. (2021) found that lower concentration of Vanadium (< 0.002 mg/kg) acts as a growth promoting factor, enhances nitrogen fixation in soil and stimulates chlorophyll production. Phytotoxic concentration of V is reported approximately more than 2 mg/kg which can induce oxidative stress, growth inhibition, leaf chlorosis and necrosis and limits the essential elements absorption (Aihemaiti et al. 2019). Accordingly, V concentrations in *S. marianum* exceeded the phytotoxic levels and was the only species that accumulated V in its root. Similarly, Franco-Hernández et al. (2010) observed the content of V only in root of *Thymophylla setifolia*.

The concentration of Cobalt in root and aerial parts (0.028–3.45 mg/kg) were less than the critical or toxic levels (25–100 mg/kg; Kabata-Pendias 2011). The maximum Co was recorded in roots of *S. marianum* (3.45 mg/kg) and shoots of *P. aviculare* (3.2 mg/kg). Compared to this results, the highest Co concentration (7.8 mg/kg) was recorded in *A. scoparia* at a chromite mining site (Nawab et al. 2016). According to current findings, accumulation of Co in Poaceae family plants was lower than the other plants, which is consistent with the results of Kasowska et al. (2017) in copper mine tailings. Generally, less availability of Co decreases its absorption from soil (Li et al. 2009). Only a small amount of Co can be uptaken by plants from the soil and its next distribution in plants is entirely species-dependent mechanisms (Page and Feller 2005).

Molybdenum is an essential micronutrient, but the physiological requirement for this element is relatively low. Sardans et al. (2008) indicated that drought disturbed the Mo uptake by plants and its concentration may increase or decrease depending on the species type. Mean levels of Mo is reported to vary between 0.33 and 1.5 mg/kg in grasses and between 0.73 and 2.3 mg/kg in legumes (Kabata-Pendias 2011). Mo uptake in studied plant species were within the normal range (0.2-5 mg/kg, Kabata-Pendias 2011). *G. fimbriligerum* effectively accumulated this metal in their root (1.35 mg/kg) and aerial parts (2.64 mg/kg) more than other species.

In the present study, the levels of Fe for all plant species were extremely low. It is well known that interaction of Fe with some other elements can cause low accumulation of this metal in plant organs (Kasowska et al. 2017). In line with present results, Kasowska et al. (2017) observed low concentration of Fe in plants grown up at cooper mining tailing than the reference area.

4.3. Bioconcentration and Transfer Factors

In this study, the values of BCF and TF varied considerably between different plant species. It is accepted that the differences of BCF and TF in plants species represent their different approaches for response to metal concentrations (Chunilall et al. 2005). Most of the plant species had TF > 1 for more than one heavy metal indicating that these plants were capable to translocate metals from roots to the aboveground parts, thereby confirming their efficacy for phytoextraction (Pandey et al. 2016). Transfer factor greater than one (TF > 1) for Al, Fe and Mn in all plants indicates that the studied species can easily translocate these metals from the roots to the aerial parts. Plants with TF and BCF < 1 recognized as excluders and are not suitable for heavy metals extraction from soils (Mganga 2014). Therefore, these plants with extensive root system can be metal resistant and suitable for phytostabilization. In this study, *K. prostrate* and *A. aucheri* were classified as Cu, Cr, Ni, Co and Pb excluders and *K. prostrate* and *H. vulgare* as Sr excluders. *H. vulgare* with a highest TF values for Cu, Cr, Ni and Co, *C. dactylon* for Mn and Mo, *G. fimbriligerum* for Sr, *C. spinosa* for Pb and *C. album* for Cd are recognized as good phytotranslocators of these metals. Three species including *C. album, C. spinosa* and *R. rugosum* had a TF > 1 for Copper, Zinc, Lead, Nickel, Manganese, Chromium, Cobalt, and Strontium. This is probably due to efficient metal transport system and immobilization of metals in leaf vacuoles and apoplast (Zhao et al. 2002). *C. album* showed a high capacity to translocate Manganese, Nickel, Strontium, Zinc, Iron, Copper, Cadmium, and Lead from soil to aerial parts (Tőzsér et al. 2019). Plants with a BCF value more than one have a high capacity to accumulate heavy metals (Branzini et al. 2012). Among the heavy metals measured, only Cd displayed BCF > 1 in most species. Similar to Zhu et al. (2018), the BCF values for Cd in the plants were considerably greater than their associated TF values except for *C. dactylon* and *H. vulgare*. This implies that these species had a good bioconcentration potential and efficiently eliminated Cd from the soil. The highest BCF value for Cd was recorded in *A. scoparia* which indicates its large capability to enrich this metal in root. This is in agreement with the study of Li et al., 2017. This fact suggests that plant species having greater BCF and TF easily absorb metals from soil by roots and transport them to aboveground parts (Zhu et al. 2018). Therefore, *C. album* and *S. marianum* can be regarded as the phytoaccumulator and suitable options for remediation of Cd rich soil. In this regard, Bhargava et al. (2007) and Hammami et al. (2018) proposed that *C. album* and *S. marianum* could clean up Cd from the soil and may be applied for phytoremediation.

5. Conclusion

The present study showed that among detected heavy metals in coal waste dumps, Vanadium concentrations exceeded the established limits for normal levels. The Igeo and CF values showed higher contamination of Cu, Ni and V than the other elements. This obviously indicates that metal elements potentially cause pollution in coal mine wastes. The heavy metals concentrations in most plants were within the normal limits and not reached toxic levels. Nevertheless, the presence of metals in different plant organs represented the metal absorbing potential. The majority of plant species have been successful in accumulating more than one metal in their aerial parts. This represents the strength of metals translocation from roots to the aerial parts of these plants.

Declarations

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Abou-Shanab R, Ghanem N, Ghanem K, Al-Kolaibe A (2007) Phytoremediation potential of crop and wild plants for multi-metal contaminated soils. Res J Agric Biol Sci 3(5):370-376. https://www.semanticscholar.org/ 269c11020decb9511edfd0bd825b67a515a37505
2. Ahirwal J, Maiti SK, Reddy MS (2017) Development of carbon, nitrogen and phosphate stocks of reclaimed coal mine soil within 8 years after forestation with *Prosopis juliflora* (Sw.) Dc. Catena 156:42-50. https://doi.org/10.1016/j.catena.2017.03.019
3. Aihemaiti A, Jiang J, Gao Y, Meng Y, Zou Q, Yang M, Xu Y, Han S, Yan W, Tuerhong T (2019) The effect of vanadium on essential element uptake of *Setaria viridis* seedlings. J Environ Manag 237:399-407. https://doi.org/10.1016/j.jenvman.2019.02.054
4. Alaboudi KA, Ahmed B, Brodie G (2018) Phytoremediation of Pb and Cd contaminated soils by using sunflower (*Helianthus annuus*) plant. Ann Agric Sci 63(1):123-127. https://doi.org/10.1016/j.aoas.2018.05.007
5. Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals-concepts and applications. Chemosphere 91(7):869-881. https://doi.org/10.1016/j.chemosphere.2013.01.075
6. Alirzayeva EG, Shirvani TS, Yazici A, Alverdiyeva SM, Shukurov ES, Ozturk L, Ali-zade VM, Çakmak I (2006) Heavy metal accumulation in Artemisia and foliaceous lichen species from the Azerbaijan flora. For Snow Landsc Res 80(3):339-348. https://www.dora.lib4ri.ch/wsl/islandora/object/wsl:15472
7. Alizadeh A, Ghorbani J, Motamedi J, Vahabzadeh G, Edraki M, van der Ent A (2022) Metal and metalloid accumulation in native plants around a copper mine site: implications for phytostabilization. Int J Phytoremediation 24(11):1141-1151. https://doi.org/10.1080/15226514.2021.2011831
8. Altaf MA, Shu H, Hao Y, Zhou Y, Mumtaz MA, Wang Z (2021) Vanadium toxicity induced changes in growth, antioxidant profiling, and vanadium uptake in pepper (*Capsicum annum* L.) seedlings. Horticulturae 8(1):28. https://doi.org/10.3390/horticulturae8010028
9. Ameh EG, Aina DO (2020) Search for autochthonous plants as accumulators and translocators in a toxic metal-polluted coal mine soil in Okaba, Nigeria. Sci Afr 10:e00630. https://doi.org/10.1016/j.sciaf.2020.e00630
10. Baker AJM, Brooks R (1989) Terrestrial higher plants which hyperaccumulate metallic elements. A review of their distribution, ecology and phytochemistry. Biorecovery 1(2):81-126. http://dx.doi.org/10.1080/01904168109362867
11. Barbieri M (2016) The importance of enrichment factor (EF) and geoaccumulation index (Igeo) to evaluate the soil contamination. J Geol Geophys 5(1):1-4. https://doi.org/10.4172/2381-8719.1000237
12. Barnhisel RI, Massey HF (1969) Chemical, mineralogical and physical properties of Eastern Kentucky acid-forming coal spoil materials. Soil Sci 108(5):367-372. https://journals.lww.com/soilsci/Citation/1969/11000/
13. Benavides MP, Gallego SM, Tomaro ML (2005) Cadmium toxicity in plants. Braz J Plant Physiol 17(1):21-34. http://dx.doi.org/10.1590/S1677-04202005000100003
14. Bhargava A, Shukla S, Srivastava J, Singh N, Ohri D (2007) Chenopodium: a prospective plant for phytoextraction. Acta Physiol Plant 30(1):111-120. https://doi.org/10.1007/s11738-007-0097-3
15. Black CA, Evans DD, White JL, Ensminger LE, Clark FE (1965) Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties, Agronomy 9, Medison, Wisconsin, USA
16. Borůvka L, Kozák J, Mühlhanselová M, Donátová H, Nikodem A, Němeček K, Drábek O (2012) Effect of covering with natural topsoil as a reclamation measure on brown-coal mining dumpsites. J Geochem Explor 113:118-123. https://doi.org/10.1016/j.gexplo.2011.11.004
17. Bouyoucos GJ (1962) Hydrometer method improved for making particle size analyses of soils. Agron J 54(5):464-465. http://dx.doi.org/10.2134/agronj1962.00021962005400050028x
18. Branzini A, González RS, Zubillaga M (2012) Absorption and translocation of copper, zinc and chromium by *Sesbania virgata*. J Environ Manag 102:50-54. https://doi.org/10.1016/j.jenvman.2012.01.033
19. Brooks RR (1980) Accumulation of nickel by terrestrial plants. In: Nriagu JO (ed) Nickel in the environment. Wiley, New York, pp 407-430
20. Brunetti G, Soler-Rovira P, Farrag K, Senesi N (2008) Tolerance and accumulation of heavy metals by wild plant species grown in contaminated soils in Apulia region, Southern Italy. Plant Soil 318(1):285-298. https://doi.org/10.1007/s11104-008-9838-3
21. Carrillo González R, González-Chávez MCA (2006) Metal accumulation in wild plants surrounding mining wastes. Environ Pollut 144(1):84-92. https://doi.org/10.1016/j.envpol.2006.01.006
22. Chaney RL (1989) Toxic element accumulation in soils and crops: protecting soil fertility and agricultural food chains In: Bar-Yosef B, Barrow NJ, Goldshmid J (ed) Inorganic contaminants in the Vadose Zone. Springer-Verlag, Berlin, pp 140-158
23. Chunilall V, Kindness A, Jonnalagadda SB (2005) Heavy metal uptake by two edible Amaranthus herbs grown on soils contaminated with lead, mercury, cadmium, and nickel. J. Environmental Sci Health 40(2):375-384. https://doi.org/10.1081/PFC-200045573

24. Ciesielczuk J, Misz-Kennan M, Hower JC, Fabiańska MJ (2014) Mineralogy and geochemistry of coal wastes from the Starzykowiec coal-waste dump (Upper Silesia, Poland). Int J Coal Geol 127:42-55. https://doi.org/10.1016/j.coal.2014.02.007
25. Dianjun L, Yanhong D, Xiaoqin C, Huoyan W, Jianmin Z (2022) Comparison of potential potassium leaching associated with organic and inorganic potassium sources in different arable soils in China. Pedosphere 32(2):330-338. https://doi.org/10.1016/S1002-0160(21)60077-2
26. Fan Y, Lu Z, Chen JL, Zhou ZX, Wu G (2003) Major ecological and environmental problems and the ecological reconstruction technologies of the coal mining areas in China. Acta Ecol Sin 23(10):2144-2152
27. Fettweis U, Bens O, Hüttl RF (2005) Accumulation and properties of soil organic carbon at reclaimed sites in the Lusatian lignite mining district afforested with *Pinus* sp. Geoderma 129 (1-2):81-91. https://doi.org/10.1016/j.geoderma.2004.12.034
28. Finkelman RB (1994) Modes of occurrence of potentially hazardous elements in coal: levels of confidence. Fuel process Technol 39(1-3):21-34. https://doi.org/10.1016/0378-3820(94)90169-4
29. Franco-Hernández MO, Vasquez-Murrieta MS, Patino-Siciliano A, Dendooven L (2010) Heavy metals concentration in plants growing on mine tailings in Central Mexico. Bioresour Technol 101(11):3864-3869. https://doi.org/10.1016/j.biortech.2010.01.013
30. Freitas H, Prasad MNV, Pratas J (2004) Plant community tolerant to trace elements growing on the degraded soils of Sao Domingos mine in the south east of Portugal: environmental implications. Environ Int 30(1):65-72. https://doi.org/10.1016/S0160-4120(03)00149-1
31. 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(2):145-150. https://www.researchgate.net/publication/277713719
32. Hammami H, Alaie E, Dastgheib SMM (2018) The ability of *Silybum marianum* to phytoremediate cadmium and/or diesel oil from the soil. Int J Phytoremediation 20(8):756-763. https://doi.org/10.1080/15226514.2018.1425664
33. Hołtra A, Zamorska-Wojdyła D (2020) The pollution indices of trace elements in soils and plants close to the copper and zinc smelting works in Poland's Lower Silesia. Environ Sci Pollut Res 27(14):16086-16099. https://doi.org/10.1007/s11356-020-08072-0
34. Hosseini-Kiasari SM (2016) Natural succession of vegetation in old coal waste of rangelands of Kiasar in Mazandaran province. M.Sc Thesis, Sari Agricultural Sciences and Natural Resources University, Iran.
35. Hou E, Chen C, Wen D, Liu XC (2014) Relationships of phosphorus fractions to organic carbon content in surface soils in mature subtropical forests, Dinghushan, China. Soil Res 52(1):55-63. https://doi.org/10.1071/SR13204
36. Jain S, Singh A, Khare P, Chanda D, Mishra D, Shanker K, Karak T (2017) Toxicity assessment of *Bacopa monnieri* L. grown in biochar amended extremely acidic coal mine spoils. Ecol Eng 108:211-219. https://doi.org/10.1016/j.ecoleng.2017.08.039
37. Jorfi S, Maleki R, Jaafarzadeh N, Ahmadi M (2017) Pollution load index for heavy metals in Mian-Ab plain soil, Khuzestan, Iran. Data in brief 15:584-590. https://doi.org/10.1016/j.dib.2017.10.017
38. Kabata-Pendias A (2011) Trace Elements in Soil and Plants, fourth ed. CRC press, Washington D.C
39. Kabata-Pendias A, Pendias H (2001) Trace Elements in Soils and Plants, third ed. CRC Press, Boca Raton
40. Kasowska D, Gediga K, Spiak Z (2017) Heavy metal and nutrient uptake in plants colonizing post-flotation copper tailings. Environ. Sci Pollut Res 25(1):824-835. https://doi.org/10.1007/s11356-017-0451-y
41. Korobova E, Ermakov A, Linnik V (1998) ^{137}Cs and ^{90}Sr mobility in soils and transfer in soil–plant systems in the Novozybkov district affected by the Chernobyl accident. Appl Geochem 13(7):803-814. https://doi.org/10.1016/S0883-2927(98)00021-3
42. Kumar A, Ahirwal J, Maiti SK, Das R (2015) An assessment of metal in fly ash and their translocation and bioaccumulation in perennial grasses growing at the reclaimed opencast mines. Int J Environ Res 9(3):1089-1096. https://www.researchgate.net/publication/281067623
43. Lashgari N, Ghorbani J, Zali SH, Vahabzadeh GH (2016) Assessing the vegetation restoration potential on coal mine waste (Case study: Karmozd Savadkoh mines, Mazandaran province). J Environ Stud 41(4):757-770. 10.22059/JES.2016.57130
44. Lane SD, Martin ES (1977) A histochemical investigation of lead uptake in *Raphanus sativus*. New Phytol 79(2):281-286. https://doi.org/10.1111/j.1469-8137.1977.tb02206.x.
45. Li HF, Gray C, Mico C, Zhao FJ, McGrath SP (2009) Phytotoxicity and bioavailability of cobalt to plants in a range of soils. Chemosphere 75(7):979-986. https://doi.org/10.1016/j.chemosphere.2008.12.068
46. Li K, Lun Z, Zhao L, Zhu Q, Gu Y, Li, M (2017) Screening for autochthonous phytoextractors in a heavy metal contaminated coal mining area. Int J Environ Res Public Health 14(9):1-14. https://doi.org/10.3390/ijerph14091068
47. Liu Y, Xiao T, Baveye PC, Zhu J, Ning Z, Li H (2015) Potential health risk in areas with high naturally-occurring cadmium background in southwestern China. Ecotoxicol Environ Saf 112:122-131. https://doi.org/10.1016/j.ecoenv.2014.10.022
48. Loneragan JF (1988) Distribution and movement of manganese in plants. In: Graham RD, Hannam RJ, Uren NC (ed) Manganese in soils and plants. Springer, Dordrecht, pp 113-124
49. Lorestani B, Cheraghi M, Yousefi N (2012) The potential of phytoremediation using hyperaccumulator plants: a case study at a lead-zinc mine site. Int J Phytoremediation 14(8):786-95. doi: 10.1080/15226514.2011.619594
50. Maiti, SK (2013) Ecorestoration of the coal mine degraded lands. Springer, New Delhi.
51. McGrath SP, Zhao FJ, Lombi E (2002) Phytoremediation of metals, metalloids, and radionuclides. Adv Agron 75:1-56. https://doi.org/10.1016/S0065-2113(02)75002-5
52. Mganga ND (2014) The potential of bioaccumulation and translocation of heavy metals in plant species growing around the tailing dam in Tanzania. Int J Sci Technol 3(10):690-697. https://www.researchgate. /publication/268446261

53. Midhat L, Ouazzani N, Hejjaj A, Ouhammou A, Mandi L (2019) Accumulation of heavy metals in metallophytes from three mining sites (Southern Centre Morocco) and evaluation of their phytoremediation potential. Ecotoxicol Environ Saf 169:150-160. https://doi.org/10.1016/j.ecoenv.2018.11.009
54. Monei NL, Puthiya Veetil SK, Gao J, Hitch M (2021) Selective removal of selenium by phytoremediation from post/mining coal wastes: practicality and implications. Int J Min Reclam Environ 35(1):69-77. https://doi.org/10.1080/17480930.2020.1801118
55. Muller G (1969) Index of geoaccumulation in sediments of the Rhine River. Geojournal 2:108-118.
56. Naicker K, Cukrowska E, McCarthy TS (2003) Acid mine drainage arising from gold mining activity in Johannesburg, South Africa and environs. Environ Pollut 122(1):29-40. https://doi.org/10.1016/S0269-7491(02)00281-6
57. Nawab J, Khan S, Shah MT, Gul N, Ali A, Khan K, Huang Q (2016) Heavy metal bioaccumulation in native plants in chromite impacted sites: a search for effective remediating plant species. Clean–Soil Air Water 44(1):37-46. https://doi.org/10.1002/clen.201400605
58. Nouri J, Khorasani N, Lorestani B, Karami M, Hassani AH, Yousefi N (2009) Accumulation of heavy metals in soil and uptake by plant species with phytoremediation potential. Environ Earth Sci 59(2):315-323. https://doi.org/10.1007/s12665-009-0028-2
59. Osanloo M (1999) Coal engineering. Naghoos publication, Tehran.
60. Page V, Feller U (2005) Selective transport of zinc, manganese, nickel, cobalt and cadmium in the root system and transfer to the leaves in young wheat plants. Ann Bot 96(3):425-434. https://doi.org/10.1093/aob/mci189
61. Pandey SK, Bhattacharya T, Chakraborty S (2016) Metal phytoremediation potential of naturally growing plants on fly ash dumpsite of Patratu thermal power station, Jharkhand, India. Int J Phytoremediation 18(1):87-93. 10.1080/15226514.2015.1064353
62. Pérez-López R, Márquez-García B, Abreu MM, Nieto JM, Córdoba F (2014) *Erica andevalensis* and *Erica australis* growing in the same extreme environments: phytostabilization potential of mining areas. Geoderma 230:194-203. https://doi.org/10.1016/j.geoderma.2014.04.004
63. R Core Team (2019) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.
64. Raj AK, Paul B, Singh G (2010) A study on the bulk density and its effect on the growth of selected grasses in coal mine overburden dumps, Jharkhand, India. Int J Environ Sci 1(4):677-684. https://indianjournals.com/ijor.aspx?target=ijor:ijes&volume=1&issue=4&article=024
65. Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting*?*. Plant Sci 180(2):169-181. https://doi.org/10.1016/j.plantsci.2010.08.016
66. Reeves RD, Baker AJM (2000) Metal-accumulating plants. In: Raskin I, Ensley BD (ed) Phytoremediation of toxic metals: using plants to clean up the environment. John Wiley & Sons, New York, pp 193-229.
67. Sahoo PK, Equeenuddin S, Powell MA (2016) Trace elements in soils around coal mines: current scenario, impact and available techniques for management. Curr Pollut Rep 2(1):1-14. https://doi.org/10.1007/s40726-016-0025-5
68. Sardans J, Penuelas J, Ogaya R (2008) Drought's impact on Ca, Fe, Mg, Mo and S concentration and accumulation patterns in the plants and soil of a Mediterranean evergreen *Quercus ilex* forest. Biogeochemistry 87(1):49-69. https://doi.org/10.1007/s10533-007-9167-2
69. Sasmaz A, Sasmaz M (2009) The phytoremediation potential for strontium of indigenous plants growing in a mining area. Env Exp Bot 67(1):139-144. https://doi.org/10.1016/j.envexpbot.2009.06.014
70. Shacklette HT, Erdman JA, Harms TF, Papp CSE (1978) Trace elements in plant foodstuffs. In: Oehme FM (ed) Toxicity of heavy metals in the environments. Marcel Dekker, New York, pp 25-68.
71. Shah A, Niaz A, Ullah, N, Rehman A, Akhlaq M, Zakir M, Suleman Khan M (2013) Comparative study of heavy metals in soil and selected medicinal plants. J Chem 2:1-5. https://doi.org/10.1155/2013/621265
72. Shahid M, Dumat C, Khalid S, Schreck E, Xiong T, Niazi NK (2017) Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. J Hazard Mater 325:36-58. https://doi.org/10.1016/j.jhazmat.2016.11.063
73. Singh N, Kaur M, Katnoria JK (2017) Analysis on bioaccumulation of metals in aquatic environment of Beas River Basin: a case study from Kanjli wetland. Geohealth 1(3):93-105. https://doi.org/10.1002/2017GH000062
74. Sut-Lohmann M, Grimm M, Kästner F, Raab T, Heinrich M, Fischer T (2023) *Brassica juncea* as a feasible hyperaccumulator of chosen potentially toxic metals under extreme environmental conditions. Int J Environ Res 17(3):1-10. https://doi.org/10.1007/s41742-023-00528-8
75. Taylor SR (1964) Abundance of chemical elements in the continental crust: a new table. Geochim Cosmochim Acta 28(8):1273-1285. https://doi.org/10.1016/0016-7037(64)90129-2
76. Tőzsér D, Tóthmérész B, Harangi S, Baranyai E, Lakatos G, Fülöp Z, Simon E (2019) Remediation potential of early successional pioneer species *Chenopodium album* and *Tripleurospermum inodorum*. Nat Conserv 36:47-69. https://doi.org/10.3897/natureconservation
77. Tripathi N, Singh RS, Hills CD (2016) Reclamation of Mine-impacted Land for Ecosystem Recovery. John Wiley & Sons.
78. Van der Ent A, Baker AJM, Reeves RD, Pollard AJ, Schat H (2012) Hyperaccumulators of metal and metalloid trace elements: facts and fiction. Plant Soil 362(1-2):319-334. https://doi.org/10.1007/s11104-012-1287-3
79. Wang W, Hao W, Bian Z, Lei S, Wang X, Sang S, Xu S (2014) Effect of coal mining activities on the environment of *Tetraena mongolica* in Wuhai, Inner Mongolia, China-A geochemical perspective. Int J Coal Geol 132:94-102. https://doi.org/10.1016/j.coal.2014.08.006
80. Wei S, Zhou Q, Wang X (2005) Identification of weed plants excluding the uptake of heavy metals. Environ Int 31(6):829-834. https://doi.org/10.1016/j.envint.2005.05.045
81. Xiao R, Wang S, Li R, Wang JJ, Zhang Z (2017) Soil heavy metal contamination and health risks associated with artisanal gold mining in Tongguan, Shaanxi, China. Ecotoxicol Environ Saf 141:17-24. http://dx.doi.org/10.1016/j.ecoenv.2017.03.002

82. Yazdi M (2003) Coal: from origin to environmental impacts. Jahad Daneshgahi Publication, Tehran, Iran.
83. Zehra SS, Arshad M, Mahmood T, Waheed A (2009) Assessment of heavy metal accumulation and their translocation in plant species. Afr J Biotechnol 8(12):2802-2810. https://doi.org/10.4314/AJB.V8I12.60879
84. Zhang S, Liu G, Sun R, Wu D (2016) Health risk assessment of heavy metals in groundwater of coal mining area: A case study in Dingji coal mine, Huainan coalfield, China. Hum Ecol Risk Assess Int J 22(7):1469-1479. http://dx.doi.org/10.1080/10807039.2016.1185689
85. Zhao FJ, Hamon RE, Lombi E, McLaughlin MJ, McGrath SP (2002) Characteristics of cadmium uptake in two contrasting ecotypes of the hyperaccumulator *Thlaspi caerulescens*. J Exp Bot 53(368):535-543. http://dx.doi.org/10.1093/jexbot/53.368.535
86. Zhu G, Xiao H, Guo Q, Song B, Zheng G, Zhang Z, Zhao J, Okoli CP (2018) Heavy metal contents and enrichment characteristics of dominant plants in wasteland of the downstream of a lead-zinc mining area in Guangxi, Southwest China. Ecotoxicol Environ Saf 151:266-271. https://doi.org/10.1016/j.ecoenv.2018.01.011

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