processes

MDPI

Article

Assessing Phytoremediation Potential: Dominant Plants in Soils Impacted by Polymetal(loid)lic Mining

Boxin Wang [1,2,3], Juan Hou [4], Xueyong Wu [4], Xuekui Niu [4] and Fengping Zhou [1,*]

1 National-Regional Joint Engineering Research Center for Soil Pollution Control and Remediation in South China, Guangdong Key Laboratory of Integrated Agro-Environmental Pollution Control and Management, Institute of Eco-Environmental and Soil Sciences, Guangdong Academy of Sciences, Guangzhou 510650, China; boxinwang2025@163.com
2 Guangdong Experimental High School, Guangzhou 510650, China
3 Shenzhen Shentai Environmental Technology Co., Ltd., Shenzhen 518045, China
4 Yunnan Research Academy of Eco-Environment Science, Kunming 650034, China; hkhoujuan2007@163.com (J.H.); nywxy1234@163.com (X.W.); ynhknxk@163.com (X.N.)
* Correspondence: fpzhou@soil.gd.cn

Abstract: Phytoremediation, an ecological approach aimed at addressing polymetal(loid)lic-contaminated mining soils, has encountered adaptability challenges. Dominant plant species, well-suited to the local conditions, have emerged as promising candidates for this purpose. This study focused on assessing the phytoremediation potential of ten plant species that thrived in heavy metal(loid)-contaminated mining soils. This investigation covered nine heavy metal(loid)s (As, Cu, Cd, Cr, Hg, Ni, Pb, Sn, and Zn) in both plants and rhizosphere soils. The results revealed a significant impact of mining activities, with heavy metal(loid) concentrations surpassing the Yunnan Province's background levels by 1.06 to 362 times, highlighting a significant concern for remediation. The average levels of the heavy metal(loid)s followed the order of As (3.98×10^3 mg kg^{-1}) > Cu (2.83×10^3 mg kg^{-1}) > Zn (815 mg kg^{-1}) > Sn (176 mg kg^{-1}) > Pb (169 mg kg^{-1}) > Cr (68.1 mg kg^{-1}) > Ni (36.2 mg kg^{-1}) > Cd (0.120 mg kg^{-1}) > Hg (0.0390 mg kg^{-1}). The bioconcentration factors (BCFs), bioaccumulation factors (BAFs), and translocation factors (TFs) varied among the native plants, indicating diverse adaptation strategies. Low BCFs and BAFs (ranging from 0.0183 to 0.418 and 0.0114 to 0.556, respectively) suggested a low bioavailability of heavy metal(loid)s. Among the species, both *J. effusus* and *P. capitata* showed remarkable abilities for As accumulation, while *A. adenophora* demonstrated a notable accumulation ability for various heavy metal(loid)s, especially Cd, with relatively high BCFs (1.88) and BAFs (3.11), and the TF at 1.66 further underscored the crucial role of translocation in preventing root toxicity. These findings emphasized the potential of these plant species in mine ecological restoration and phytoremediation, guiding targeted environmental rehabilitation strategies.

Keywords: phytoremediation; polymetal(loid)lic contamination; native dominant plants; adaption strategies; ecological restoration

Citation: Wang, B.; Hou, J.; Wu, X.; Niu, X.; Zhou, F. Assessing Phytoremediation Potential: Dominant Plants in Soils Impacted by Polymetal(loid)lic Mining. *Processes* **2024**, *12*, 833. https://doi.org/10.3390/pr12040833

Academic Editor: Juan Francisco García Martín

Received: 27 March 2024
Revised: 11 April 2024
Accepted: 16 April 2024
Published: 19 April 2024

1. Introduction

Mining operations are integral to the provision of materials and energy for human society; however, they often lead to extensive soil contamination with heavy metal(loid)s, primarily attributed to the disposal of mine tailings and wastewater discharge. This prevalent issue, notably pronounced in China, poses substantial environmental threats characterized by the enduring, concealed, and cumulative nature of heavy metal(loid)s pollution [1]. The consequences extend to adverse effects on soil quality, water resources, crop productivity, and, ultimately, human health through the food chain. Addressing this issue necessitates the blocking and remediation of heavy metal(loid)s-contaminated areas to mitigate their impact on the ecosystem.

Various soil remediation methodologies, spanning physical, chemical, and biological approaches, have been employed [2]. Nevertheless, physical and chemical methods often present drawbacks such as high costs, irreversible alterations to soil properties, and potential secondary pollution. In contrast, phytoremediation emerges as a promising strategy due to its cost-effectiveness, environmental friendliness, minimal secondary pollution, and operational simplicity, making it suitable for large-scale applications [3]. Phytoremediation essentially refers to the utilization of plants and associated soil microbes to lower the concentrations of contaminants in soil or mitigate their adverse effects [4]. This approach can not only address heavy metal(loid)s but also organic pollutants. Phytoremediation also boasts low installation and maintenance costs compared to alternative remediation options. In terms of cost-effectiveness, phytoremediation can be as economical as 5% of the cost of alternative cleanup methods [5]. Notably, plants typically address contaminants without disturbing the topsoil, thereby conserving its fertility and utility, and may even enhance soil fertility through organic matter inputs [6]. It is particularly suitable for implementation on large field sites even where other remediation technologies may not be cost-effective or practical. Phytoremediation encompasses technologies (phytostabilization, phytoextraction, and phytodegradation) utilizing higher plants to remediate contaminated sites and has garnered significant research attention in the past two decades [7]. In phytostabilization, the heavy metal(loid)s in soil are immobilized, minimizing their transport and bioavailability [8]. Phytoextraction involves plants removing contaminants from the soil and storing them in harvestable tissues [9], and a successful phytoextraction strategy typically seeks high translocation factor (TF) values, facilitating the translocation of metal(loid)s into above-ground plant parts for harvest. The choice of plant species is pivotal, with adaptability to local environments, substantial biomass, and the ability to either transfer contaminants to above-ground biomass (for phytoextraction) or exhibit a high tolerance for the contaminants (for phytostabilization) being critical factors. The bioconcentration factor (BCF) and bioaccumulation factor (BAF), as well as the TF of heavy metal(loid)s in plants, are commonly determined to estimate the phytoremediation potential [10,11].

Plants, especially hyperaccumulators, with notable capacities for accumulating contaminants serve as the foundation for phytoremediation, offering practical solutions for decontaminating polluted soils [12]. These plants typically exhibit three key characteristics [10]. Firstly, they possess the ability to accumulate contaminants in their stems and leaves at concentrations notably higher (ranging from 10 to 100 times) than those observed in common plants thriving in uncontaminated soils. Secondly, they demonstrate a TF exceeding 1, indicating the efficient biotranslocation and bioaccumulation of contaminants (usually heavy metal(loid)s) from the roots to the above-ground biomass. Thirdly, these species exhibit robust growth even in environments with elevated concentrations of contaminants. Consequently, dominant plant species have been extensively screened and utilized in phytoremediation, particularly in the restoration of mine tailings [13–15].

However, challenges persist in mining areas, ranging from nutrient deficiencies to extreme pH levels, loose and erodible soil, and water retention issues [16]. These factors collectively pose obstacles to the survival and optimal functioning of phytoremediation plants. For instance, while *Sedum alfredii* exhibits strong tolerance, absorption, and accumulation abilities for Zn, with a bioaccumulation factor ranging from 1.25 to 1.94, its growth may be hindered in cold, high-altitude regions [17]. Similarly, *Pteris vittata* can effectively absorb high concentrations of As, with a bioaccumulation factor of 4.31–5.23, but its growth is restricted in northern China due to the relatively low temperatures [18,19]. Consequently, it is essential to screen for suitable plants capable of thriving under local contaminated and climatic conditions to ensure the success of phytoremediation efforts. To overcome these challenges, considerable efforts have been directed towards identifying dominant plant species that are well-adapted to local climate conditions while also exhibiting a high accumulating capacity of heavy metal(lodi)s. Native dominant plants, having evolved over millennia in naturally elevated heavy metal environments, are believed to possess inherent traits that confer resistance to heavy metal toxicity. As a result, they play a crucial role in soil restoration endeavors, particularly in heavy metal-contaminated soils in mining areas. Numerous previous studies have underscored the significance of native dominant plants in phytoremediation, highlighting their effectiveness in mitigating heavy metal pollution in mining environments [20–22]. For example, Bothe (2011) has demonstrated that metallophytes, plants thriving in metal-rich environments, have a long history of exposure to heavy metal(loid)s [23]. Singh et al. (2022) have identified dominant plant species suitable for the phytoremediation of arsenic-contaminated soil, noting that ten of these plants exhibited a BCF higher than 1, indicating their potential role in As remediation and site restoration [24]. Moreover, previous research has consistently emphasized that traits such as high biomass production, rapid growth, strong resistance, and suitability for remediating various soil types are key criteria in plant selection that also represent challenges in phytoremediation efforts [25–27].

In the specific case of Gejiu city, in the Yunnan Province, China, where severe contamination has ensued due to the accumulation of multiple tailings, the utilization of native plants for phytoremediation remains underexplored. This study aims to address this knowledge gap by investigating the spatial distribution of heavy metal(loid)s, exploring vegetation abundance and distribution in proximity to the tailings, measuring metal(loid) contents in native dominant plants, and evaluating their enrichment and migration potentials. The research outcomes are anticipated to guide future phytoremediation projects in similar mine tailing areas, providing insights into the remediation of heavy metal(loid)s-contaminated soil under comparable environmental conditions.

2. Experimental

2.1. Sites and Sampling

The investigated tailings area is situated in Gejiu city, Yunnan Province, China (approximately 1911 m altitude, 103°14′ E, 23°31′ N), predominantly composed of non-ferrous metal(loid)s, with As, Cu, Pb, and Zn as the predominant constituents. The tailings' storage facility adopts a valley-type configuration. It has been decommissioned since 2018, with a total volume of 31.5 million m^3. Currently, the site exhibits the spontaneous growth of numerous herbaceous plants. These species, characterized by a substantial biomass and widespread distribution, are also prevalent in other tailings facilities in Gejiu and are recognized as dominant species in the local ecosystem. The specific sampling locations are presented in Figure 1.

The selection of the plant species was based on three key criteria. Firstly, all the chosen species demonstrate rapid growth and possess a substantial biomass in the tailing dumpsites, indicating their potential for effective phytoremediation. Secondly, these species exhibit a preference for growing abundantly on slag heaps or similar contaminated sites, with limited occurrence in uncontaminated areas (e.g., development land or agriculture land), suggesting their adaptive advantage in contaminated environments and their potential for successful colonization and remediation. Lastly, prior research studies and references have reported on the phytoremediation potential of these selected species, affirming their suitability for this study. Accordingly, samples from ten high-biomass plant species were collected within the tailings area, and Table 1 provides a comprehensive overview of the sampling location and information for each plant species. It should be noted that both below-ground and above-ground parts of the plant species were collected separately. For every plant species, a selection was made of three individual plants, with their samples meticulously combined into one composite plant sample. A minimum of two composite samples were gathered for each plant species. Concurrently, about 2000 g of the corresponding rhizosphere soil of each plant species, located approximately 30 cm deep and around a 2/3 area from the center of vertical crown projection, was excavated using a narrow-bladed trowel. All the plant and rhizosphere soil samples were hermetically sealed in polyethylene bags for their subsequent transport to the laboratory. Upon arrival at the laboratory, the plant samples underwent a meticulous cleansing process. Initial rinsing with water was performed to eliminate surface soil particles, followed by three rinses with ultrapure water. The samples were then air-dried. Subsequently, the dried plant samples were placed in an oven at 105 °C for 30 min to arrest the metabolic processes. Further drying at 80 °C continued until a constant weight was attained. The resulting dried plant materials were finely ground using a stainless-steel grinder, deposited into polyethylene bags with assigned labels for subsequent analysis.

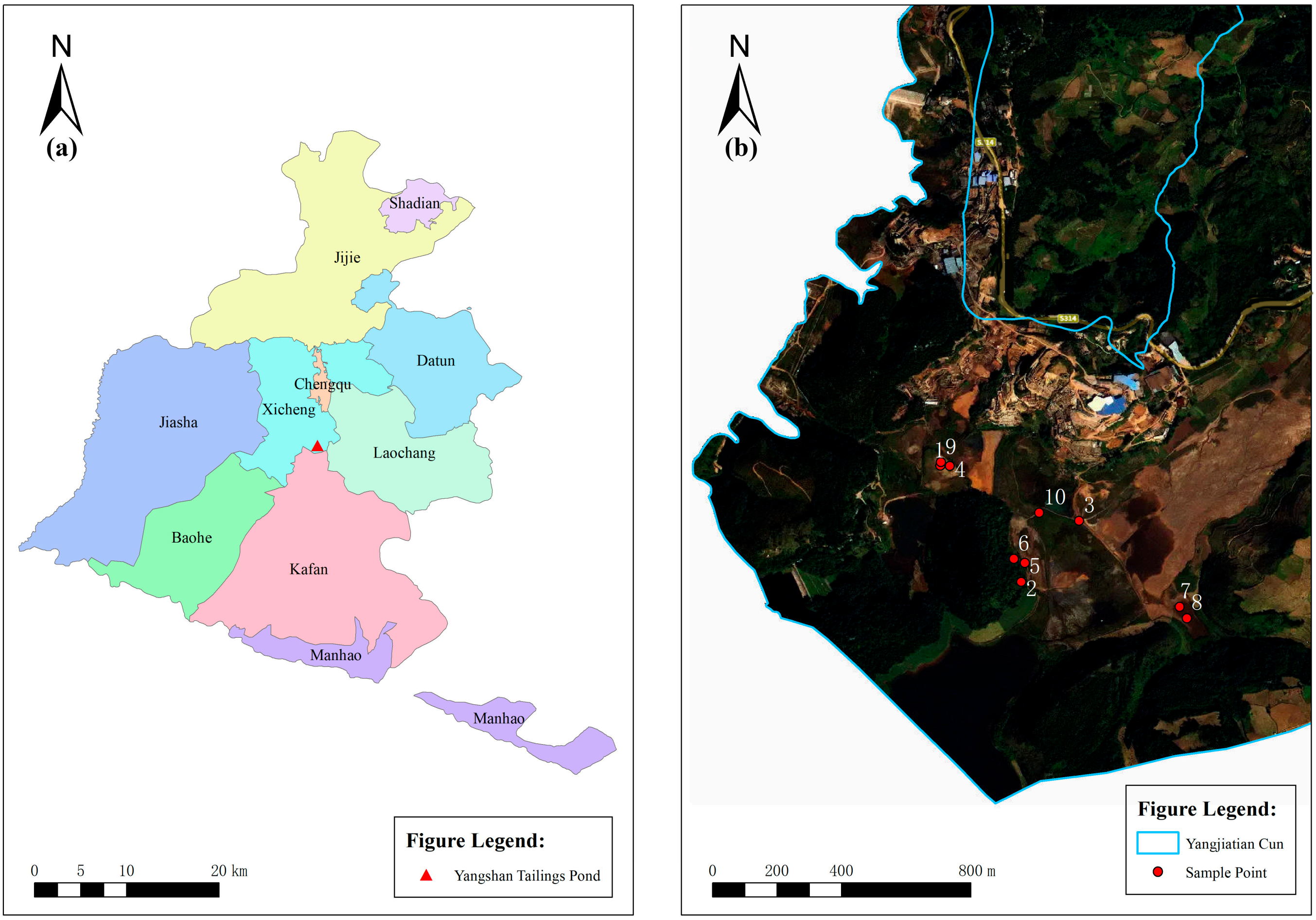

Figure 1. The map of (**a**) Gejiu city, Yunnan Province, China, and (**b**) the sampling location.

Table 1. Plant species investigated in this study.

Pictures of Plants	Sites	Plant Name	Family	Location (Longitude, Latitude, and Altitude)	Average Size of Plants (cm)	
					Above-Ground	Underground
	1	*Ageratina adenophora* (Spreng.) R. M. King & H. Rob.	*Asteraceae*	103°9′ E, 23°18′ N 1.90×10^3 m	78.5	31.5

Table 1. *Cont.*

Pictures of Plants	Sites	Plant Name	Family	Location (Longitude, Latitude, and Altitude)	Average Size of Plants (cm)	
					Above-Ground	Underground
	2	*Buddleja lindleyana* Fortune	*Scrophulariaceae*	103°8′ E, 23°18′ N 1.91×10^3 m	87.0	45.0
	3	*Coriaria nepalensis* Wall. (Morus calva Coriaria kweichowensis Coriaria sinica)	*Coriariaceae*	103°8′ E, 23°18′ N 1.92×10^3 m	40.5	22.0
	4	*Juncus effusus* L.	*Juncaceae*	103°9′ E, 23°18′ N 1.91×10^3 m	60.0	27.0
	5	*Leycesteria formosa* Wall.	*Caprifoliaceae*	103°8′ E, 23°18′ N 1.90×10^3 m	101	30.0
	6	*Puhuaea sequax* (Wall.) H. Ohashi & K. Ohashi	*Fabaceae*	103°8′ E, 23°18′ N 1.92×10^3 m	65.0	80.5
	7	*Pseudognaphalium affine* (D. Don) Anderb.	*Asteraceae*	103°8′ E, 23°18′ N 1.92×10^3 m	35.0	13.5

Table 1. *Cont.*

Pictures of Plants	Sites	Plant Name	Family	Location (Longitude, Latitude, and Altitude)	Average Size of Plants (cm)	
					Above-Ground	Underground
	8	*Pyracantha fortuneana* (Maxim.) H. L. Li	*Rosaceae*	103°8′ E, 23°18′ N 1.91×10^3 m	45.0	24.0
	9	*Persicaria capitata* (Buch.-Ham. ex D. Don) H. Gross	*Polygonaceae*	103° 8′ E, 23°18′ N 1.91×10^3 m	34.5	51.0
	10	*Swertia bimaculata* (Siebold & Zucc.) Hook. f. & Thomson ex C. B. Clarke	*Gentianaceae*	103°8′ E, 23°18′ N 1.92×10^3 m	36.0	12.0

At the same time, the soil samples underwent an initial air-drying phase to remove extraneous materials. They were then subjected to thorough grinding in a mortar and pestle, sieved through a 0.75 µm nylon sieve, and placed into sealed bags.

2.2. Analysis Methods

Both the soil and plant samples underwent acidic digestion before the analyses. In detail, 0.1000 g of the samples was mixed with 8.0 mL of aqua regia solution and subjected to microwave digestion using a MARS6 system (CEM, Charlotte, NC, USA) at a temperature of 190 °C for a duration of 2 h. The resulting solution was diluted to 20 mL by adding 2% HNO_3 solution before being analyzed. The concentrations of As, Cu, Cd, Cr, Hg, Ni, Pb, Sn, and Zn were determined using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Avio 500, Perkin Elmer, Hopkinton, MA, USA). Moreover, soil pH measurements were conducted using a pH meter (Five-Easy FE20, Mettler Toledo, Greifensee, Switzerland) with a soil-to-solution ratio of 1: 5. The pH measurement process employed ultrapure water (Milli-Q® IQ Element, Merck Life, Darmstadt, Germany). All the measurement methods were detailed in Table 2.

2.3. Data Analyses

In this study, TF, BCF, and BAF were employed to reflect the ability of plants to absorb heavy metal(loid)s from the soil and the transfer of heavy metal(loid)s from plants' roots to their above-ground parts. The specific calculation formulas are listed as follows, in Equations (1)–(3).

$$BCF = C_{root}/C_{soil} \quad (1)$$

$$TF = C_{shoot}/C_{root} \quad (2)$$

$$BAF = C_{shoot}/C_{soil} \quad (3)$$

where C_{shoot} and C_{root} represent the concentrations of heavy metal(loid)s in the above-ground and below-ground parts of the plant, respectively (mg kg^{-1}), and C_{soil} represents the concentration of heavy metal(loid)s in the corresponding rhizosphere soil of the plant (mg kg^{-1}).

Table 2. Methods used to determine heavy metal(loid) contents in soil and plant samples.

Heavy Metal(loid)s	Soil Sample Pre-Treatment and Analysis Method	Plant Sample Pre-Treatment and Analysis Method
Cu	HJ 491-2019	GB 5009.268-2016
Cr	HJ 491-2019	GB 5009.268-2016
Ni	HJ 491-2019	GB 5009.268-2016
Zn	HJ 491-2019	GB 5009.268-2016
Pb	GB/T 17141-1997	GB 5009.268-2016
Cd	GB/T 17141-1997	GB 5009.268-2016
As	GB/T 22105.2-2008	GB 5009.268-2016
Sn	USEPA 6020B-2014	GB 5009.268-2016
Hg	GB/T 22105.1-2008	GB 5009.17-2021

3. Results and Discussion

3.1. Total Concentration of Heavy Metal(loid)s in the Soil

The concentrations of various heavy metal(loid)s in the rhizosphere soil of the investigated plants are illustrated in Figure 2, and their average concentrations and coefficient variations are listed in Table 3. As noted, the average concentrations of As, Cu, Zn, Sn, Pb, Cr, Ni, Cd, and Hg in the rhizosphere soil were 3.98×10^3 mg kg^{-1}, 2.83×10^3 mg kg^{-1}, 815 mg kg^{-1}, 176 mg kg^{-1}, 169 mg kg^{-1}, 72.2 mg kg^{-1}, 57.5 mg kg^{-1}, 5.69 mg kg^{-1}, and 0.200 mg kg^{-1}, respectively. Site 10 exhibited complex contamination patterns of heavy metal(loid)s, with notably elevated concentrations of As (2.56×10^4 mg kg^{-1}), Sn (372 mg kg^{-1}), Pb (397 mg kg^{-1}), Cr (208 mg kg^{-1}), and Ni (139 mg kg^{-1}), attributed to its proximity to the tailings. The average concentrations of As, Cu, Zn, and Cd exceeded their background values in other soils of the Yunnan Province by 316, 83.3, 10.5, and 49.1 times, while Pb, Cr, Ni, and Hg surpassed them by 4.46, 1.06, 1.59, and 5.02 times, respectively, highlighting the necessity for the remediation intervention. Beyond the elevated concentrations of heavy metal(loid)s, substantial variation exists among different sampling sites. The coefficients of variation across the sites all surpassed 45%, with As and Cr exhibiting the highest coefficients at 182% and 86.7%, respectively. This underscored significant spatial heterogeneity in heavy metal(loid) pollution in the soil, which can be associated with both anthropogenic and natural environmental factors. Specifically, some previous research on five Sn polymetallic deposits in Gejiu, including Malage, Songshujiao, Gaosong, Laochang, and Kafang, showed approximately 300 Mt of Sn ores at a mean grade of 1 wt% Sn, another 300 Mt of Cu ores averaging 2 wt% Cu, and 400 Mt of Pb-Zn ores with a mean grade of 7 wt% Pb/Zn [28] due to a protracted history of mining activities, including a Pb/Zn/Sn smelter, which resulted in the liberation and migration of the polymetallic elements [29–31]. Notably, As and Cr, unlike other heavy metal(loid) cations, generally exist in the form of oxygen-containing anions (AsO_4^{3-} and CrO_4^{2-}) in the soil [32,33], resulting in a strong affinity to soil mineral surfaces and, consequently, a lower mobilization capacity.

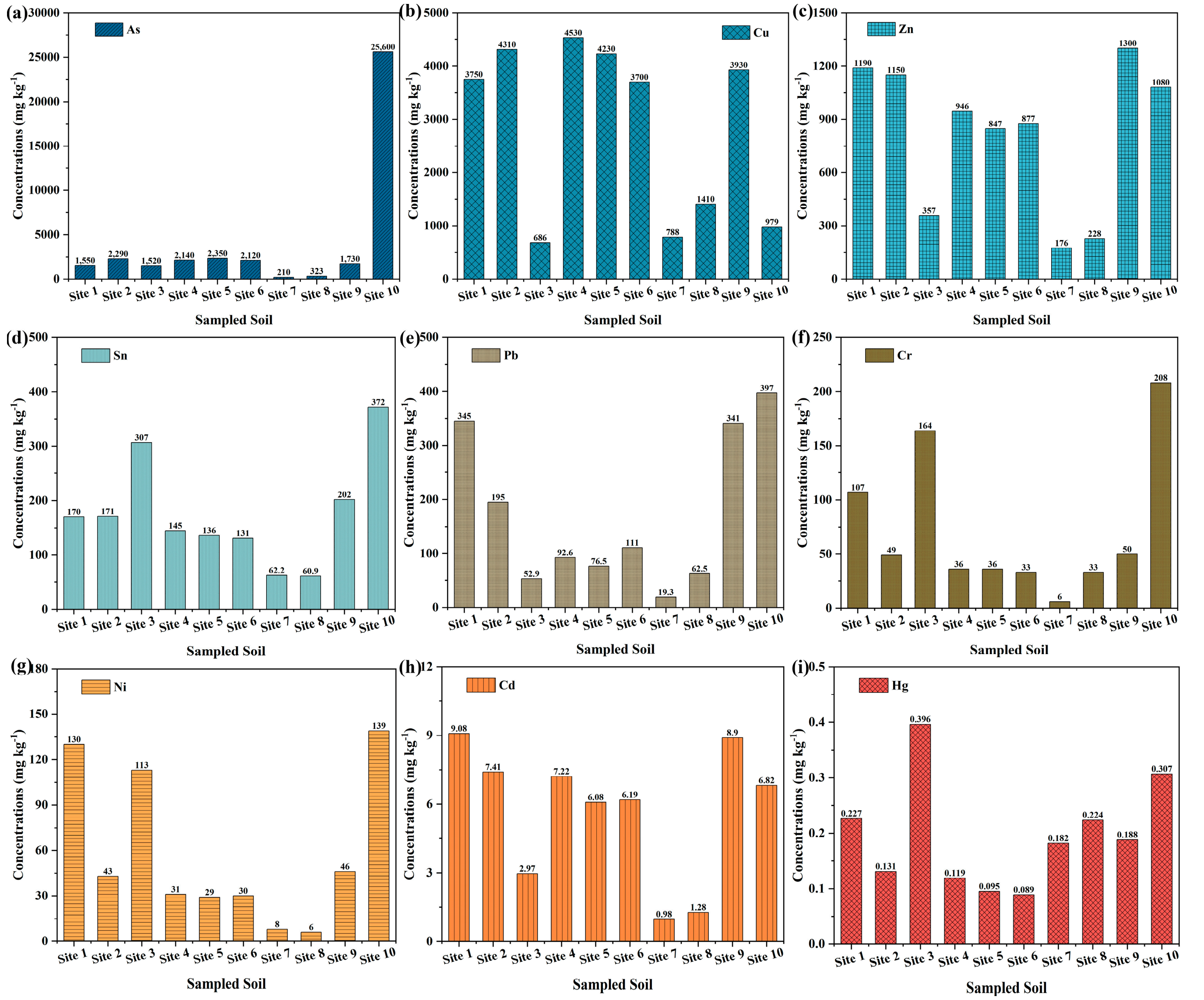

Figure 2. Distribution of different heavy metal(loid)s in the collected soil samples ((**a**) As; (**b**) Cu; (**c**) Zn; (**d**) Sn; (**e**) Pb; (**f**) Cr; (**g**) Ni; (**h**) Cd; and (**i**) Hg).

Table 3. Static concentrations of heavy metal(loid)s in the soil samples.

	As	Cu	Zn	Sn	Pb	Cr	Ni	Cd	Hg
Min. (mg kg^{-1})	2.56×10^3	686	176	60.9	19.3	6.00	6.00	0.980	0.089
Max. (mg kg^{-1})	210	4.53×10^3	1300	372	397	208	139	9.08	0.396
Average (mg kg^{-1})	3.98×10^3	2.83×10^3	815	176	169	72.2	57.5	5.69	0.200
Coefficient of variation	182%	54.8%	48.2%	53.1%	78.9%	86.7%	82.8%	49.0%	47.4%
Average contents in Yunnan Province, China [34]	11.0	34.0	77.7	/	37.9	68.1	36.2	0.120	0.0400
Soil environmental quality–risk control standard for soil contamination of agricultural land (GB 15618-2018) *	20.0	200	300	/	240	350	190	20.0	1.00

* Risk screening value, paddy field, pH > 7.5.

3.2. Concentration of Heavy Metal(loid)s in Plants

The concentrations of heavy metal(loid)s in both the above-ground and below-ground parts of the plants are depicted in Figure 3. Comparatively, the total concentrations of heavy metal(loid)s within the same plants from different sites exhibited minimal variation, consistently maintaining coefficients of variation below 10%. Regarding plant species, *P. capitata* exhibited the highest heavy metal(loid) uptake, with a total concentration of 689 mg kg^{-1}, followed by *B. lindleyana*, with 616 mg kg^{-1}. These findings align with some previous research, emphasizing the prevalence of these two plants in areas affected by mining activities, showcasing relatively high concentrations of various heavy metal(loid)s [35,36]. In general, *S. bimaculate*, *J. effuses*, and *L. formosa* shared a similar translocation behavior, with the concentration of all heavy metal(loid)s in below-ground parts higher than those in above-ground parts, while the others presented the opposite trend, possibly due to their well-developed root systems compared to plants, leading to the high biomass of the below-ground parts.

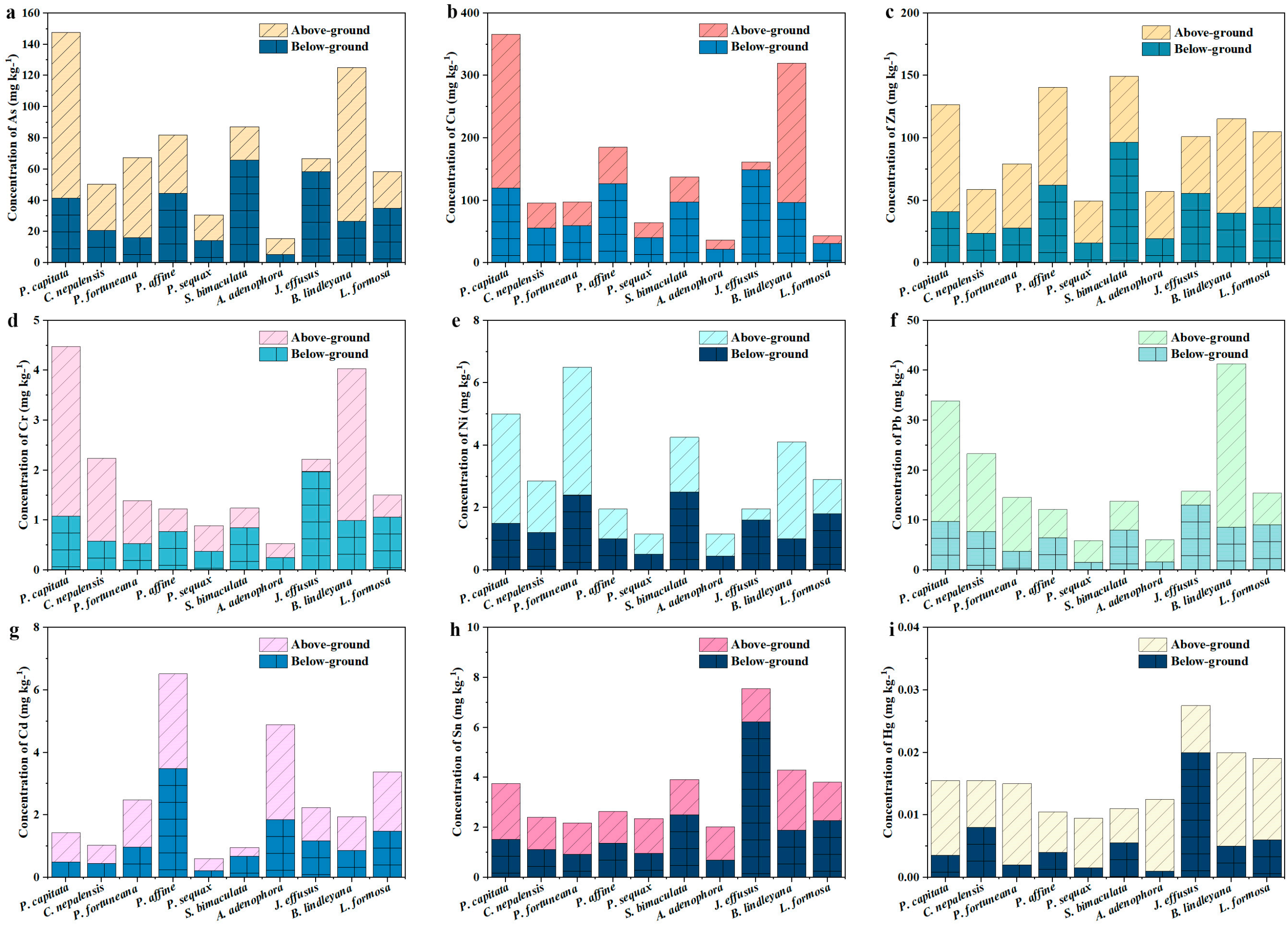

Figure 3. Concentration of heavy metal(loid)s in both above-ground and below-ground parts of the plants ((**a**) As; (**b**) Cu; (**c**) Zn; (**d**) Cr; (**e**) Ni; (**f**) Pb; (**g**) Cd; (**h**) Sn; (**i**) Hg).

From the elemental perspective, As and Cr display an analogous geochemical behaviors, inclined to form oxygen-based anions in soil, so they shared similar distributions in the plants except for *S. bimaculate*, *J. effuses*, and *L. formosa*. Other plants exhibited a great translocation ability of As and Cr as the concentration of the above-ground part significantly surpassed that of the below-ground part. Previous research indicated that, in alkaline oxidized soils (average pH = 8.28), As and Cr generally existed in the forms of As(V) and Cr(VI), respectively, and were readily absorbed by plant roots [37,38]. It is noteworthy that both As(V) and Cr(VI) can exhibit phytotoxic effects on plant growth, thereby impeding plant development [39–41]. To adapt to environments rich in these contaminants, plants transport As and Cr from their below-ground parts to their above-ground parts through compartmentalization to detoxify, resulting in relatively high concentrations in the above-ground tissues. It should be noted that these processes might involve physiological redox transformations of the elements. For example, in *Pteris vittata*, a plant species known for As hyperaccumulation, several mechanisms have been identified for its detoxification, including efficient uptake in roots via phosphate transporters *PvPht1;4*, reduction in roots via As(V) reductases, and translocation and metabolism from roots to fronds and storage into frond vacuoles via As(III) antiporters [42]. It has been reported that the reduced translocation of Cr(VI) to aerial plant parts occurs due to the conversion of Cr(VI) to Cr(III) inside the plants, along with the propensity of Cr(III) to bind to cell walls [38,43]. Compared to As, Cu, Zn, and Pb, plants exhibit significantly lower absorption and accumulation of Cd, primarily due to the relatively low total Cd content in the soil environment (with an average value of 5.69 mg kg^{-1}). Only *P. affine* demonstrates a relatively strong enrichment capability for Cd, with Cd contents in the above-ground and below-ground parts being comparable at 3.03 mg kg^{-1} and 3.49 mg kg^{-1}, respectively. In other plants, Cd tends to accumulate more in the above-ground parts. Recent research also reported the Cd phytoremediation potential of *P. affine* [44–46].

It is noteworthy that, despite the prolonged history of Sn mining in the area and the notably high average soil Sn content of 176 mg kg^{-1}, the ten predominant plant species displayed only moderate capabilities for absorbing and accumulating Sn, with an average concentration of 3.81 mg kg^{-1}. The highest recorded value was observed in *J. effusus*, reaching 7.56 mg kg^{-1} within 1.33 mg kg^{-1} in the above-ground part and 6.23 mg kg^{-1} in the below-ground part. This phenomenon may be attributed to the diminished bioavailability inherent in the specific type of Sn ores present. Previous research reported that, with the exception of oxidized Sn ores, the remaining four types of Sn ores were intricately linked to granitic intrusions, resulting in a relatively low bioavailability [28]. Additionally, only a few plants have been reported for Sn accumulation [47,48].

3.3. Bioconcentration and Translocation of Heavy Metal(loid)s in Plants

To explore the biological uptake of heavy metal(loid)s in the sampled plants, the bioconcentration factors (BCFs) of these plants were analyzed, as depicted in Figure 4. Notably, the relatively high concentration of heavy metal(loid)s in the rhizosphere soil did not consistently translate to higher concentrations in the plants. For instance, despite the rhizosphere soil at site 1 owning a total concentration of 7.25×10^3 mg kg^{-1}, the dominant plant *P. capitata* exhibited a total concentration of 689 mg kg^{-1}, with BCF values of 0.0298. This discrepancy may result from competitive adsorption and a lower bioavailability. For individual heavy metal(loid)s, despite the rhizosphere soil having average concentrations of As, Cu, Cr, and Sn of 3.98×10^3 mg kg^{-1}, 2.83×10^3 mg kg^{-1}, 68.1 mg kg^{-1}, and 176 mg kg^{-1}, respectively, the average BCF values for the dominant plants were lower than 0.05, indicating diverse phytoremediation mechanisms. Among the dominant plants, only *J. effusus* exhibited exceptional transferability of multiple heavy metal(loid)s, including As, Cu, Zn, Ni, Pb, and Cd, with BCF values of 0.181, 0.106, 0.244, 0.267, and 0.918, respectively. Klaudia et al. similarly observed that *J. effuses* played a pivotal role as a phytostabilizer for various heavy metals within the research site [14]. Additionally, Ladislas et al. utilized *J. effuses* for the removal of dissolved heavy metals, noting that Cd and Ni exhibited higher accumulation in roots compared to shoots [49].

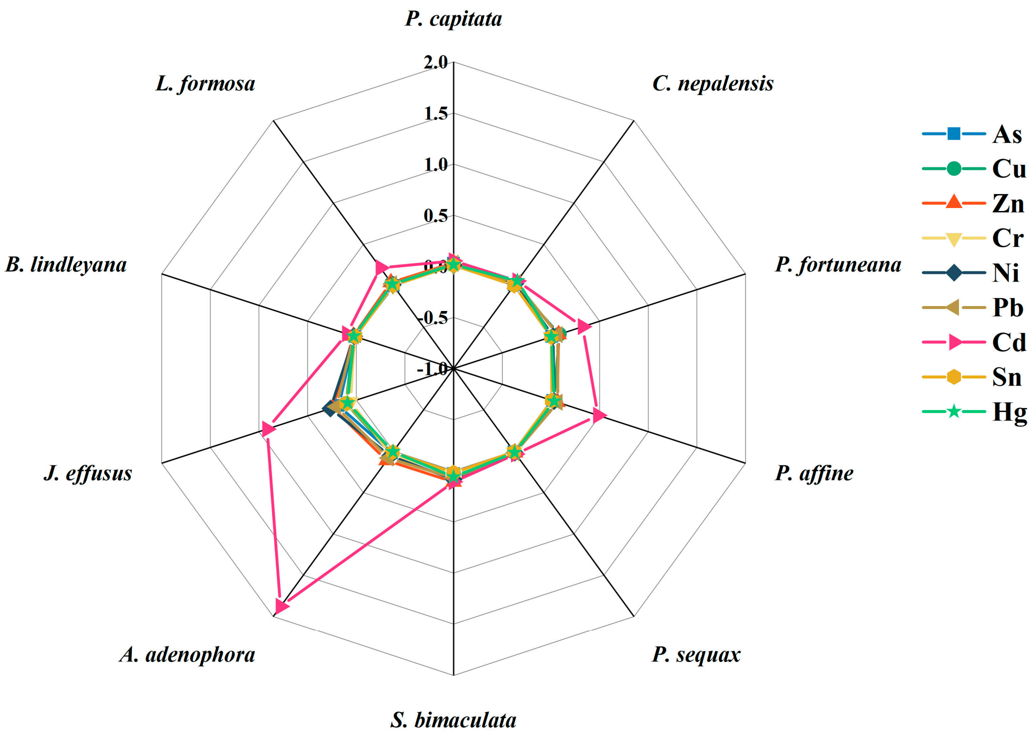

Figure 4. Bioconcentration factor (BCF) values of different heavy metal(loid)s in dominant plants.

The TF values elucidate the transfer and redistribution of heavy metal(loid)s among different plant parts. Plants with strong transferability prefer to absorb heavy metal(loid)s in the rhizosphere soil through their roots and transfer them to their shoots, protecting roots from toxicity. The average TF values decreased in the following order: Hg (3.59) > Pb (1.94) > As (1.59) > Zn (1.53) > Cr (1.48) > Ni (1.39) > Cd (1.30) > Sn (1.11) > Cu (0.84), as illustrated in Figure 5. Among these dominant plants, *P. capitata*, *C. nepalensis*, *P. fortuneana*, *P. sequax*, *A. adenophora*, and *B. lindleyana* exhibited strong transfer abilities for multiple heavy metal(loid)s, with average TF values exceeding 1, indicating their efficacy in bioextracting and biotranslocating heavy metal(loid)s away from the complex soil, to some extent. *P. capitata* displayed excellent biotransfer abilities for Zn, Cr, Cd, and Sn, with the highest TF values of 2.10, 3.17, 1.92, and 1.49, respectively. *B. lindleyana* demonstrated some greater biotransfer abilities for As (3.69), Cu (2.30), Ni (3.10), and Pb (3.85). Interestingly, only *P. capitata* and *B. lindleyana* exhibited TF values for Cu higher than 1, despite the relatively high concentrations of Cu in rhizosphere soils. Conversely, although the average concentration of Hg in rhizosphere soils was 0.196 mg kg^{-1}, significantly lower than Cu (2.83×10^3 mg kg^{-1}), the average TF values of Hg among the dominant plants were higher than those of Cu, indicating a higher bioavailability of Hg in the soils. *A. adenophora* exhibited the highest TF values for Hg of 11.5, despite the total concentration of Hg in the corresponding rhizosphere soil being 0.182 mg kg^{-1}. In addition to its capacity to phytoextract Hg, *A. adenophora* demonstrated significant potential for various heavy metal(loid)s, including As, Zn, Cr, Ni, Pb, Cd, and Sn, with IF values exceeding 1.0. This highlighted the versatility of *A. adenophora* as a potential candidate for a wide array of heavy metal removal applications. While *A. adenophora* is classified as an invasive species, it possesses attributes that render it suitable for ecological restoration, particularly in phytoremediation. Several invasive plant species have demonstrated tolerance to environmental stresses and have been identified as prospective candidates for the phytoremediation of contaminated sites. For instance, research has shown that invasive plants like *Typha latifolia*, *Ipomoea carnea*, and *Ricinus communis* have the ability to tolerate and even thrive in degraded environments, such as coal fly ash deposits, making them promising candidates for the restoration of these deposits [50]. Thus, *A. adenophora,* which possesses hyperaccumulation traits for heavy metal(loid)s, can be considered a potential phytoremediation candidate [51,52]. Nevertheless, it is crucial to implement effective monitoring and management strategies to prevent its spread beyond the intended remediation sites and mitigate any potential negative impacts on surrounding ecosystems. For other species, *S. bimaculata* and *J. effuses* displayed TF values of less than 1.0 for all heavy metal(loid)s, along with lower BCFs (<0.05), indicating their resistance and plant-stabilized barrier capabilities, consistent with total concentrations in their corresponding rhizosphere soils of 7.01×10^3 mg kg^{-1} (Site 6) and 2.12×10^3 mg kg^{-1} (Site 8). Although previous research reported a relatively high tolerance threshold for Zn in *S. bimaculata*, up to 56 mg L^{-1}, in this research, the TF and BCF values of Zn in *S. bimaculata* were 0.551 and 0.110, respectively, emphasizing the habitat-specific variations in heavy metal(loid) accumulation and tolerance among plants.

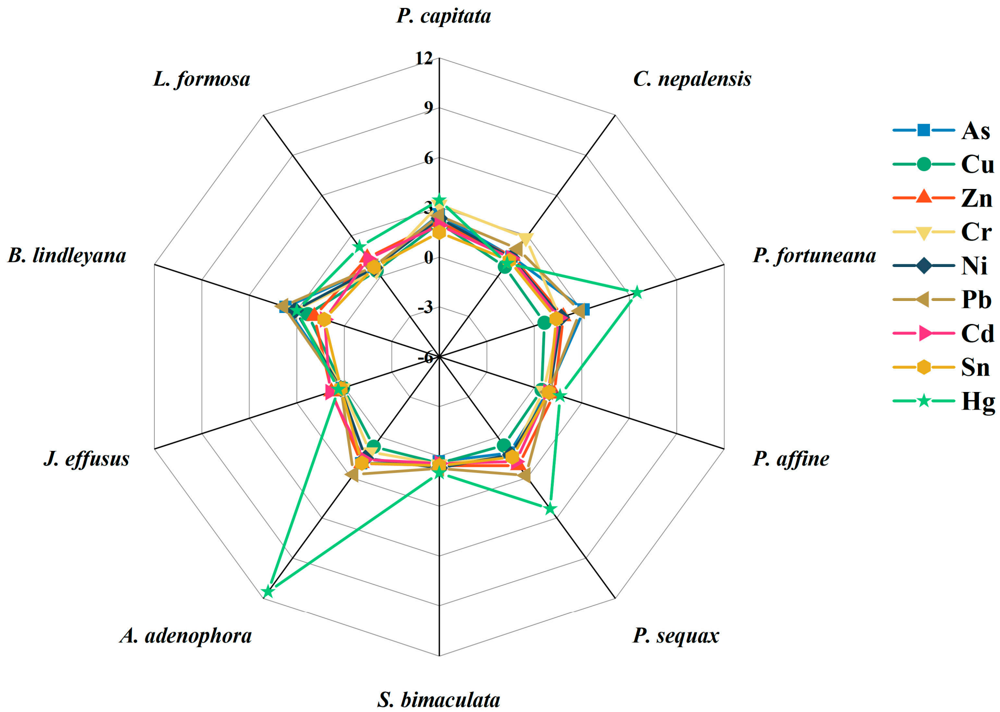

Figure 5. Transfer factor (TF) values of different heavy metal(loid)s in dominant plants.

3.4. Potential Candidates for Phytoremediation

Phytoremediation stands out as an economically advantageous approach when compared to alternative approaches like soil excavation, washing, or disposal. Utilizing dominant plants not only reduces the costs related to maintenance, such as mowing and replanting but also avoids soil disturbance, especially when potentially toxic metal(loid)s accumulate in easily harvestable plant parts, mainly the shoots. The suitability of the identified plants for phytoremediation in discharged mining areas is influenced by various factors. Previous research indicates that the efficiency of phytoextraction depends on two pivotal factors: the capacity of plants to accumulate metal(loid)s and their biomass production. The design considerations for phytoremediation systems involve the BAF, representing the ratio of metal(loid) content in the shoots to that in the soil, and plant productivity, measured by harvestable biomass. Preferably, metal(loid) accumulation in the shoots is more cost-effective than in the roots, as the former allows for straightforward removal through pruning, whereas the latter necessitates uprooting the entire plant. Specific characteristics of the study sites, where shoots accumulate multiple heavy metal(loid)s from the soil, highlight the need for fast-growing plants that are easily harvestable and accumulate significant concentrations of heavy metal(loid)s in their harvestable tissues. Knowledge about plant species with BCFs and BAFs is crucial for selecting the most suitable plants for phytoremediation, potentially reducing operation and maintenance costs.

Figure 6 illustrated various BAF values of the heavy metal(loid)s in the dominant plants. Notably, despite the total Cd concentration in the rhizosphere soil at site 7 of only 0.98 mg kg^{-1}, *A. adenophora* exhibited the highest BAF value (3.11) for Cd, while the values ranged from 0.0420 to 0.829 for other species, demonstrating the highest accumulation in the shoot. It should be highlighted that the BCF of Cd in *A. adenophora* was also higher than 1 (1.66), indicating its potential as a phytoremediation candidate for Cd-contaminated soil. Previous research has emphasized the benefits of Cd accumulation against generalist pathogens, particularly under lower Cd levels, suggesting elemental defense as a key mechanism in the invasion success of *A. adenophora* in areas with prior industrial activity [51]. Moreover, *A. adenophora* has been widely identified as one of the most efficient hyperaccumulators of Cd, attributing its success to the metabolic pathways and enzymatically catalyzed reactions in hairy roots which contribute to the uptake, transformation, conjugation, and compartmentalization of Cd in vacuoles and/or cell walls, crucial detoxification sites in plants [53]. Therefore, *A. adenophora* emerges as the most representative species for phytoremediation, characterized by rapid growth, large leaves, and high Cd accumulation, making it suitable for phytoremediation purposes. The adaptability of *A. adenophora* to eroded and mining soils is evidenced by its rapid growth and substantial Cd accumulation in roots (BCF) and shoots (BAF).

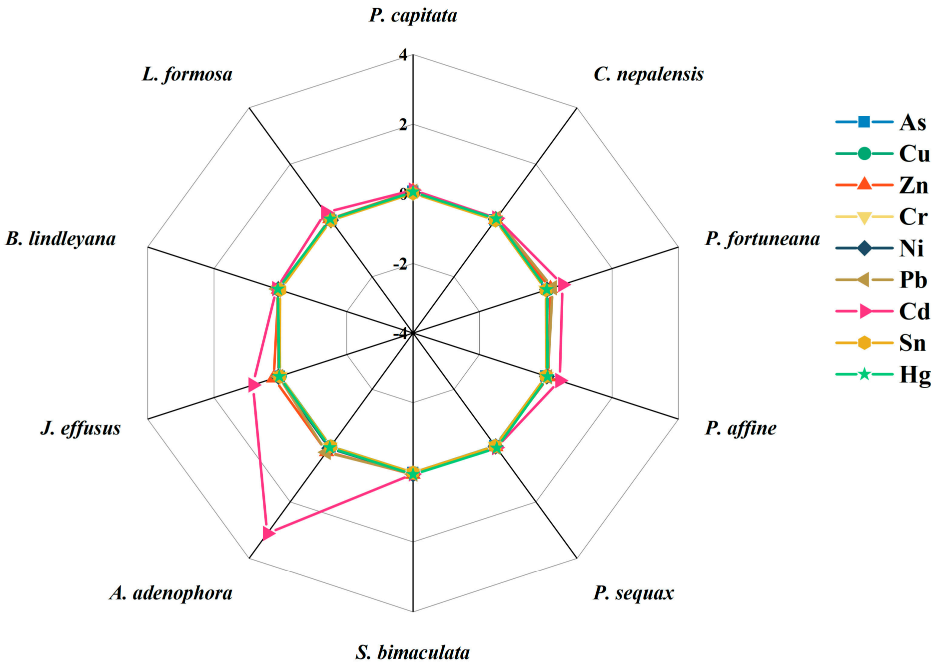

Figure 6. Bioaccumulation factor (BAF) values of different heavy metal(loid)s in dominant plants.

3.5. Prospects

In the studied area, the issue of As contamination has emerged as a significant concern due to its relatively high concentration. Notably, among the collected plant species, both *J. effusus* and *P. capitata* showed remarkable abilities for As accumulation. They exhibited the highest BCF and BAF values for As, indicating their superior tolerance to As contamination. While they may not strictly meet the criteria for hyperaccumulation [12], these species possess self-protection mechanisms against As toxicity in the soil, rendering them potential candidates for As accumulation in soil remediation and ecological restoration efforts within mining areas. Additionally, *A. adenophora* has emerged as a promising candidate for sites contaminated with multiple heavy metal(loid)s, demonstrating excellent accumulation capacities for various heavy metals (except Cu). The high TF values observed for all the elements suggest their potential in immobilizing heavy metal(loid)s from the soil and efficiently transporting them to the above-ground parts of the plant for further harvesting. However, the use of *A. adenophora* should be closely monitored and managed to prevent its spread beyond the intended remediation site and mitigate potential negative impacts on surrounding ecosystems. Interestingly, the soil in the area contained Cu concentrations second only to the concentrations of As. However, all the dominant plant species exhibited extremely low BCF and BAF values for Cu, indicating a limited bioavailability of Cu in the soil. Therefore, alternative physicochemical methods may need to be considered for remediating Cu-contaminated soil.

Furthermore, based on this investigation, a comprehensive analysis and validation of the correlation between heavy metal concentrations in plants within tailing dumpsites and their speciation in soils will be conducted. Although soil heavy metal risk control currently relies on total concentrations, the speciation of these metalloids is crucial as it dominates environmental risk. Thus, further investigation of the relationship between heavy metal forms and bioavailability is essential, providing a theoretical basis for relevant standards and policies [22].

4. Conclusions

This study, conducted in Gejiu city, Yunnan Province, focused on identifying potential candidates for phytoremediation in polymetallic-contaminated soils. The results highlighted the significant impact of historical mining activities on soil composition, particularly heavy metal(loid) contents in plants and rhizosphere soils. Different plants showed distinct adaptation strategies, including phytoextraction and phytostabilization. This study identified ten dominant plant species as promising candidates for phytoremediation due to their rapid growth, substantial biomass, adaptive advantage, successful colonization, and remediation capabilities. Among them, *P. capitata* and *J. effusus* exhibited promising potential for As phytoremediation, while *A. adenophora* showed efficiency in Cd phytoremediation. However, dominant plant species had a limited capacity for Cu accumulation, suggesting the need for alternative approaches in Cu-contaminated soils. Overall, this study provided valuable insights into the adaptive strategies employed by dominant plants in highly contaminated soils and identified specific plant candidates for effective phytoremediation strategies tailored to prevailing metal(loid) pollution.

Author Contributions: B.W.: sampling, investigation, formal analysis, and writing—original draft preparation; J.H.: experiments and investigation; X.W.: methodology, funding acquisition, and resources; X.N.: experiments and methodology; and F.Z.: supervision, conceptualization, formal analysis, visualization, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Key Technologies Research and Demonstration Project for Soil Remediation (No. 2018BC004), funded by the Yunnan Provincial Department of Science and Technology.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: Author Boxin Wang was employed by the company Shenzhen Shentai Environmental Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The Shenzhen Shentai Environmental Technology Co., Ltd. had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Li, Z.; Ma, Z.; van der Kuijp, T.J.; Yuan, Z.; Huang, L. A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Sci. Total Environ.* **2014**, *468–469*, 843–853. [CrossRef] [PubMed]
2. Liu, L.; Li, W.; Song, W.; Guo, M. Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Sci. Total Environ.* **2018**, *633*, 206–219. [CrossRef] [PubMed]
3. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals—Concepts and applications. *Chemosphere* **2013**, *91*, 869–881. [CrossRef] [PubMed]

4. Álvarez-Mateos, P.; Alés-Álvarez, F.J.; García-Martín, J.F. Phytoremediation of highly contaminated mining soils by *Jatropha curcas* L. and production of catalytic carbons from the generated biomass. *J. Environ. Manag.* **2019**, *231*, 886–895. [CrossRef] [PubMed]
5. Prasad, M.N.V. Phytoremediation of Metal-Polluted Ecosystems: Hype for Commercialization. *Russ. J. Plant Physiol.* **2003**, *50*, 686–701. [CrossRef]
6. Mench, M.; Schwitzguebel, J.P.; Schroeder, P.; Bert, V.; Gawronski, S.; Gupta, S. Assessment of successful experiments and limitations of phytotechnologies: Contaminant uptake, detoxification and sequestration, and consequences for food safety. *Environ. Sci. Pollut. Res. Int.* **2009**, *16*, 876–900. [CrossRef] [PubMed]
7. Wang, J.; Aghajani Delavar, M. Techno-economic analysis of phytoremediation: A strategic rethinking. *Sci. Total Environ.* **2023**, *902*, 165949. [CrossRef] [PubMed]
8. Mendez, M.O.; Maier, R.M. Phytoremediation of mine tailings in temperate and arid environments. *Rev. Environ. Sci. Bio/Technol.* **2008**, *7*, 47–59. [CrossRef]
9. Yan, A.; Wang, Y.; Tan, S.N.; Mohd Yusof, M.L.; Ghosh, S.; Chen, Z. Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land. *Front. Plant Sci.* **2020**, *11*, 359. [CrossRef]
10. Baker, A.J.M.; Brooks, R.R. Terrestrial higher plants which hyperaccumulate metal elements. A review of their distribution, ecology, and phytochemistry. *Biorecovery* **1989**, *1*, 81–126.
11. Mocek-Plociniak, A.; Mencel, J.; Zakrzewski, W.; Roszkowski, S. Phytoremediation as an Effective Remedy for Removing Trace Elements from Ecosystems. *Plants* **2023**, *12*, 1653. [CrossRef] [PubMed]
12. Li, J.-t.; Gurajala, H.K.; Wu, L.-h.; Van Der Ent, A.; Qiu, R.L.; Baker, A.J.M.; Tang, Y.-t.; Yang, X.-E.; Shu, W.-S. Hyperaccumulator Plants from China: A Synthesis of the Current State of Knowledge. *Environ. Sci. Technol.* **2018**, *52*, 11980–11994. [CrossRef] [PubMed]
13. Niu, X.; Jia, Y.; Wu, X.; Wang, S.; Hou, J.; Zhang, W. Phytoremediation potential of indigenous plants growing in soils affected by mine activities in Gejiu City, Yunnan Province. *Int. J. Phytoremediat.* **2022**, *25*, 880–888. [CrossRef] [PubMed]
14. Schachtschneider, K.; Chamier, J.; Somerset, V. Phytostabilization of metals by indigenous riparian vegetation. *Water SA* **2017**, *43*, 177–185. [CrossRef]
15. Zeidler, M.; Šipoš, J.; Banaš, M.; Černohorský, J. The successive trend of vegetation confirms the removal of non-indigenous woody species as an insufficient restoration action. *Biodivers. Conserv.* **2021**, *30*, 699–717. [CrossRef]
16. Albert, K.M. Role of revegetation in restoring fertility of degraded mined soils in Ghana: A review. *Int. J. Biodivers. Conserv.* **2015**, *7*, 57–80. [CrossRef]
17. Yang, X.e.; Long, X.; Ni, W.; Fu, C. *Sedum alfredii* H: A new Zn hyperaccumulating plant first found in China. *Chin. Sci. Bull.* **2002**, *47*, 1634–1637. [CrossRef]
18. Xu, W.; Du, Q.; Yan, S.; Cao, Y.; Liu, X.; Guan, D.X.; Ma, L.Q. Geographical distribution of As-hyperaccumulator *Pteris vittata* in China: Environmental factors and climate changes. *Sci. Total Environ.* **2022**, *803*, 149864. [CrossRef] [PubMed]
19. Visoottiviseth, P.; Francesconi, K.; Sridokchan, W. The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environ. Pollut.* **2002**, *118*, 453–461. [CrossRef]
20. Oyuela Leguizamo, M.A.; Fernández Gómez, W.D.; Sarmiento, M.C.G. Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands—A review. *Chemosphere* **2017**, *168*, 1230–1247. [CrossRef]
21. Wu, B.; Peng, H.; Sheng, M.; Luo, H.; Wang, X.; Zhang, R.; Xu, F.; Xu, H. Evaluation of phytoremediation potential of native dominant plants and spatial distribution of heavy metals in abandoned mining area in Southwest China. *Ecotoxicol. Environ. Saf.* **2021**, *220*, 112368. [CrossRef] [PubMed]
22. Du, Y.; Tian, Z.; Zhao, Y.; Wang, X.; Ma, Z.; Yu, C. Exploring the accumulation capacity of dominant plants based on soil heavy metals forms and assessing heavy metals contamination characteristics near gold tailings ponds. *J. Environ. Manag.* **2024**, *351*, 119838. [CrossRef] [PubMed]
23. Bothe, H. Plants in Heavy Metal Soils. In *Detoxification of Heavy Metals*; Sherameti, I., Varma, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 35–57.
24. Singh, S.; Karwadiya, J.; Srivastava, S.; Patra, P.K.; Venugopalan, V.P. Potential of indigenous plant species for phytoremediation of arsenic contaminated water and soil. *Ecol. Eng.* **2022**, *175*, 106476. [CrossRef]
25. Odoh, C.K.; Zabbey, N.; Sam, K.; Eze, C.N. Status, progress and challenges of phytoremediation—An African scenario. *J. Environ. Manag.* **2019**, *237*, 365–378. [CrossRef] [PubMed]
26. Mahar, A.; Wang, P.; Ali, A.; Awasthi, M.K.; Lahori, A.H.; Wang, Q.; Li, R.; Zhang, Z. Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicol. Environ. Saf.* **2016**, *126*, 111–121. [CrossRef] [PubMed]
27. Lee, S.-H.; Park, H.; Kim, J.-G. Current Status of and Challenges for Phytoremediation as a Sustainable Environmental Management Plan for Abandoned Mine Areas in Korea. *Sustainability* **2023**, *15*, 2761. [CrossRef]
28. Zhang, Y.H.; Zhou, J.X.; Tan, S.C.; Li, H.M.; Hao, S.; Jiang, Y.G.; He, X.H. Genesis of the oxidized Sn ores in the Gejiu district, Yunnan Province, SW China. *Ore Geol. Rev.* **2020**, *121*, 103474. [CrossRef]
29. Sun, S.; Dong, C.; Zhang, H.; Yang, H.; Zhang, N.; Bao, L. Heavy Metal Risk Assessment of Soils and Crops in the Intensive Mining Area of Gejiu, Yunnan Province. *J. Geosci. Environ. Prot.* **2022**, *10*, 128–139. [CrossRef]
30. Xiao, Y.; Liu, C.; Hu, N.; Wang, B.; Zheng, K.; Zhao, Z.; Li, T. Contributions of ectomycorrhizal fungi in a reclaimed poplar forest (*Populus yunnanensis*) in an abandoned metal mine tailings pond, southwest China. *J. Hazard. Mater.* **2023**, *448*, 130962. [CrossRef]

31. Li, C.; Dong, P.; Yan, J.; Gong, R.; Meng, Q.; Yao, J.; Yu, H.; Ma, Y.; Liu, B.; Xie, R. Analytical study on heavy metal output fluxes and source apportionment of a non-ferrous smelter in southwest China. *Environ. Pollut.* **2023**, *331*, 121867. [CrossRef]
32. Ascar, L.; Ahumada, I.; Richter, P. Influence of redox potential (Eh) on the availability of arsenic species in soils and soils amended with biosolid. *Chemosphere* **2008**, *72*, 1548–1552. [CrossRef]
33. Gil-Cardeza, M.L.; Ferri, A.; Cornejo, P.; Gomez, E. Distribution of chromium species in a Cr-polluted soil: Presence of Cr(III) in glomalin related protein fraction. *Sci. Total Environ.* **2014**, *493*, 828–833. [CrossRef] [PubMed]
34. Ma, P.; Zhang, Y.; Gao, L.; Guo, J.; Xu, L.; Ding, Y. Clustering and Principal Component Analysis for the Heavy Metal Contents of Soil in Yunnan Province. In Proceedings of the 2012 Second International Conference on Electric Technology and Civil Engineering, Bangalore, India, 3–4 August 2012; IEEE Computer Society: Washington, DC, USA, 2012; pp. 657–660.
35. Nedelkoska, T.V.; Doran, P.M. Characteristics of heavy metal uptake by plant species with potential for phytoremediation and phytomining. *Miner. Eng.* **2000**, *13*, 549–561. [CrossRef]
36. Zhang, Y.; Song, B.; Zhu, L.; Zhou, Z. Evaluation of the metal(loid)s phytoextraction potential of wild plants grown in three antimony mines in southern China. *Int. J. Phytoremediat.* **2020**, *23*, 781–790. [CrossRef] [PubMed]
37. Peng, H.; Yi, L.; Liu, C. Spatial distribution, chemical fractionation and risk assessment of Cr in soil from a typical industry smelting site in Hunan Province, China. *Environ. Geochem. Health* **2024**, *46*, 113. [CrossRef] [PubMed]
38. Shahid, M.; Shamshad, S.; Rafiq, M.; Khalid, S.; Bibi, I.; Niazi, N.K.; Dumat, D.C.; Rashid, M.I. Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-plant system: A review. *Chemosphere* **2017**, *178*, 513–533. [CrossRef] [PubMed]
39. Ran, M.; Lu, Y.; Ren, Y.; He, L.; Li, J. Efficient reduction of Cr(VI) by guava (*Psidium guajava*) leaf extract and its mitigation effect on Cr toxicity in rice seedlings. *J. Environ. Sci.* **2024**, *141*, 1–15. [CrossRef] [PubMed]
40. Bouhadi, M.; Lahmidi, A.; Am, A.; Elhajjouji, H.; Elkouali, M.; Talbi, M.; Fougrach, H. Study of the Toxicity and Translocation of Chromium (VI) in *Vicia faba* Plant. *Bull. Environ. Contam. Toxicol.* **2024**, *112*, 40. [CrossRef] [PubMed]
41. Farooq, M.A.; Islam, F.; Ali, B.; Najeeb, U.; Mao, B.; Gill, R.A.; Yan, G.; Siddique, K.H.M.; Zhou, W. Arsenic toxicity in plants: Cellular and molecular mechanisms of its transport and metabolism. *Environ. Exp. Bot.* **2016**, *132*, 42–52. [CrossRef]
42. Sun, D.; Zhang, X.; Yin, Z.; Feng, H.; Hu, C.; Guo, N.; Tang, Y.; Qiu, R.; Ma, L.Q.; Cao, Y. As-hyperaccumulator Pteris vittata and non-hyperaccumulator *Pteris ensiformis* under low As-exposure: Transcriptome analysis and implication for As hyperaccumulation. *J. Hazard. Mater.* **2023**, *458*, 132034. [CrossRef]
43. Han, F.X.; Su, Y.; Sridhar, B.B.M.; Monts, D.L. Distribution, transformation and bioavailability of trivalent and hexavalent chromium in contaminated soil. *Plant Soil.* **2004**, *265*, 243–252. [CrossRef]
44. Soubasakou, G.; Cavoura, O.; Damikouka, I. Phytoremediation of Cadmium-Contaminated Soils: A Review of New Cadmium Hyperaccumulators and Factors Affecting their Efficiency. *Bull. Environ. Contam. Toxicol.* **2022**, *109*, 783–787. [CrossRef] [PubMed]
45. Li, Q.; Liu, X.; Qin, Y. Cadmium phytoremediation potential of *Gnaphalium affine D. Don.* and physiological response in metal tolerance. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *546*, 042029. [CrossRef]
46. Padmavathiamma, P.K.; Li, L.Y. Phytoremediation Technology: Hyper-accumulation Metals in Plants. *Water Air Soil Pollut.* **2007**, *184*, 105–126. [CrossRef]
47. Liu, Y.; Xu, W.; Wang, Y.; Hao, W.; Zhou, Q.; Liu, J. Growth Responses and Accumulation Characteristics of Three Ornamental Plants to Sn Contamination in Soil. *Agriculture* **2021**, *11*, 205. [CrossRef]
48. Ashraf, M.A.; Maah, M.J.; Yusoff, I. Assessment of phytoextraction efficiency of naturally grown plant species at the former tin mining catchment. *Fresenius Environ. Bull.* **2012**, *21*, 523–533.
49. Ladislas, S.; Gérente, C.; Chazarenc, F.; Brisson, J.; Andrès, Y. Performances of Two Macrophytes Species in Floating Treatment Wetlands for Cadmium, Nickel, and Zinc Removal from Urban Stormwater Runoff. *Water Air Soil Pollut.* **2013**, *224*, 1408. [CrossRef]
50. Singh, S.; Saha, L.; Kumar, M.; Bauddh, K. Chapter 12—Phytoremediation potential of invasive species growing in mining dumpsite. In *Phytorestoration of Abandoned Mining and Oil Drilling Sites*; Bauddh, K., Korstad, J., Sharma, P., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 287–305.
51. Dai, Z.C.; Cai, H.H.; Qi, S.S.; Li, J.; Zhai, D.L.; Wan, J.S.H.; Du, D.L. Cadmium hyperaccumulation as an inexpensive metal armor against disease in Crofton weed. *Environ. Pollut.* **2020**, *267*, 115649. [CrossRef]
52. Khan, I.U.; Qi, S.-S.; Gul, F.; Manan, S.; Rono, J.K.; Naz, M.; Shi, X.-N.; Zhang, H.; Dai, Z.-C.; Du, D.-L. A Green Approach Used for Heavy Metals 'Phytoremediation' Via Invasive Plant Species to Mitigate Environmental Pollution: A Review. *Plants* **2023**, *12*, 725. [CrossRef]
53. Agostini, E.; Talano, M.A.; González, P.S.; Oller, A.L.W.; Medina, M.I. Application of hairy roots for phytoremediation: What makes them an interesting tool for this purpose? *Appl. Microbiol. Biotechnol.* **2013**, *97*, 1017–1030. [CrossRef]