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Effect of wild peach and Chinese pine on Absorption and Remediation of Heavy Metals in Contaminated Soil of Coal District in Yulin of China

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Abstract

Preliminary examination revealed the adsorbing effect of wild peach (*Pyrus ussurensis*) and Chinese pine (*Pinus tabulaeformis*) on cadmium (Cd). However, whether these two woody plants can be applied in the remediation of fields contaminated with heavy metals needs to be investigated. Coal mining activities are important anthropogenic sources of heavy metals to the local environment. To explore the modification effect of peach and pine on heavy metals in contaminated soil of coal mine, the Mahuangliang Coal Mine area in Yulin City of China was selected for field experiments. Heavy metal concentrations in roots and leaves of wild peach, Chinese pine, and soil samples were measured by using inductively coupled plasma mass spectrometry. Results indicate that Cd pollution is the most serious contaminant, followed by Cu pollution. Moreover, high risks of Pb, Cr, and As contamination were observed. The heavy metal bioconcentration factors of wild peach leaves and roots vary between 0.1 and 0.4 for all of detected heavy metals, and the values in roots are higher than those in leaves. However, the bioconcentration factor of Hg in pine leaves is 1.61, which is 7 times higher than the value in roots, and the concentration of Hg in leaves is 6.95 times higher than that in roots. Results suggest that wild peach and Chinese pine are potential materials for the restoration of heavy metals in contaminated soils, but different tissues of different plant species function differently. The enrichment capacities of wild peach and Chinese pine for Cd, As, Pb, Cr, Cu, and Zn are higher than those of leaves, while leaves are mainly applicable for the absorption of Hg from the atmosphere.

Keywords: Coal mining area, Phytoremediation, Pyrus ussurensis, Pinus tabulaeformis, heavy metal, bioconcentration factor.

1. Introduction

Development and utilization of coal resources played a critical role in boosting the economic development of China. However, coal exploitation caused a series of ecological problems in coal mining areas, including geological morphology destruction, water pollution, plant ecological diversity interruption, water–soil loss, and even desertization. The high content of heavy metal in wastes, such as rock soils, gangues, and tailings, resulting from coal mining, leads to increased heavy metal contamination in coal mining districts by discharging these wastes into surrounding soils, water areas, and atmosphere [1–3]. Heavy metal pollution of soils is characterized by hidden, durable, surface-aggregation; irreversibility and difficult degradation; loss of the available land resources, food yield, and quality; and also threatens human health by transmission, accumulation, and amplification of pollutants in the food chain [4–5]. Furthermore, heavy metal pollution may also bring serious potential risks to food safety, ecological safety, and even social harmony in coal mine areas and surrounding regions.

The current application of physical, chemical, or industrial engineering methods in controlling heavy metal pollution in agricultural soils is limited due to the associated labor consumption, material consumption, financial consumption, large work quantity, high investment, damage to soil mass structure, vulnerable to destroy physical and chemical properties of soils, and reversal of repair effect [6]. Phytoremediation is a promising strategy for heavy metal remediation as it claims low costs and the ability to maintain the stability of soil structure. However, drawbacks limit the application of phytoremediation, including low content of available heavy metal in plant organisms and low biomass of repairing plants [6]. Currently, associated researchers are mainly focusing on tolerant plant screening, capacity of tolerance and heavy metal translocation from root to shoot, effect of exogenous modifier (e.g., chelating agent and growth regulatory substance) on heavy metal hyperaccumulator [6]. Nevertheless, the practical application of woody plants in the control of heavy metal in soils is rarely discussed. Therefore, a phytoremediation test of heavy metal polluted soils in farmlands surrounding the Mahuangliang Coal Mine was conducted. The Mahuangliang Coal Mine is located in Yulin City, Shaanxi Province, China. In this test, wild peach (*Pyrus ussurensis*) and Chinese pine (*Pinus tabulaeformis*) were chosen with consideration to local ecological environmental characteristics. Influences of tree plants on heavy metal concentration in coal contaminated soils were discussed. Feasibility and potential capacities of peach and pine to relieve soil pollution were investigated. Moreover, heavy

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metal accumulation behaviors of tree plants in soils were analyzed. Results provide guidelines and available approaches to alleviate heavy metal pollution in soils surrounding region of coal mines by woody plants.

2. State of the art

Currently, many efforts have been applied to investigate the situation of heavy metal pollution in soils that surround coal mine areas. Bhuiyan et al. [7] found that Mn, Zn, As, Pb, and Ti were the main heavy metal pollutants in agricultural soils that surround a coal mine in north Bangladesh. Liu et al. [8] revealed the dominating heavy metal pollutants (Cd, As, Ni, Pb, and Cr) in soil surrounding a coal mine in the north of Longkou City by combining geographic information system technology with statistical analysis, principal component analysis, and weighted averaging comprehensive analysis methods. Su et al. [9] found that farmlands surrounding a coal mine area in Suzhou City, Anhui Province, China, were seriously contaminated by Hg and Cd, and the severity of heavy metal pollution decreased with distance from the coal mine area.

Yulin City is located in Northwest China and possesses more than 140 billion tons of proven coal reserves, accounting for 86% and 12% of proven reserves in Shaanxi province and China, respectively. The annual output of coal in Yulin reaches 1,800 million tons, making Yulin an important energy-chemical industry base center in Northwest China [10]. However, a series of environmental problems, including surface subsidence, water-soil loss, vegetation degradation, and heavy metal pollution in soil and water, arise in Yulin City due to large-scale coal mining activities [11–12]. Yulin City is the boundary between Loess Plateau and Muus Desert. Previous studies were mainly focused on water-soil retention and ecological environmental improvement. Only a few studies have discussed the remediation of soil pollution in coal mine areas. Heavy metals in soils surrounding coal mine areas are mainly attributed to dust from coal mining. Dust enters soil by atmospheric bulk deposition, thereby intensifying the pollution of surrounding soils. Heavy metals in soils surrounding the Yulin Coal Mine were investigated, and different degrees of heavy metal (e.g., Cd, Cr, Cu, Mn, and Ni) pollutions were revealed as a consequence of long-term exploitation and transportation of coal resources [13]. Qi et al. (2017) [14] analyzed heavy metal pollution in soils of Yulin City. They detected different degrees of accumulations of Cd, Cu, Mn, and Cr in the study area, which were mainly caused by human activities (coal exploitation and coal combustion). Thus, studying heavy metal pollution caused by coal mining activities is necessary. This process is conducive to relieve ecological environmental pollution, to ensure safe production of foods, and to promote sustainable development of the regional economy.

Remediation of heavy metal pollution in soil can be divided into physical, chemical, and biological technologies. Physical remediation technology involves heat treatment, vitrification, backfilling, and replace with out-soil. Chemical remediation technology includes immobilization, chemical leaching, electrodynamics, chemical extraction, and oxidation-reduction method. Biological remediation technology includes microbial remediation, earthworm remediation, and phytoremediation [15]. Phytoremediation technologies are highly acknowledged for their low cost, strong adaption, and zero secondary pollution.

The key point in phytoremediation technologies is screening plant species with extensive growth adaptation, strong tolerance to heavy metal stress, and high biomass [15]. At present, herbaceous plants such as *Bidens pilosa* L, *Solanum nigrm* L, and *Sedum alfredii* H, possess strong adsorption capacity for heavy metals. However, some disadvantages, including small biomass, high requirements on growth environment, low degree of enrichment, limit the application effectiveness of these plants in remedying soil heavy metals [16–18]. Therefore, the primary goal of associated studies is to identify ligneous plants with high biomass and certain accumulation and enrichment of heavy metals [19]. Studies reported that ligneous plants (aspen and willow) have strong adsorption of Cd. *Pittosporum tobira* is superior to privet, gingko, yellow cinnamon root or stem, and tulip tree in terms of resistance to Cd stress. Moreover, plants like mulberry, *Camellia japonica*, *Sylnplocos caudata*, and spiraea have certain tolerance to Cd [20–23]. According to initial studies in our laboratory, peach has a strong adsorption capacity to Cd. The relevant physiological mechanism was disclosed (research content is planned to be published in the Journal of Nuclear Agricultural Sciences (Vol. 6), 2019). However, remediation effect of ligneous plants to heavy metal pollution in soils requires further investigation. Hence, the strong root system of ligneous plants in polluted soils in coal mine areas can prevent water–soil loss and adsorb heavy metals in soils. Therefore, ligneous plants are important in local ecological restoration.

In this study, heavy metal concentrations in farmlands surrounding the coal mine area of Mahuangliang Town, Yulin City, Shaanxi Province, China, were analyzed first. Analysis results were compared with background values in Shaanxi Province and relevant national standards to determine the severity of heavy metal pollution in the selected area. Second, wild peach and Chinese pine seedlings were planted in farmland soils that surround the study area. One year later, heavy metal concentrations in roots and leaves of wild peach and Chinese pine as well as those in soils were tested. Based on test data, effects of wild peach and Chinese pine on remediation of heavy metal pollution in soils were discussed. Research conclusions provide a theoretical basis for the application of woody plants to control heavy metal concentration in soils.

3. Methodology

3.1 Introduction for the study area

The test field was selected in the coal mine area in Mahuangliang Town, Yulin City, Shaanxi Province, China. The field is located approximately 28 km away from Yulin City. This coal mine has been exploited and constructed for more than 10 years since December 15, 2008. The annual output of raw coal is set to 1.2 million tons. The industrial mining square area and mining area are 300 mu and 17.68 km^2, respectively, and the proven resource reserve is 115 million tons. Desert and loess plateau morphology are present in the study area and are characterized by arid and semi-arid continental climates. The annual average air temperature, annual average precipitation, annual average evaporation capacity, annual average hours of sunshine, and frost-free season in the study area are 8.6 °C, 315.25 mm, 1,900 mm, 29 h, and approximately 167 d, respectively.

3.2 Materials and methods

3.2.1 Experimental design
A practical field remediation test was conducted on a farmland in a new rural planning area in Mahuangliang Coal Mine in April 2017. One-year-old wild peach and Chinese pine seedlings were transplanted from the experimental greenhouse into the test field. The test field was 40 m in length and 24 m in width. A total of 27 wild peaches or Chinese pines were separately grown in three plots, and each plot contained 9 plants. The row spacing and plant spacing were both 4 m (Fig. 1). Wild peach and Chinese pine seedlings of the same size were selected for transplantation. Moreover, three wild peach and Chinese pine plants were selected from the experimental greenhouse as the control group. In the soil from experimental greenhouse, contents of Cd, Hg, As, Pb, Cr, Cu, and Zn were 0.17, 0.21, 8.93, 17.27, 58.13, 25.86, and 45.89 mg/kg, respectively.

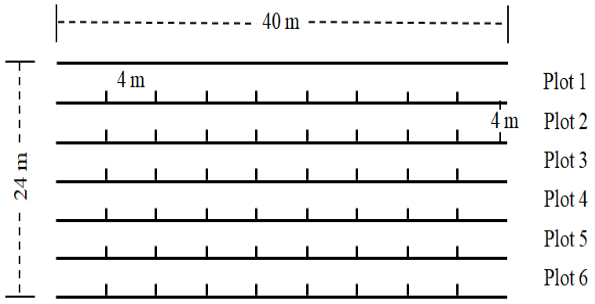

Fig. 1 The planting plan for wild peach and Chinese pine

Note: Each plant species contain 27 tree seedlings with one year old. Plot 1-3 were the places for planting wild peaches, Plot 4-6 were places for planting Chinese pines. Each plot contains 9 plants.

3.2.2 Sample collection and processing
One year later, rhizosphere soil samples and plant samples (surface layer 5–20 cm, which is 5–10 cm away from the main root) were collected in approximately 10 middle days of May. Five plants and their corresponding rhizosphere soil were collected in each plot. Rhizosphere soil samples were collected using a shovel and were stored in individual sealed polyethylene bags to prevent cross pollution, followed by natural air-drying. Soil samples were ground first and then sieved using a 150-mesh nylon sieve before being sealed in polyethylene bags. Root and leaf (needle) samples were collected from two plants. All plant samples were washed with tap water first and then rinsed using deionized water thrice. Later, all samples were dried in an oven at 110 °C first and then at 70–80 °C to a constant weight. Samples for determining the content of Hg and As were air-dried at room temperature to prevent Hg and As loss. Finally, plant samples were ground into powder using a micromill.

3.3 Sample analysis
Soil samples were first digested using 1.0 mL of HNO_3 and 0.5 mL of HF. Cd, Hg, As, Pb, Cr, Cu, and Zn content in soil samples were measured using an inductively coupled plasma source mass spectrometer (ICPMS, Thermo Fisher Scientific).

Plant samples were digested using a microwave digestion system (ETHOSONE). Contents of Cd, Hg, As, Pb, Cr, Cu, and Zn in digestion solution were estimated using ICPMS. Soil pH assay was conducted according to the method of NY/T1377-2007. A total of 10±0.1 g dry soil samples were placed in a centrifuge tube and 25 mL of ultrapure water was added. The centrifuge tube was oscillated for 5 min and then put on static mode for 1–3 h to detect pH with PHS-3C/3E (NY/T 1377-2007). In the sample digestion, three blank control groups and two sample control groups with 10% standard substances (soil: GBW10020; plants: GBW10045) were set up in each testing experiment. The recovery rates of soil and plant standard substances are 90.7%–108.5% and 91.3%–110.1%, respectively. The parallel range of samples is 89.4%–113.7%.

3.4 Bioconcentration factor
Bioconcentration factor (BCF) of heavy metals refers to the ratio of heavy metal content in a plant organ to the heavy metal content in soil. BCF is an important index that describes the accumulation trend of chemical substances in plants. The value of BCF partly indicates the shifting degree and enrichment efficiency of heavy metals from soils into plants. The calculation formula of BCF is:

$$BCF = \frac{C_{plant}}{C_{soil}} \tag{1}$$

where C_{plant} is the concentration (mg/kg) of heavy metals at one part (roots or leaves) of plant and C_{soil} is the concentration (mg/kg) of heavy metals in soil.

3.5 Data statistic analysis
Data were expressed in values relative to the control level in different stages. A statistical analysis of test data was conducted using IBM SPSS Statistics 20. Intergroup data analysis adopted ANOVA, and the significant difference level was $P<0.05$. Data analysis map was drawn using Origin 8.5 (Origin Lab, USA).

4 Results and Discussion

4.1 Distribution characteristics of heavy metal concentrations in soils
The heavy metal composition in soils from the coal mine area in Mahuangliang Town, Yulin City is showed in Table 2. The mean soil pH was 7.96±0.12 and ranged between 7.75 and 8.13. The average content of Cd, Hg, As, Pb, Cr, Cu and Zn in test soils before remediation decreased slightly after the remediation. The content of all the heavy metals in test soils were higher than the average background values in Shanxi Province, with exception of Zn and Hg. Specifically, Cd content exceeds the second level of national limit standard, and Cu content is higher than the national level 1 limit. The average content of Pb, Cr, and As approximately reach to the national level 1 limit (Table 1). Results demonstrate that Cd and Cu are dominant pollutants in soils from the selected coal mine area, accompanied by potential risks of Pb, Cr, and As pollution. Xu et al. (2018) evaluated heavy metal pollution in farmland soils in the Pingdingshan Coal Mine by using the Nemerow comprehensive pollution index method, and they concluded that Cd>Pb>Cu>Cr=Ni>Zn with respect to severity of pollution. Cd caused the most serious soil pollution, which is in consistent with the findings in the present study [24]. Wang et al. (2010) analyzed the situation of heavy metal pollution in soils from Shenmu Coal Mine, and the results showed that Cd was the key pollutant, accompanied with potential risks of Cu, Cr, and Mn pollution. Moreover, heavy metal pollution in soils is closely related to years of exploitation, soil texture, and wind directions [13]. In conclusion, Cd is

the predominant pollutant in soils of the coal mine areas, and Cu, Pb, Cr, and As are the high-risk pollutants. Heavy metal pollutants are mainly produced from dust during exploitation and transportation of coal resources, weathering of coal gauges, and sewage discharge by coal washing [14, 25–26].

Table 1 Statistical analysis of heavy metals in soils of the experimental area (mg/kg)

Metal element	Pre-remediation	Variable coefficient (%)	Post-remediation	Variable coefficient	Background value in Shanxi Province	National soil environmental standards		
						Level1	Level 2	Level 3
pH	7.96±0.12	1.5	7.75±0.14	1.7	-	-	-	-
Cu	41.12±5.47	13.3	39.86±4.25	11.53	20.1	35	100	400
Zn	47.55±11.28	23.72	46.59±12.01	21.37	66.1	100	300	500
Pb	33.08±9.86	29.8	29.68±7.78	28.18	20.9	35	350	500
Cd	0.634±0.27	41.3	0.618±0.21	42.06	0.086	0.2	0.6	1
Cr	77.05±12.34	16.02	76.24±12.03	16.09	61.1	90	250	300
Hg	0.082±0.023	27.71	0.075±0.031	26.92	0.217	0.15	1	1.5
As	11.83±4.57	38.63	11.57±4.18	37.58	10.8	15	25	40

4.2 Accumulation profile of heavy metals in plants

4.2.1 Accumulation profile of heavy metals in wild peach

The mean content of Cd, Hg, As, Pb, Cr, Cu, and Zn in two-year-old wild peach roots are 0.20±0.068, 0.025±0.012, 3.42±0.43, 8.43±2.57, 19.47±4.75, 11.11±1.13, and 12.03±3.01 mg/kg, respectively (Fig. 2a). Heavy metals in the wild peach root system are slightly higher than those in the control group. Specifically, the mean content of Cd, Hg, As, Pb, Cr, Cu, and Zn increased by 25%, 19%, 10%, 1.9%, 1.1%, 8.1%, and 1.2% (Fig. 2a), respectively. These results imply that roots of wild peach tend to absorb heavy metals (Cd, Hg, As, Pb, Cr, Cu, and Zn) from the selected soils. Two-year-old wild peach seedlings can absorb heavy metals to some extent. Therefore, experimental data from a long study period are needed to verify the exact heavy metal absorption efficiency of wild peach. Previous investigations have indicated that contents of available heavy metals in soils increased substantially after planting vegetation with the aid of secreta from rhizospheric microbes, which improve the absorption of heavy metals from soils into a plant root system [27–28]. Hence, the increased heavy metal concentration in wild peach root system may be related to root secretion and rhizospheric microorganisms.

The average concentrations of Cd, Hg, As, Pb, Cr, Cu, and Zn in wild peach leaves are 0.16±0.032, 0.021±0.0089, 2.56±0.44, 6.79±2.87, 16.12±3.24, 8.43±1.08, and 10.44±3.14 mg/kg, respectively (Fig. 2b). Compared with the control group, concentrations of Cd, Hg, As, Pb, Cr, Cu, and Zn in wild peach leaves increased by 23%, 31%, 8.0%, 2.6%, 4.6%, 2.6%, and 9.8%, respectively, which are similar to the results in roots (Fig. 2b). Given that leaves can absorb Hg from the atmosphere, Hg concentration in wild peach leaves increased more than that in a root system. Previous relevant research results indicate that leaves have a stronger ability to absorb Hg from the atmosphere than do roots and stems. Hg concentration in leaves is significantly positively correlated with Hg concentration in the atmosphere [29]. Consequently, Hg concentration in the atmosphere is higher than that in other non-polluted regions. Hg in the atmosphere may come from waste residues during coal exploitation and coal combustion [30].

4.2.2 Accumulation profile of heavy metal in Chinese pine

The average concentrations of Cd, Hg, As, Pb, Cr, Cu, and Zn in one-year-old Chinese pine roots are 14%, 5.6%, 8.4%, 17%, 4.7%, 4.8%, and 7.2%, respectively, higher than those in the control group (Fig.3a). This finding indicates that heavy metals in the soil samples are easily absorbed by Chinese pine roots compared with those in the control group. According to previous studies, Chinese pine can absorb Cd, Hg, As, Pb, Cr, Cu, and Zn. Absorption and accumulation of heavy metals in rhizosphere soil are related to the proportion of available heavy metals [31]. The content of heavy metals in polluted soils is varied with rhizospheric microorganisms, including ectomycorrhizal fungi. Accordingly, Chinese pine growth and accumulation distribution of heavy metals are affected [32].

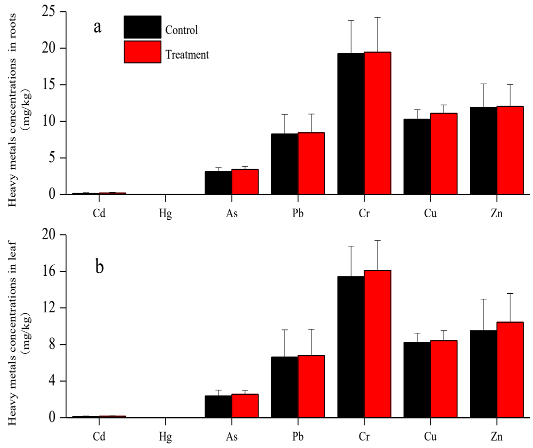

Fig. 2 Distribution pattern of heavy metal concentration in the roots and leaves of wild peach

Average concentrations of Cd, Hg, As, Pb, Cr, Cu, and Zn in Chinese pine needle are 0.090±0.046, 0.13±0.020, 1.55±0.58, 4.34±1.34, 10.23±1.67, 5.39±1.23, and 6.21±1.58 mg/kg (Fig. 3b), respectively, which are slightly higher (13%, 0.76%, 0.65%, 1.1%, 1.3%, 0.94%, and 0.49%) than those in the control group. Heavy metal concentrations in Chinese pine needles are slightly higher than those in roots. Liu et al. [33] monitored heavy metal contents in Chinese pine needles that were sourced from the third ring of Beijing. They reported that the average content of Cd, Hg, Pb, Cr, Cu, and Zn are 0.95±0.89, 1.11±0.79, 11.30±8.78, 1.82±2.00, 5.00±3.17, and 15.47±4.93 mg/kg, respectively. Heavy metals in Chinese pine needles mainly come from soils, transportation, and combustion, which accounted for approximately 40%, 20%, and 20%, respectively, of heavy metal concentrations in Chinese pine needles. Heavy metal concentration in Chinese pine needles was significantly higher than those in Chinese pine needles from polluted areas of Mahuangliang Coal Mine.

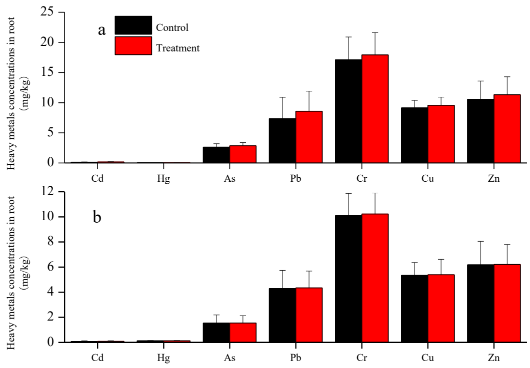

Fig.3 Distribution pattern of heavy metals in Chinese pine roots and needles

4.3 BCF of soil heavy metals in wild peach and Chinese pine plants

BCFs of Cd, Hg, As, Pb, Cr, Cu, and Zn are 0.32, 0.30, 0.29, 0.25, 0.25, 0.27 and 0.25, respectively, in wild peach roots, which are higher than those (0.25, 0.26, 0.22, 0.21, 0.21, 0.21 and 0.22) in wild peach leaves (Table 2). Wang et al. [34] argued that ligneous plants with BCF higher than 0.4 can effectively control soil heavy metals, ligneous plants with BCF ranging between 0.1 and 0.4 can control soil heavy metals to some extent, and plants with BCF lower than 0.1 can hardly control soil heavy metals. According to this criterion, wild peach can control heavy contamination in soils to a certain extent with the BCF ranging from 0.21–0.32 in roots and leaves of wild peach.

BCFs of Cd, Hg, As, Pb, Cr, Cu, and Zn are 0.25, 0.23, 0.24, 0.26, 0.23, 0.23, and 0.24, respectively, in Chinese pine roots, and 0.14, 1.61, 0.13, 0.13, 0.13, 0.13, and 0.13, respectively, in needles (Table 2). BCFs of Cd, As, Pb, Cr, Cu, and Zn in Chinese pine needles are lower than those in roots, with the exception of Hg. BCFs of Cd, As, Pb, Cr, Cu, and Zn in Chinese pine roots and needles range between 0.1 and 0.4. Wang et al. [34] indicate that Chinese pine can be applied in controlling Cd, As, Pb, Cr, Cu, and Zn in soils. In addition, Hg concentration in Chinese pine needle is 6.95 times higher than that in root, and the BCF of Hg in needles is 1.61, which is significantly higher than the BCF of Hg in roots. This result implies that Hg in Chinese pine needles mainly comes from the atmosphere. Therefore, Chinese pine can purify Hg pollution in the atmosphere. Previous studies indicate that atmosphere–leaf interaction is crucial to Hg migration from plants to the environment. A significantly positive correlation is found between Hg concentration in Chinese pine leaf and Hg concentration in the atmosphere, but Hg concentration in leaves is less related to Hg in roots [35–36]. This finding indicates that Hg in leaves do not come from the soil but from the air. Hg concentration in the atmosphere influences plant growth more than Hg concentration in soils does. Therefore, Hg tends to be enriched in Chinese pine needles. Thus, Chinese pine can be planted in coal mine areas and industrial parks with high Hg concentration in the atmosphere for purification.

Table 2 Heavy metals BCF of wild peach and Chinese pine

Heavy metal	Wild peach		Chinese pine	
	Roots	Leaves	Roots	Leaves
Cd	0.32	0.25	0.25	0.14
Hg	0.30	0.26	0.23	1.61
As	0.29	0.22	0.24	0.13
Pb	0.25	0.21	0.26	0.13
Cr	0.25	0.21	0.23	0.13
Cu	0.27	0.21	0.23	0.13
Zn	0.25	0.22	0.24	0.13

5. Conclusions

Absorption and enrichment effects of wild peach and Chinese pine on soils contaminated with heavy metals (Cd, Hg, As, Pb, Cr, Cu, and Zn) in Mahuangliang Coal Mine in Yulin City were evaluated and analyzed by using a comparative analysis and enrichment coefficient. Research conclusions offer references for heavy metal control in coal-polluted soils based on ligneous plants. Some major conclusions can be drawn as follows:
(1) Cd is the dominant pollutant in the study area, followed by Cu. Moreover, potential risks of Pb, Cr, and Ar pollution are observed.
(2) Wild peach and Chinese pine roots are the main parts that absorb Cd, As, Pb, Cr, Cu, and Zn.
(3) Hg in wild peach leaves and Chinese pine needles mainly comes from the atmosphere. Thus, wild peaches and Chinese pines are more applicable to be planted in regions with heavy atmospheric Hg pollution.

In summary, Chinese pine can enrich Cd, As, Pb, Cr, Cu, Zn, and Hg in soils to a certain extent, and can be applied to soil–water retention and heavy metal control in soils surrounding coal mine areas. However, relevant data is inadequate. Further data observations should be drawn from substantially long study periods to obtain accurate results.

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