Article

Hydroponic Phytoremediation of Ni, Co, and Pb by *Iris Sibirica* L.

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Abstract: Heavy metal pollution in mine wastelands is quite severe. *Iris sibirica* L., an emergent wetland plant, is characterized by an ability to survive under high stress of heavy metals. This study aimed to explore the phytoremediation ability of nickel (Ni), cobalt (Co), and lead (Pb) by *Iris sibirica* L. under hydroponic conditions. A series of tests were conducted at different metal stress conditions to evaluate the phytoextraction and tolerance of *Iris sibirica* L. The concentrations of Ni, Co, and Pb in plant shoots reached their highest values in 500 mg L⁻¹ treatments, where they were 6.55%, 23.64%, and 79.24% higher than those in 300 mg L⁻¹, respectively. The same concentrations in roots also reached their peak in 500 mg L⁻¹ treatments, where they were 5.52%, 33.02%, and 70.15% higher than those in 300 mg L⁻¹, respectively. Bioconcentration factors (BCF) for Ni, Co, and Pb revealed the phytoextraction ability of *Iris sibirica* L., and the translocation factors (TCF) showed that Ni may be most easily translocated in the plant, followed by Co and Pb. This study indicates that, compared with Ni and Co, *Iris sibirica* L. is more suitable for the phytoremediation of Pb-contaminated metal mine wastelands.

Keywords: heavy metal; phytoremediation; *Iris sibirica* L.; hyperaccumulator; phytoextraction

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1. Introduction

Heavy metal (HM) pollution in the soil has become a global problem. Akin to many other countries in the world, China is facing severe soil metal pollution due to the country's fast development over the past few decades [1–3]. Mining is considered to be one of the most significant sources of HMs [4,5]. It is estimated that 1.5 million ha of wasteland have been generated by mining in China, and the area of polluted land is increasing at a rate of 46,700 ha/year [6].

Nickel (Ni), cobalt (Co), and lead (Pb) are often widely contained in metal mining [7]. Pb is one of the most toxic HMs at low concentrations; if its concentration exceeds 0.15 µg L⁻¹, it can destroy the central nervous system, kidney, liver, and gastrointestinal system and cause diseases (such as anemia, encephalopathy, hepatitis, and nephritic syndrome) directly or indirectly [8,9]. Although Co and Ni are essential nutrients, excessive doses cause a variety of adverse responses. Co and Ni at high concentrations result in different diseases such as myocarditis, pulmonary fibrosis, and renal oedema [7]. These elements display a range of properties in soils including differences in mobility and bioavailability, leaching losses, and plant uptake [10]. HM accumulation in organisms

through the food chain would inevitably pose threats to humans and ecosystems [2,11–13]. Therefore, it is important to find an effective way to remediate soil contaminated by mine/tailing spills.

Modern remediation approaches increasingly focus on in situ techniques, such as assisted natural attenuation and phytostabilisation often primed by the addition of soil amendments. Stabilization of inorganic contaminants by processes of adsorption, binding, or co-precipitation with the additive amendments has been widely researched in the last decade [14]. Phytoremediation is considered an economic and environmentally friendly method to remediate polluted soils [15–17]. Among the various factors that affect phytoremediation efficiency, plant species is the most important concern. Hyper-accumulator plants, which are capable of growing in severely contaminated soils and accumulating very high concentrations of elements in their shoots, are always the best choice for phytoremediation [18]. So far, hundreds of hyper-accumulators have been identified with the majority of species being originally discovered in contaminated fields [19]. Numerous wetland plants including *Acorus calamus* and *Thalia dealbata* have been applied to the phytoremediation of eutrophic water in constructed wetlands [20]. They have been widely studied for effluents treatment due to their high tolerance and bioaccumulation capacity for HMs.

The *Iris sibirica* L., a flowering plant species in the family *Iridaceae*, can grow both in soil and wetland. It is an evergreen emergent plant with a one-month recovery period (after harvesting) and an eleven-month water purification period [21,22]. Its well-developed root system can provide a large surface area for attached microorganisms, thus increasing the potential for uptake of metals. Gao et al. [22] found that *Iris sibirica* L. has good tolerance and high translocation abilities under cadmium (Cd) stress in vertical subsurface flow constructed wetlands. Even though numerous studies have reported HM contamination from mine spills [4,12,23], and some emergent wetland plants have shown a remarkable capability for HM removal, there are few studies on hyper-accumulators which are both suitable for contaminated soil and for wetland.

In view of that, a hydroponic experiment was carried out to investigate the uptake and tolerance of *Iris sibirica* L. to Pb, Co, and Ni. The objectives of this study were: (1) to highlight the physiological responses/tolerance under Ni, Co, and Cd stress under a series of concentrations; (2) to evaluate the metal contents in shoots and roots, and their relationships; (3) to assess the bioconcentration factors (BCFs) and translocation factors (TCFs) in order to reflect the capacity of HM uptake and accumulation of *Iris sibirica* L.

2. Materials and Methods

2.1. Hydroponic Culture

On 1 June 2017, six-month-old plants with visually similar biomass were picked from a nursery garden in the Daxing district, Beijing. Original Ni, Co, and Pb concentrations in the shoots were 1607.90, 88.71, and 259.58 mg kg^{−1}, respectively, while the concentration in the roots were 5224.77, 15.68, and 151.65 mg kg^{−1}, respectively. The plants were washed thoroughly with running tap water to remove any remaining sediment and were rinsed with deionized water. Finally, all the plants were cultured in plexiglass containers with an internal diameter of 200 mm and a working volume of 10 L.

For the experiment, three plants were placed in each container and were exposed to a 10 L nutrient solution. The nutrient solution included 5.00 mmol KNO₃, 5.00 mmol Ca(NO₃)₂·4H₂O, 1.00 mmol KH₂PO₄, 2.00 mmol MgSO₄·7H₂O, 9.00 mmol MnCl₂·4H₂O, 0.80 mmol ZnSO₄·7H₂O, 0.30 mmol CuSO₄·5H₂O, 4.00 mmol H₃BO₃, 0.01 mmol H₂MoO₄·H₂O, and 0.80 mmol Fe₂(SO₄)₃ citrate (as the iron source) [24]. After two weeks of basic adaptation, Ni, Co, and Pb were added at 0, 25, 50, 100, 150, 300, and 500 mg L^{−1} to evaluate their effects on phytoextraction. For each HM, the experiments were conducted in triplicate at each concentration. Deionized water was added to maintain a constant volume of solution daily, and the nutrient solutions were completely replaced every week.

The experiment was carried out in a greenhouse located in the Shunyi district, Beijing, for 60 days before harvesting (from 15 June 2017 to 13 August 2017). The range of the

recorded room temperature in the greenhouse over the culture period was from 21 °C to 28 °C, and the average photoperiod was 15 h light/9 h dark.

2.2. Sample Collection and Preparation

After 60 days of hydroponic culture, the plants collected from each container were washed with 0.01 M HCl for 5 min and then soaked in deionized water. The excess water was wiped off the samples, which were dissected into leaf, stem, and root. Each tissue sample was oven dried at 70 °C for 72 h to remove the moisture and ground to a fine powder using an analytical mill and were homogenized to ensure uniform element distribution. After being passed through a 160 µm diameter sieve, the powder was weighed and was ready for subsequent analysis.

2.3. Analytical Methods

To determine the metal concentrations in plants, 0.20 g of the powdered sample was digested in a Teflon digestion vessel. The digestion solution comprised 7 mL of 65 wt% nitric acid (HNO₃) and 1 mL of 30 wt% hydrogen peroxide (H₂O₂) [25]. The vessels were then capped, fitted into rotor segments, and inserted into the microwave digestion system. The samples were radiated for 35 min. Upon cooling, the vessels were uncapped, and the solutions were transferred to 100 mL volumetric flasks. Sample analysis was performed using an inductively coupled plasma mass-spectrophotometer (ICP-MS) instrument (Agilent 7500cx); 2 wt% nitric acid was used as a blank.

2.4. Statistical Analysis

All values described in this study are the means of three replicates. Analysis of variance (ANOVA) was performed using a statistical software, Statistical Product and Service Solutions (SPSS) version 22.0, to determine the significant difference between mean values. The least significant difference (LSD) for the Student's *t*-test was used to compare changes at $p < 0.05$.

3. Results and Discussion

3.1. Physiological Responses of Emergent Wetland Plants

The basic ability of hyperaccumulators is their high tolerance to metal stress, indicating these plants' ability to resist the adverse and toxic conditions induced by HMs. Such hypertolerance is a pivotal property that facilitates hyperaccumulation [26]. Generally, plants may show obvious toxic effects such as dehydration, scorch, and necrosis under HM stress. The influences of Ni, Co, and Pb on *Iris sibirica* L. after 60 days of hydroponic culture are presented in Figure 1. Under stress with all concentrations of Ni exposure, *Iris sibirica* L. showed serious toxicity symptoms. The treatments with above 25 mg L⁻¹ Ni caused significant Ni-induced visible phytotoxicity symptoms as dehydration and chlorosis after 8 days. Under 50 to 500 mg L⁻¹ of Ni, more severe symptoms and necrosis were observed in the whole plants after 21 days. The plants died after 34 days in 500 mg L⁻¹ of Ni, 42–45 days in 150–300 mg L⁻¹, and 49–51 days in 50–100 mg L⁻¹. These physiological responses indicate that *Iris sibirica* L. was adversely affected by Ni addition.

Iris sibirica L. showed slight chlorosis and little scorch since the Co concentration was 25 mg L⁻¹. Moreover, the Co supply inhibited root growth, and all the roots of *Iris sibirica* L. became a dark brown color under Co stress. The Co intoxication phenomenon of *Iris sibirica* L. became increasingly obvious with increasing amounts of Co spiked in the solution. In contrast, such toxicity symptoms were not observed in *Iris sibirica* L. under any of the Pb treatments. All the plants grew new roots and maintained the intrinsic and extrinsic shoot and root features, even at the highest Pb concentration (500 mg L⁻¹). The above results suggest that *Iris sibirica* L. has strong tolerance to Pb stress, whereas its tolerance to Ni and Co is poor. The tolerance of *Iris sibirica* L. to the HMs tested in this study followed the order Pb > Co > Ni.

Figure 1. Growth of *Iris sibirica* L. under Ni, Co, and Pb stress.

Dry weight was also measured as an important index of plant tolerance to metal stress in this study. Figure 2 shows the changes in total biomass for *Iris sibirica* L. cultured with increasing Ni, Co, and Pb concentrations in the hydroponic solution. According to these results, the concentration of Ni markedly affected the biomass of *Iris sibirica* L. Both the root and shoot biomass appeared erratic with the increasing concentrations of Ni. The biomass of *Iris sibirica* L. reached its highest level at 500 mg L⁻¹ of Ni. Nevertheless, increasing concentrations of Co led to an initial increase and subsequent decrease in the leaf, stem, and root biomass of *Iris sibirica* L. The results indicate that an optimal concentration of Co facilitates the growth and development of each plant part [27]. In addition, the lowest biomass of *Iris sibirica* L. was found when the Co concentration was 100 mg L⁻¹. After 60 days of Pb exposure, compared to the control, the dry weights of the leaves and stems continually increased under all Pb concentrations. However, the dry biomass amounts of roots were reduced by nearly 24.15%, 21.34%, 21.51%, 49.42%, and 12.82% under 25, 50, 100, 150, and 300 mg L⁻¹ Pb treatments, respectively, whereas there was an increase of 35.18% observed for *Iris sibirica* L. at the 500 mg L⁻¹ Pb treatment.

3.2. Ni, Co, and Pb Concentrations in Plant Tissues

As depicted in Table 1 and Figure 3, under various treatments, application of Ni, Co, and Pb significantly affected the uptake and distribution of HMs in *Iris sibirica* L. The concentration changes of Ni, Co, and Pb in all parts of *Iris sibirica* L. basically manifested the same trend, showing increased concentration with increasing amounts of spiked metal ions in the solution (except for the stems at 150 mg L⁻¹ Ni and 300 mg L⁻¹ Co). All the concentrations of Ni, Co, and Pb in the leaves, stems, and roots reached a plateau at 500 mg L⁻¹; the Ni concentrations in the root, stem, and leaf were 7.81%, 3.68% and 5.85% higher than at 300 mg L⁻¹, respectively; the Co concentrations in the root, stem, and leaf were 84.39%, 27.94% and 54.13% higher than at 300 mg L⁻¹, respectively; the Pb

concentrations in the root, stem, and leaf were 43.81%, 363.52% and 235.00% higher than at 300 mg L⁻¹, respectively.

Figure 2. Changes in total biomass of *Iris sibirica* L. under Ni, Co, and Pb stress. Data are means $\pm$ S.D. (n = 3).

Table 1. Concentrations of HMs in the roots, stems, and leaves of *Iris sibirica* L. under Ni, Co, and Pb treatment (mg kg⁻¹).

Treatment mg/L		Leaf		Stem		Root	
Ni	ck	471.39 ± 8.47	a	1136.51 ± 16.12	a	5224.77 ± 41.54	a
	25	3740.77 ± 4.48	b	8221.67 ± 22.21	b	11,526.72 ± 74.49	b
	50	11,420.60 ± 33.34	c	13,602.18 ± 56.93	c	15,317.35 ± 60.67	c
	100	19,194.75 ± 1.64	d	22,199.13 ± 104.93	d	25,299.34 ± 85.46	d
	150	20,080.49 ± 12.75	e	20,998.29 ± 52.74	e	28,449.05 ± 100.63	e
	300	40,800.75 ± 147.96	f	39,193.93 ± 203.33	f	40,976.35 ± 216.99	f
	500	43,987.28 ± 241.52	g	40,638.43 ± 204.56	g	43,372.37 ± 333.63	g
Co	ck	60.55 ± 3.87	a	28.16 ± 1.97	a	15.68 ± 4.39	a
	25	367.04 ± 3.58	b	3644.68±26.68	b	8566.31 ± 51.09	b
	50	1660.75 ± 7.23	c	14 599.58 ± 130.66	c	23,059.15 ± 40.74	c
	100	3363.70 ± 11.34	d	22,558.34 ± 74.16	d	95,754.99 ± 533.49	d
	150	11,016.48 ± 64.99	e	23,833.24 ± 21.78	e	108, 553.93 ± 435.95	e
	300	14,176.08 ± 68.20	f	23,564.26 ± 57.06	f	124,405.28 ± 282.92	f
	500	26,140.43 ± 9.04	g	30,148.81 ± 51.24	g	191,748.30 ± 383.09	g
Pb	ck	198.43 ± 10.98	a	61.15 ± 6.27	a	151.65 ± 4.90	a
	25	211.02 ± 1.64	b	996.97 ± 11.36	b	5036.57 ± 5.37	b
	50	660.33 ± 2.37	c	579.22 ± 2.73	c	15,045.06 ± 78.42	c
	100	663.52 ± 3.40	d	5849.08 ± 47.78	d	47,747.68 ± 144.02	d
	150	760.70 ± 33.77	e	6061.20 ± 53.38	e	48,355.87 ± 125.95	e
	300	1892.23 ± 5.40	f	7022.88 ± 14.61	f	71,562.62 ± 449.44	f
	500	2721.30 ± 11.30	g	32,552.21 ± 67.95	g	239,736.98 ± 1010.22	g

Notes: Data are means $\pm$ S.D. (n = 3). One-way ANOVA (2 factor: different metal ions and different concentration treatments) was performed for each parameter. Means with different letters are significantly different from each other ($p < 0.05$) according to the LSD test.

The HM (Ni, Co and Pb) concentration in the roots was higher than that in the leaves or stems. This is consistent with the results of previous studies that show most HM ions were first stored in the roots, and some were then translocated to the stems and leaves. Translocation of HM ions highly protected the photosynthetic machinery of the plant, thus, leading to better tolerance of the HM ions [28]. According to Orłowska, Przybyłowicz [29], the most Ni accumulated in cortical cells near the endodermis of roots; the cortex acts as a barrier for the movement of HMs between the roots and shoots. The barrier also explains the good tolerance of plants to high concentrations of non-essential metal ions [30]. However,

the Pb and Co contents in the roots are much higher than those in the stems or leaves, probably because of the limited transport of HMs from the roots to above-ground parts.

Figure 3. Concentration and accumulation of HMs in *Iris sibirica* L. under Ni (a,d), Co (b,e), and Pb (c,f) treatment. Note: shoot HM concentration is calculated as $(C_{\text{stem}} \times M_{\text{stem}} + C_{\text{leaf}} \times M_{\text{leaf}}) / (M_{\text{stem}} + M_{\text{leaf}})$; shoot HM accumulation is $(C_{\text{stem}} \times M_{\text{stem}} + C_{\text{leaf}} \times M_{\text{leaf}})$, where C is the concentration of HM and M is the biomass of the plant.

The quotient of HM concentration in the leaf to that in the stem of the plant may be considered as an index of the capacity for metal transportation from the stem to leaf. The differences of Ni concentration in the leaves and stems were relatively small. With increasing Ni concentrations in the hydroponic solution, the ratio ($C_{\text{leaf}}/C_{\text{stem}}$) increased continuously and ranged from 0.45 to 1.08. At Ni levels of 300 and 500 mg L⁻¹, the data show that Ni largely accumulated in the leaves compared to the stems. Ni is an essential

nutrient for plants; therefore, the Ni concentration in leaves was even higher than that in the roots at 500 mg L⁻¹ Ni, which is consistent with the results of a previous study that shows that most of the Ni accumulated in the leaf of *I. melanadenia* and *Tephrosia longipes* [31]. This phenomenon is also coincident with earlier reports that the concentration of Ni in the leaves and stems was higher than that in the roots of *Alyssum lesbiacum*, *I. melanadenia*, and *T. longipes* [32,33]. Additionally, adequate Co, as an essential nutrient, is beneficial for plant growth, but excessive Co is toxic to terrestrial and aquatic plants and results in a variety of adverse responses [34]. Different from Ni, the $C_{\text{leaf}}/C_{\text{stem}}$ of *Iris sibirica* L. was 0.10–0.15 in the low and medium Co solution (25–100 mg L⁻¹) and was 0.46–0.87 in the high Co solution (150–500 mg L⁻¹). This result suggests that Co is a less essential nutrient than Ni in the process of plant growth, and that Co ions can only be transported from the stem to leaf under high concentrations. In contrast, Pb is not an essential element for plant metabolism and can prove toxic [35]. Different from Co, the Pb concentration in the stems from the high Pb solution was significantly higher than that in the leaves. In particular, the minimum quotient of leaf to stem (0.08) was found at 500 mg L⁻¹, indicating that Pb mainly accumulates in the roots and is difficult to transport from the stem to leaf [36]. The overall result may be related to the internal demand for the three selected HM ions in *Iris sibirica* L.

Generally, a hyperaccumulator of HMs (Ni, Co, or Pb) is often defined as a plant with a threshold value of 1000 mg kg⁻¹ in shoots [19,37]. The influence of Ni, Co, and Pb concentration on the shoot and root concentrations of *Iris sibirica* L. is illustrated in Figure 3a–c. It is obvious that the concentration changes of *Iris sibirica* L., for both the shoot and root parts basically manifested the same trend. Increasing concentrations of Ni, Co, and Pb were observed with increasing amounts of spiked metal ions in the hydroponic solution (except for the shoot at 150 mg L⁻¹ Ni). Both the Ni and Co concentrations in *Iris sibirica* L. exceeded the critical level (1000 mg kg⁻¹ for Ni, and 300 mg kg⁻¹ for Co) [19] within 60 days of growing in the 25 mg L⁻¹ solution. However, the threshold value of 1000 mg kg⁻¹ was not found in the shoots of *Iris sibirica* L. until the 100 mg L⁻¹ Pb treatment. This is because Ni and Co are essential nutrients for plant metabolism, whereas Pb is not essential and is even toxic [35,38]. Thus, *Iris sibirica* L. can be considered as a potential hyperaccumulator for Ni, Co, and Pb. *Iris sibirica* could remove metal ions (Ni, Co, Pb) from aqueous solutions containing different initial concentrations. They all reached the highest level when the concentration of metal ions in hydroponic solution reached 500 mg L⁻¹. Under the stress of high Ni and Co concentrations, cells could be destroyed and a water potential could be caused by the imbalance of osmotic pressure [39]. This might be the most likely cause for HM redistribution. The maximum values of Ni, Co, and Pb in the shoot of *Iris sibirica* L. were 42,133.86, 28,016.03, and 21,839.47 mg kg⁻¹, or 6.55%, 23.64%, and 79.24% higher than those in the 300 mg L⁻¹ hydroponic solution, respectively. The same concentrations in roots also reach the highest values in 500 mg L⁻¹ treatments, where they were 5.52%, 33.02% and 70.15% higher than in the 300 mg L⁻¹ treatments, respectively.

As shown in Figure 3d–f, similar results were also observed for the accumulation of Ni, Co, and Pb in *Iris sibirica* L., which increased with rising ion concentration in the hydroponic solution. The maximum values were found under the 500 mg L⁻¹ treatment; the accumulation of Ni, Co, and Pb in the shoot and root of *Iris sibirica* L. reached 1576.65, 820.87, 2498.87 mg per plant, and 5947.22, 27,354.81, 41,114.89 mg per plant respectively. Although the gap in the concentrations between the shoot and root was small under Ni treatment, the overall uptake amounts of Ni, Co, and Pb in roots was far greater than that in shoots due to their relatively small shoot biomass.

3.3. Bioconcentration Factor (BCF) and Translocation Factor (TCF)

The BCF and TCF can be used to assess the uptake and accumulation ability of plants [40,41]. It is widely accepted that the BCF is one of the most important parameters used to assess whether a plant is a hyperaccumulator or not. In this article, the BCF is defined as the quotient of the total concentration of pollutants in the shoot to that in

hydroponic solution [41,42]. A BCF value higher than 1.0 indicates that the plant is a hyperaccumulator for the special pollutant [27,43]. It can be used as an index to reflect the ability to uptake metal ions. As shown in Figure 4a, for *Iris sibirica* L., with increasing concentrations of Ni and Co, there are downward trends of BCF, which dropped to their lowest level at the 500 mg L⁻¹ treatment. In contrast, for Pb, the BCF changes proceeded erratically; the value was at its lowest level when the Pb concentration was 50 mg L⁻¹. Evidently, the BCF values for *Iris sibirica* L. were far greater than or very close to 10 under exposure to Ni, Co, and Pb contamination, revealing the high phytoextraction ability of *Iris sibirica* L. Moreover, the mean values of BCF followed a sequence, Ni > Co > Pb, which is in agreement with the demand for these elements in *Iris sibirica* L.

Figure 4. BCF (a) and TCF (b) for *Iris sibirica* L. under Ni, Co, and Pb stress. Results are expressed as means $\pm$ S.D (n = 3).

The TCF is defined as the quotient of the total concentration of pollutants in the shoot to that in the root of the plant and is an index of the capacity of metal transportation from root to shoot [44,45]. All the TCF values for *Iris sibirica* L. were less than 1.0 (Figure 4b), indicating that *Iris sibirica* L. is not efficient at translocating Ni, Co, and Pb. The TCF increased with the contents of Ni and Pb in the solution but decreased from 0.48 to 0.15 with an increase of Co from 50 to 500 mg L⁻¹. The highest TCF (0.55–0.97 for 300 and 500 mg L⁻¹, closest to 1.0) were found in the hydroponic solution containing Ni, confirming that *Iris sibirica* L. has a better ability to translocate Ni from root to shoot compared with Co and Pb. The TCFs under Co and Pb stress were 0.15–0.48 and 0.04–0.14. In general, plants with BCF greater than 1.0 and TCF less than 1.0 have potential for phytostabilisation [46,47]. It can thus be concluded that *Iris sibirica* L. can be a good choice for phytoremediation in HM contaminated sites.

4. Conclusions

The present study assessed the Ni, Co, and Pb tolerance and accumulation characteristics of *Iris sibirica* L. Under hydroponic conditions, the concentrations of Ni, Co, and Pb in the shoots were all above the threshold as a hyperaccumulator. The HM tolerance and uptake capabilities of *Iris sibirica* L. followed the order Pb > Co > Ni. Although the translocation ability of Pb was relatively limited, the BCF for Pb was significantly higher than 1.0. Since *Iris sibirica* L. can be easily harvested from metal mine wastelands, accumulation in the shoot and root is equally important. Further site experiments are still needed, however, our study shows that *Iris sibirica* L. can be considered as a candidate Pb hyperaccumulator for phytoremediation on contaminated metal mine wastelands.

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References

1. Zhao, F.J.; Ma, Y.; Zhu, Y.G.; Tang, Z.; McGrath, S.P. Soil Contamination in China: Current Status and Mitigation Strategies. *Environ. Sci. Technol.* **2015**, *49*, 750–759. [\[CrossRef\]](#)
2. Zhang, X.; Zhong, T.; Liu, L.; Ouyang, X. Impact of Soil Heavy Metal Pollution on Food Safety in China. *PLoS ONE* **2015**, *10*, e0135182. [\[CrossRef\]](#)
3. Li, P.; Lin, C.; Cheng, H.; Duan, X.; Lei, K. Contamination and health risks of soil heavy metals around a lead/zinc smelter in southwestern China. *Ecotoxicol. Environ. Saf.* **2015**, *113*, 391–399. [\[CrossRef\]](#)
4. Zhuang, P.; McBride, M.B.; Xia, H.; Li, N.; Li, Z. Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China. *Sci. Total Environ.* **2009**, *407*, 1551–1561. [\[CrossRef\]](#) [\[PubMed\]](#)
5. 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. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Xiao, R.; Wang, S.; Li, R.; Wang, J.J.; Zhang, Z. Soil heavy metal contamination and health risks associated with artisanal gold mining in Tongguan, Shaanxi, China. *Ecotoxicol. Environ. Saf.* **2017**, *141*, 17–24. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Redondo-Gómez, S.; Mateos-Naranjo, E.; Andrades-Moreno, L. Accumulation and tolerance characteristics of cadmium in a halophytic Cd-hyperaccumulator, *Arthrocnemum macrostachyum*. *J. Hazard. Mater.* **2010**, *184*, 299–307. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Gupta, V.K.; Rastogi, A.; Nayak, A. Biosorption of nickel onto treated alga (*Oedogonium hatei*): Application of isotherm and kinetic models. *J. Colloid Interface Sci.* **2010**, *342*, 533–539. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Martins, B.L.; Cruz, C.C.; Luna, A.S.; Henriques, C.A. Sorption and desorption of Pb²⁺ ions by dead *Sargassum* sp. biomass. *Biochem. Eng. J.* **2006**, *27*, 310–314. [\[CrossRef\]](#)
10. Nicholson, F.A.; Smith, S.R.; Alloway, B.J.; Carlton-Smith, C.; Chambers, B.J. An inventory of heavy metals inputs to agricultural soils in England and Wales. *Sci. Total Environ.* **2003**, *311*, 205–219. [\[CrossRef\]](#)
11. Duruibe, J.O.; Ogwuegbu, M.O.C.; Ekwurugwu, J.N. Heavy metal pollution and human biotoxic effects. *Int. J. Phys. Sci.* **2007**, *2*, 112–118.
12. Lei, K.; Giubilato, E.; Critto, A.; Pan, H.; Lin, C. Contamination and human health risk of lead in soils around lead/zinc smelting areas in China. *Environ. Sci. Pollut. Res.* **2016**, *23*, 13128–13136. [\[CrossRef\]](#)
13. Abbas, T.; Rizwan, M.; Ali, S.; Zia-Ur-Rehman, M.; Farooq Qayyum, M.; Abbas, F.; Hannan, F.; Rinklebe, J.; Sik Ok, Y. Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination. *Ecotoxicol. Environ. Saf.* **2017**, *140*, 37–47. [\[CrossRef\]](#)
14. Karami, N.; Clemente, R.; Moreno-Jiménez, E.; Lepp, N.W.; Beesley, L. Efficiency of green waste compost and biochar soil amendments for reducing lead and copper mobility and uptake to ryegrass. *J. Hazard. Mater.* **2011**, *191*, 41–48. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Padmavathamma, P.K.; Li, L.Y. Phytoremediation Technology: Hyper-accumulation Metals in Plants. *Water Air Soil Pollut.* **2007**, *184*, 105–126. [\[CrossRef\]](#)
16. Wuana, R.A.; Okieimen, F.E. Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecol.* **2011**, *2011*, 1–20. [\[CrossRef\]](#)
17. Wan, X.; Lei, M.; Chen, T. Cost-benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. *Sci. Total Environ.* **2016**, *563–564*, 796–802. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Rascio, N.; Navari-Izzo, F. Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Sci.* **2011**, *180*, 169–181. [\[CrossRef\]](#)
19. Van der Ent, A.; Baker, A.J.M.; Reeves, R.D.; Pollard, A.J.; Schat, H. Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. *Plant Soil* **2012**, *362*, 319–334. [\[CrossRef\]](#)
20. Zhao, F.; Xi, S.; Yang, X.; Yang, W.; Li, J.; Gu, B.; He, Z. Purifying eutrophic river waters with integrated floating island systems. *Ecol. Eng.* **2012**, *40*, 53–60. [\[CrossRef\]](#)
21. Ma, N.; Wang, W.; Gao, J.; Chen, J. Removal of cadmium in subsurface vertical flow constructed wetlands planted with *Iris sibirica* in the low-temperature season. *Ecol. Eng.* **2017**, *109*, 48–56. [\[CrossRef\]](#)
22. Gao, J.; Zhang, J.; Ma, N.; Wang, W.; Ma, C.; Zhang, R. Cadmium removal capability and growth characteristics of *Iris sibirica* in subsurface vertical flow constructed wetlands. *Ecol. Eng.* **2015**, *84*, 443–450. [\[CrossRef\]](#)

23. Navarro, M.; Pérez-Sirvent, C.; Martínez-Sánchez, M.J.; Vidal, J.; Tovar, P.J.; Bech, J. Abandoned mine sites as a source of contamination by heavy metals: A case study in a semi-arid zone. *J. Geochem. Explor.* **2008**, *96*, 183–193. [\[CrossRef\]](#)
24. Mânzatu, C.; Nagy, B.; Ceccarini, A.; Iannelli, R.; Giannarelli, S.; Majdik, C. Laboratory tests for the phytoextraction of heavy metals from polluted harbor sediments using aquatic plants. *Mar. Pollut. Bull.* **2015**, *101*, 605–611. [\[CrossRef\]](#)
25. Hajar, E.W.I.; Bin Sulaiman, A.Z.; Sakinah, A.M. Assessment of Heavy Metals Tolerance in Leaves, Stems and Flowers of Stevia Rebaudiana Plant. *Procedia Environ. Sci.* **2014**, *20*, 386–393. [\[CrossRef\]](#)
26. Wang, B.; Wang, J.; Zhao, H.; Zhao, H. Stress induced plant resistance and enzyme activity varying in cucumber. *Colloids Surfaces B Biointerfaces* **2006**, *48*, 138–142. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Sun, Y.; Zhou, Q.; Liu, W.; An, J.; Xu, Z.; Wang, L. Joint effects of arsenic and cadmium on plant growth and metal bioaccumulation: A potential Cd-hyperaccumulator and As-excluder *Bidens pilosa* L. *J. Hazard. Mater.* **2009**, *165*, 1023–1028. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Amari, T.; Ghnaya, T.; Debez, A.; Taamali, M.; Ben Youssef, N.; Lucchini, G.; Sacchi, G.A.; Abdelly, C. Comparative Ni tolerance and accumulation potentials between *Mesembryanthemum crystallinum* (halophyte) and *Brassica juncea*: Metal accumulation, nutrient status and photosynthetic activity. *J. Plant Physiol.* **2014**, *171*, 1634–1644. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Orłowska, E.; Przybyłowicz, W.J.; Orłowski, D.; Mongwaketsi, N.P.; Turnau, K.; Mesjasz-Przybyłowicz, J. Mycorrhizal colonization affects the elemental distribution in roots of Ni-hyperaccumulator *Berkheya coddii* Roessler. *Environ. Pollut.* **2013**, *175*, 100–109. [\[CrossRef\]](#)
30. Zhang, X.; Zhu, Y.; Zhang, Y.; Liu, Y.; Liu, S.; Guo, J.; Li, R.; Wu, S.; Chen, B. Growth and metal uptake of energy sugarcane (*Saccharum* spp.) in different metal mine tailings with soil amendments. *J. Environ. Sci.* **2014**, *26*, 1080–1089. [\[CrossRef\]](#)
31. Mogopodi, D.; Mosetlha, K.; Torto, N.; Wibetoe, G. Accumulation patterns of Cu and Ni for *Indigofera melanadenia* and *Tephrosia longipes* plant species growing in Cu–Ni mining area in Botswana. *J. Geochem. Explor.* **2008**, *97*, 21–28. [\[CrossRef\]](#)
32. Adamidis, G.; Aloupi, M.; Kazakou, E.; Dimitrakopoulos, P. Intra-specific variation in Ni tolerance, accumulation and translocation patterns in the Ni-hyperaccumulator *Alyssum lesbiacum*. *Chemosphere* **2014**, *95*, 496–502. [\[CrossRef\]](#)
33. Hassan, Z.; Aarts, M.G. Opportunities and feasibilities for biotechnological improvement of Zn, Cd or Ni tolerance and accumulation in plants. *Environ. Exp. Bot.* **2011**, *72*, 53–63. [\[CrossRef\]](#)
34. Ashfaq, M.; Ali, S.; Hanif, M.A. Bioaccumulation of cobalt in silkworm (*Bombyx mori* L.) in relation to mulberry, soil and wastewater metal concentrations. *Process Biochem.* **2009**, *44*, 1179–1184. [\[CrossRef\]](#)
35. Bonanno, G. Comparative performance of trace element bioaccumulation and biomonitoring in the plant species *Typha dominicensis*, *Phragmites australis* and *Arundo donax*. *Ecotoxicol. Environ. Saf.* **2013**, *97*, 124–130. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Bonanno, G.; Giudice, R.L. Heavy metal bioaccumulation by the organs of *Phragmites australis* (common reed) and their potential use as contamination indicators. *Ecol. Indic.* **2010**, *10*, 639–645. [\[CrossRef\]](#)
37. January, M.C.; Cutright, T.J.; Van Keulen, H.; Wei, R. Hydroponic phytoremediation of Cd, Cr, Ni, As, and Fe: Can *Helianthus annuus* hyperaccumulate multiple heavy metals? *Chemosphere* **2008**, *70*, 531–537. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Mirzahossini, Z.; Shabani, L.; Sabzalian, M.R.; Sharifi-Tehrani, M. ABC transporter and metallothionein expression affected by NI and *Epichloe* endophyte infection in tall fescue. *Ecotoxicol. Environ. Saf.* **2015**, *120*, 13–19. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Kuzovkina, Y.A.; Volk, T.A. The characterization of willow (*Salix* L.) varieties for use in ecological engineering applications: Co-ordination of structure, function and autecology. *Ecol. Eng.* **2009**, *35*, 1178–1189. [\[CrossRef\]](#)
40. Favas, P.J.; Pratas, J.; Prasad, M. Accumulation of arsenic by aquatic plants in large-scale field conditions: Opportunities for phytoremediation and bioindication. *Sci. Total Environ.* **2012**, *433*, 390–397. [\[CrossRef\]](#)
41. Pusz, A.; Wiśniewska, M.; Rogalski, D. Assessment of the Accumulation Ability of *Festuca rubra* L. and *Alyssum saxatile* L. Tested on Soils Contaminated with Zn, Cd, Ni, Pb, Cr, and Cu. *Resources* **2021**, *10*, 46. [\[CrossRef\]](#)
42. Álvarez-López, V.; Prieto-Fernandez, A.; Cabello-Conejo, M.; Kidd, P. Organic amendments for improving biomass production and metal yield of Ni-hyperaccumulating plants. *Sci. Total Environ.* **2016**, *548–549*, 370–379. [\[CrossRef\]](#)
43. Luo, J.; Cai, L.; Qi, S.; Wu, J.; Gu, X.S. A multi-technique phytoremediation approach to purify metals contaminated soil from e-waste recycling site. *J. Environ. Manag.* **2017**, *204*, 17. [\[CrossRef\]](#)
44. Agnello, A.; Bagard, M.; van Hullebusch, E.D.; Esposito, G.; Huguenot, D. Comparative bioremediation of heavy metals and petroleum hydrocarbons co-contaminated soil by natural attenuation, phytoremediation, bioaugmentation and bioaugmentation-assisted phytoremediation. *Sci. Total Environ.* **2016**, *563–564*, 693–703. [\[CrossRef\]](#)
45. Singh, J.; Lee, B.K. Influence of nano-TiO₂ particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): A possible mechanism for the removal of Cd from the contaminated soil. *J. Environ. Manag.* **2016**, *170*, 88–96. [\[CrossRef\]](#)
46. Roccotiello, E.; Serrano, H.C.; Mariotti, M.G.; Branquinho, C. Nickel phytoremediation potential of the Mediterranean *Alyssoides utriculata* (L.) Medik. *Chemosphere* **2015**, *119*, 1372–1378. [\[CrossRef\]](#)
47. Luo, J.; Wu, J.; Huo, S.; Qi, S.; Gu, X.S. A real scale phytoremediation of multi-metal contaminated e-waste recycling site with *Eucalyptus globulus* assisted by electrical fields. *Chemosphere* **2018**, *201*, 262–268. [\[CrossRef\]](#)