

Article

Reduction of Some Polluting Metals in Contaminated Mining and Metallurgical Land

Ivan Jovanović ^{1,*}, Ana Kostov ^{1,*}, Violeta Nikolić ², Hadi Waisi ² and Novica Staletović ²

¹ Mining and Metallurgy Institute Bor, 19210 Bor, Serbia; ivan.jovanovic@irmbor.co.rs

² Faculty of Ecology and Environmental Protection, Union Nikola Tesla University, 11158 Belgrade, Serbia; violetanikolic22@unionnikolatesla.edu.rs (V.N.); hwaisi@unionnikolatesla.edu.rs (H.W.); nstaletovic@unionnikolatesla.edu.rs (N.S.)

* Correspondence: ana.kostov@irmbor.co.rs; Tel.: +381-30-454-108

Abstract

This study analyzed the content of polluting and toxic elements (Cr, Ni, Cu, Zn, As, Cd and Pb) in the cadastral municipalities immediately surrounding the mining and metallurgical complex Bor in Serbia. The soil is exposed to hazardous substances due to historical pollution. Soil pollution at different locations was assessed based on the measured concentration of metals and the contamination factor (Cf). The increased content of the toxic metals was determined mostly for copper and arsenic. Three types of different plants were used in order to reduce the content of toxic metals in the contaminated mining and metallurgical land. The results showed that these plants (*barley Hordeum sativum*, *sugar grazer Sorghum bicolor*, and *hybrid BMR 333 Sudan grass*) were capable of growing and accumulating metals in plants at copper-mined and metallurgical sites.

Keywords: mining; metallurgy; pollution; toxic metals; copper; arsenic

1. Introduction

Pollution is any entry of harmful substances into habitats/ecosystems, which leads to changes in the composition of the living world and diminishes its diversity. Teng et al. pointed out that mining and metallurgical activities usually produce a large number of heavy metals and potentially toxic elements, which have exceeded the standard prescribed values several dozen times and seriously harm the surrounding soil and vegetation growth [1].

The most developed industries in the Timok Area, mining and metallurgy, have greatly affected the pollution of the environment. The over a hundred-and-twenty-year mining of the Copper Mining and Smelting Complex Bor (RTB Bor) have left behind polluted air, dead rivers, and damaged and destroyed agricultural soil, with over 11,000 tons of mining waste per inhabitant of the city [2].

The risk to the environment becomes even greater over time, and its consequences could be catastrophic for the Western and Central Balkans, Danube, and the Black Sea. The main environmental problems that have been identified in the Timok Area are pollution of air, water, and soil, and increasing amounts of mining and metallurgical waste. The dominant sources of pollution in this area are related to the exploitation and processing of copper ore. Sources and causes of soil pollution are related to the most developed industrial branches in the Timok Area, such as:

Academic Editor: Srecko Stopic

Received: 29 June 2026

Revised: 23 July 2026

Accepted: 31 July 2026

Published: 3 August 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

- Mining—physical degradation of terrain, forming soil fills of overburden and flotation tailings, and wastewater spillage.
- Metallurgy—waste gases with high carbon dioxide, arsenic, and heavy metals.

The copper mine and metallurgical complex have degraded the agricultural soil in the area of Bor city and its surroundings. Plants that grow on extremely toxic substrates have the potential for their application in phytoremediation, phyto-mining, and phyto-metallurgy [3]. Phyto-mining-metallurgy has proven to be a promising biotechnology for the extraction of rare and precious metals from naturally enriched or polluted soils by special groups of plants—metallophytes. According to Baker, metallophytes are plants able to tolerate high concentrations of metals (mostly nickel, Ni; copper, Cu; or cobalt, Co) in soil that are toxic for most other species [4]. Metallophytes can survive and grow on metal-rich substrates and are generally classified into true metallophytes and pseudo-metallophytes) [5]. Various groupings are made depending on the metal that the metallophytes absorb; for example, cuprophytes absorb copper [6].

On the other hand, concerns regarding environmental contamination have led to the development of appropriate technologies for metal cleanup of soil [7,8], such as phytoremediation [9,10].

It is well known that plants that can grow on metalliferous soils can be classified based upon their trace element uptake, such as excluder, bioindicator, and hyperaccumulator [11]. Hyperaccumulators absorb these elements in high concentrations and reduce the toxicity of the soil, and the plant can grow unhindered. Tolerance to certain trace elements and their accumulation patterns have been widely studied over the past decades, as one of the green technologies to produce metals and their derivatives from secondary raw materials (biomass of hyperaccumulators), as well as a technology for environmental protection [12]. Given that hyperaccumulation occurs in the aboveground parts of the plant, hyperaccumulator species are potentially suitable for use in phyto-mining-metallurgy and subsequent treatment of cut aboveground biomass. One of the most significant limiting factors for the use of hyperaccumulator plants is their relatively small biomass, and efforts are being made to find species that produce greater biomass. According to [13], on the territory of the Balkan Peninsula, a total of 31 plant species with the ability to hyperaccumulate metals were found [14].

Based on previous studies [15] in the surroundings of the Bor copper mine and metallurgy complexes, copper and arsenic are the most abundant of all potentially toxic elements in the contaminated soil. Other research also confirmed that tailings stacking of iron ore has caused Cu pollution in the surrounding topsoils [16].

Copper is an essential transition metal involved in biological processes such as photosynthesis, respiration, and cell wall metabolism. Despite that, copper can also be highly toxic [8], whereby an overall reduction in plant biomass, inhibition of root growth, chlorosis, bronzing, and necrosis are the usual reported symptoms of copper excess. Normal copper content ranges from 1 to 20 ppm and tolerance values are up to 100 ppm [17,18].

According to [19], about 35 species accumulate copper. Copper accumulation has been studied in numerous species, such as *Haumaniastrum katangense*, *Crepidiorhopalon tenuis*, *Lamiaceae*, *Nyssaceae*, *Pteris melanocaulon*, *Cynodon dactylon*, and *Anisopappus chinensis*, mainly in Katanga, Congo [6,20–24]. In the territory of Serbia, the species *Minuartia recurva* showed hyperaccumulation of copper in above-ground parts [13,14].

Arsenic is commonly associated with ores such as copper. Arsenic content in the Earth's crust is relatively small and amounts to $1 \times 10^{-4}\%$. The factors that affect the behavior of arsenic compounds in the soil are pH and the content of Fe, Al, Ca and Mg. Due to its extremely high soil absorption, arsenic accumulation should be expected in the surface layers. In the absence of substances that absorb it strongly (clay, organic matter), it rinses into deeper layers and even into water. The arsenic content in the plants is usually

much lower than in the soil [18]. Arsenic is a nonessential element for plants and generally highly phytotoxic.

Most studies of arsenic hyperaccumulators have focused on phytoremediation rather than phyto-mining-metallurgy, due to the great risk this metal poses to human health and the environment. Arsenic hyperaccumulation has been described for several *Pteris* species [25–28]. *Pteris vittata* (brake fern) can tolerate soils containing as much as 1500 mg/kg and can take up large amounts of arsenic into its fronds in a short time [29]. High amounts of arsenic can also be tolerated by *Pityrogramma calomelanos* [30,31] and *Viola arsenica* [32]. Arsenic exists in the plant mostly as an inorganic species and is mainly present as arsenite.

Generally, in Europe there are not many plants capable of “absorbing” copper, so this practice is not widespread. Most tests and analyses were done at the local level, i.e., in individual cases and on individual contaminated lands, mostly in rural areas and usually as sporadic cases [33–35]. Significantly more papers focus on the field of phytoremediation and the use of different types of plants in reducing soil pollution [9,36–41]. Attention has been given to the study [42] of the mobility and phytoextraction of toxic metals Cu, Zn, Pb and Cd during the phytoextraction process in historically polluted soil with the aim of reducing their concentrations in Indian mustard (*Brassica juncea*) plants growing in the soil, especially during periods of high rainfall.

Phytoremediation technologies were widely used in many experimental studies [36,37]. Phytoremediation with corn is used for the reduction of lead from contaminated agricultural land in [38], and the used corn is further used as bioenergy fuel. Mining operations have resulted in the release of toxic metals into the environment. The focus is given to phytoextraction and phytostabilization as the most promising and alternative methods for contaminated soil remediation [39]. Application of *Festuca arundinacea* in phytoremediation of soils contaminated with heavy metals and petroleum hydrocarbons was given in [40]. The study in [9] summarized the roles of soil chemistry and plant microbiology interactions in the phytoremediation of heavy metal-contaminated soil using the *Sorghum bicolor* plant.

The identification of plants that have the capacity to withstand and/or accumulate heavy metals is very important in the reclamation of metal-contaminated soils.

Recent references relating to the reduction of heavy metals from soil contaminated by mining and metallurgical activities at sites in Europe (Germany, Czech Republic, and Romania) are given in the literature [43–47].

The aim of this paper is to present the results of toxic polluting metal content in contaminated soil from mining and metallurgical activities and to try to reduce their content based on the use of selected agricultural plants and thus perform remediation and revitalization of contaminated land.

2. Materials and Methods

Description of the study site: the Bor copper mine and metallurgical complex is located in Eastern Serbia, in the Balkans (a historical and geographical region of south-eastern Europe) and in the Pannonian Plain (a region of central Europe) [48].

Soil samples were collected (0–30 cm depth) from a mining and metallurgy area situated in the town of Bor (44° 04′ N/22° 05′ E). The soil used for testing originates from the agricultural land in the immediate vicinity of mining and metallurgy sites resulting from the exploitation of copper.

Materials and methods used in this research are mostly standard methods based on the regulations of the program for systematic monitoring of soil quality, indicators for assessing the risk of land degradation, and the methodology for the development of remediation programs, RS Official Gazette, No. 88/2010, ISO 18400 Soil Quality-Sampling and

which are in accordance with the newly adopted Directive (EU) 2025/2360 of the European Parliament and of the Council on soil monitoring and resilience (Soil Monitoring Law).

In this paper, soil sampling was performed at 3 different locations: Location 1 (L1)—5.5 km north of the mining and metallurgy complex, Location 2 (L2)—2.5 km east of the mining and metallurgy complex, and Location 3 (L3)—4.5 km west of the mining and metallurgy complex. The sampling locations were selected to consider the impact of the gases and existing flotation tailings on the surrounding fields.

Topsoil is the most important part of the soil profile for degradation control; it is the most fertile and the most important layer for plant growth. Thus, sampling was performed up to a depth of 30 cm.

Each location covered an area of approximately 5500 m². Considering the expected spatial variability in the distribution of potentially toxic metals in soils affected by mining and metallurgy activities, a grid-based sampling design was applied. After evaluating the terrain configuration, a 25 × 25 m plot was delineated and subdivided into 25 equal squares (5 × 5 m). Soil samples were collected from holes opened within selected grid cells. Screw sampler with a two-stroke and four-stroke Honda engine, complete with an 80 mm diameter screw by Blue Bird Industries, Vicenza, Italy, was used for sampling.

Specifically, six squares were randomly selected, and one subsample was taken from each corresponding grid cell. The six subsamples collected were combined to form one composite soil sample at each location, which was thoroughly prepared prior to further chemical analysis.

Soil samples were air-dried at room temperature, homogenized by grinding, and passed through a 2 mm sieve prior to analysis. Microwave-assisted acid digestion was performed in accordance with EPA Method 3051A (acid digestion of sediments, sludges, and soils). A known dry weight of each soil sample was transferred into a digestion vessel, and a 1:1 solution of nitric acid (HNO₃) was added. The mixture was heated to 95 ± 5 °C and refluxed without boiling. After cooling, concentrated HNO₃ was added and the heating step was repeated. Subsequently, deionized water and 30% hydrogen peroxide (H₂O₂) were added to initiate the peroxide oxidation reaction. Following an additional heating and cooling cycle, the digests were diluted appropriately and prepared for elemental analysis. Multi-elemental determination was carried out using inductively coupled plasma mass spectrometry (ICP-MS) in accordance with EPA Method 6020B, which describes the determination of trace elements in environmental samples by ICP-MS. The average analytical uncertainty for all target elements was below 5%. Total metal concentrations were determined in triplicate for each digest, and the results are presented as mean values ± standard deviation (SD). All concentrations were calculated on a dry weight basis (mg/kg DW). Certified reference material (CRM) was Trace metals—Sewage Sludge 4, No. CRM055-50G, Lot. 015148 by Sigma Aldrich RTC, Inc., Laramie, WY, USA. Repeatability in duplicate.

After obtaining chemical analysis of the initial soil (this soil is used as the initial zero state), three different types of agricultural plants were selected and planted in laboratory conditions. The pots were placed in the laboratory at a constant temperature of 20 °C, an air relative humidity of 80%, a 12/12 light/dark cycle, and the soil humidity was kept at optimal values by daily watering. Plant growth was monitored for up to 6 months. Throughout the experiment, the plants were tended and watered to maintain an optimal level of soil humidity (approx. 70% of field capacity). After a planting period, the plants were uprooted. The samples were dried, ground, and analyzed. The content of polluting metals in the soil and in the plants was examined.

Three different types of plants were used for remediation, as follows: *barley Hordeum sativum*, *sugar grazer sorghum bicolor*, and *hybrid BMR 333 Sudan grass*.

The results are shown for metal content in soil samples in the initial zero state and in the soil after the use of the plants, following a period of 6 months of planting.

2.1. Contamination Factor (C_{fi})

For the assessment of soil pollution with element i , an individual index—contamination factor (C_{fi}) was used. According to [49], contamination factor C_{fi} represents the ratio of the concentration of element i at the examined location C_i and the reference natural concentration of the polluting and toxic metal in the soil without anthropogenic influence, the so-called background C_{ib} (background value), according to the formula:

$$C_{fi} = C_i/C_{ib} \quad (1)$$

2.2. Bioconcentration Factor (BCF)

The bioconcentration factors have been determined for the assessment of the level of remediation in three different plants. The bioconcentration factor, determined as the quotient of the content of a given heavy metal in the plant to its content in the soil, defines the ability of the plant to accumulate that metal. The plant's competency for metal uptake from soil was obtained by formula [50]:

$$BCF = C_{\text{plant}}/C_{\text{soil}} \quad (2)$$

where C_{plant} refers to metal concentration in the plant tissues, and C_{soil} represents the metal concentration in the soil (mg/kg).

3. Results

After planting, the growth and progress of the plants were monitored in laboratory conditions for the initial zero state and after six months.

Chemical analysis of the initial zero state of contaminated soil, before planting the plants, is given in Table 1. The determinations were completed by referring to certified material. Certified values and percent recovery for tested metals are also given in Table 1.

Table 1. Metal content in soil samples in the initial zero state, certified values, and percent recovery for tested metals in certified material.

Metal (mg/kg)	L1	L2	L3	Certified Value	Metal Tested	Percent Recovery
Cr	104.2 ± 4.3	35.4 ± 2.7	66.4 ± 3.1	289 ± 30.4	302.4	104.6
Ni	8.8 ± 0.41	9 ± 0.62	24.2 ± 1.1	163 ± 13.5	159.3	97.7
Cu	365 ± 4.8	336.4 ± 4.5	218.6 ± 4.3	482 ± 50.4	461.6	95.8
Zn	94.1 ± 3.4	96.5 ± 3.3	74.6 ± 2.6	1240 ± 181	1185	95.5
As	16.6 ± 1.0	47.5 ± 2.1	31.2 ± 1.5	229 ± 26.7	217.6	95.0
Cd	0.5 ± 0.02	0.64 ± 0.03	0.52 ± 0.02	60.6 ± 2.96	61.8	102
Pb	34.6 ± 1.6	40.1 ± 1.8	46.2 ± 2.1	154 ± 12.4	148.7	96.6

The results of the metal content in the *barley Hordeum sativum* plant, as well as in the soil after the use of the *barley* plant for a period of six months of planting, are shown in Table 2 and Table 3, respectively.

Table 2. Metal content in *barley Hordeum sativum* plant.

Metal (mg/kg)	L1	L2	L3
Cr	3.1	4.5	3.3
Ni	4.7	4.4	6.3
Cu	126.9	174.7	261.2
Zn	147	118.1	92.9
As	3.4	5.9	7.5
Cd	0.64	1.55	0.43
Pb	25	25.9	41.8

Table 3. Metal content in the soil after *barley Hordeum sativum* planting.

Metal (mg/kg)	L1	L2	L3
Cr	82.5	74.9	78.3
Ni	17.8	14.5	8.4
Cu	236.9	250.6	315.1
Zn	77	72	77.1
As	33.5	36	46.5
Cd	0.44	0.61	0.72
Pb	39.2	46.4	49.6

The results of the metal content in the *sugar grazer Sorghum bicolor* plant, as well as in the soil after the use of the *sugar grazer* plant for a period of six months of planting, are shown in Table 4 and Table 5, respectively.

Table 4. Metal content in *sugar grazer Sorghum bicolor* plant.

Metal (mg/kg)	L1	L2	L3
Cr	5.6	32.3	13.2
Ni	4.3	6.7	7.4
Cu	259.6	136	297.5
Zn	119.4	106	92.9
As	5.4	14.6	16
Cd	1.46	0.94	3.03
Pb	33.1	17.8	31.5

Table 5. Metal content in the soil after *sugar grazer Sorghum bicolor* planting.

Metal (mg/kg)	L1	L2	L3
Cr	110.8	101.1	112.5
Ni	9.6	14.7	13.2
Cu	267.3	267.9	256
Zn	70	76.7	70.3
As	23.6	22.3	36.6
Cd	0.44	0.5	0.44
Pb	36.2	41.9	39.3

The results of the metal content in the *hybrid BMR 333 Sudan grass* plant, as well as in the soil after the use of the *hybrid BMR 333* plant for a period of six months of planting, are shown in Table 6 and Table 7, respectively.

Table 6. Metal content in *hybrid BMR 333 Sudan grass* plants.

Metal (mg/kg)	L1	L2	L3
Cr	2.8	4.3	4.1
Ni	8.8	5.4	3.7
Cu	134	82.8	149.9
Zn	64	160.7	80.9
As	3.4	2.8	4.2
Cd	0.94	1.6	1.37
Pb	20.7	11.5	19.5

Table 7. Metal content in the soil after *hybrid BMR 333 Sudan grass* planting.

Metal (mg/kg)	L1	L2	L3
Cr	95.1	43	98
Ni	7.9	10.3	24.2

Cu	358.4	299.9	217.7
Zn	144.7	81.1	80.2
As	15.2	43.9	31.4
Cd	0.44	0.65	0.52
Pb	30.2	45.9	43.9

The comparative analysis of the metal content at the three different locations in the initial zero state of soil under the influence of mining and metallurgy activities and the soil after planting the plants is shown in Figures 1–3, respectively.

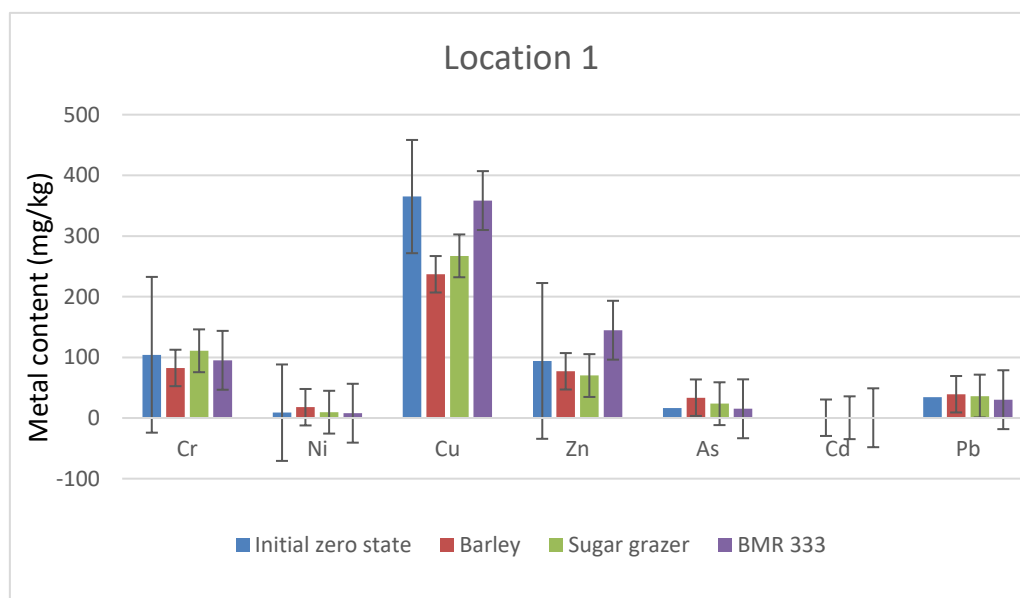


Figure 1. Comparative analysis of metal content at Location 1.

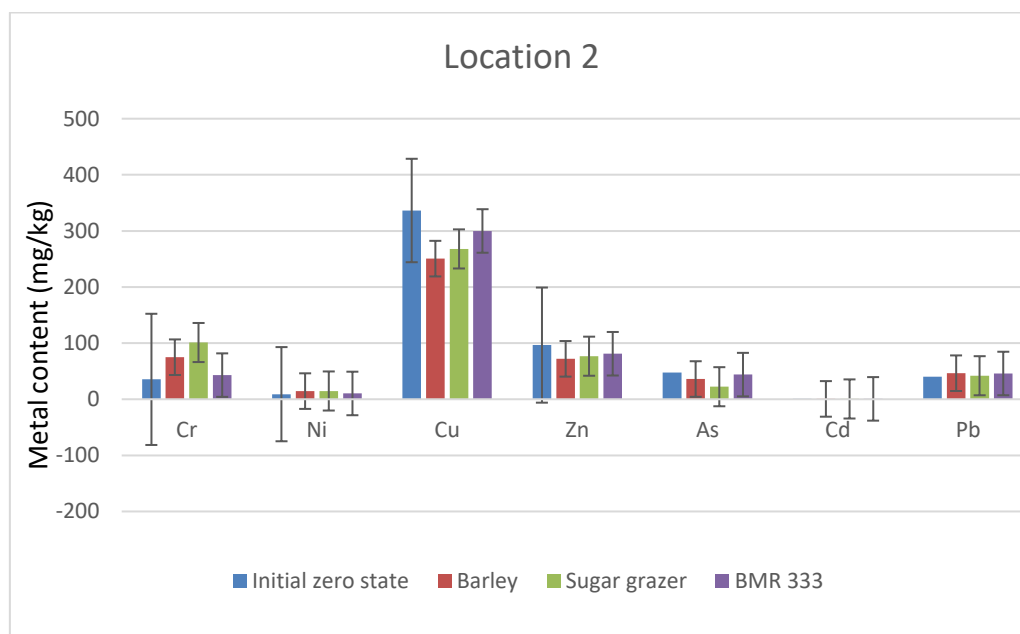


Figure 2. Comparative analysis of metal content at Location 2.

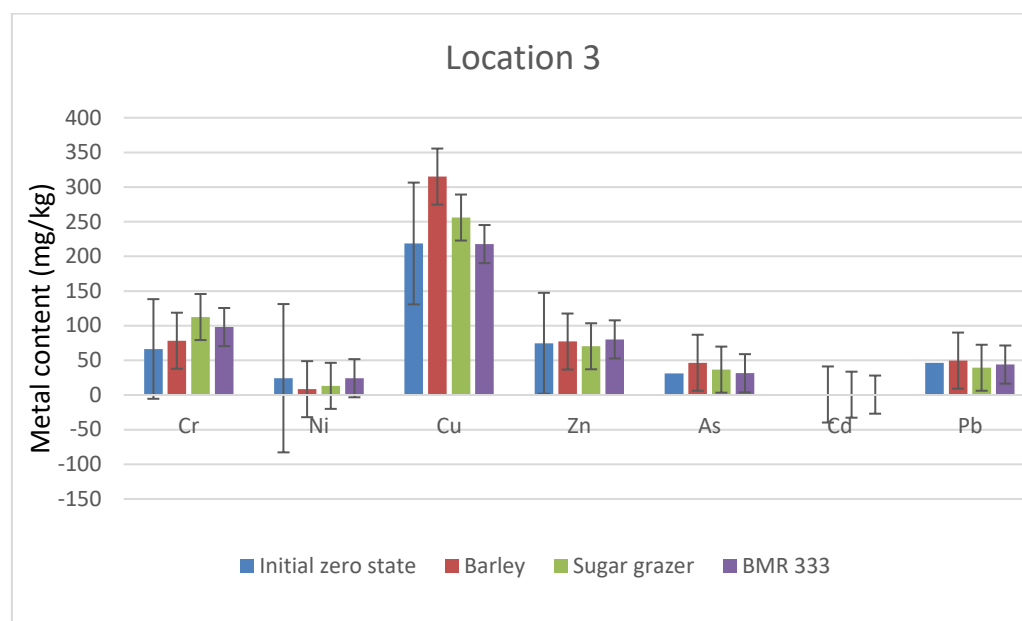


Figure 3. Comparative analysis of metal content at Location 3.

Given that statistical analyses cannot be performed due to insufficient replication, the presented results indicate a trend rather than definitive findings and should be interpreted accordingly.

4. Discussion

The content of metals in the initial zero state of contaminated soil (before planting the plants), the limit values (LVs), and remediation values (RVs) proposed by the Serbian Regulations on the limit values of polluting, harmful and dangerous substances in land [51], such as background values (BVs) for these elements (BVs), are given in Table 8. The background values are taken from the literature for soils in Serbia [52].

Table 8. Content of metals in the initial zero state of contaminated soil with limit values (LVs), remediation values (RVs) and background values for these elements (BVs).

Metal (mg/kg)	L1	L2	L3	LV	RV	BV
Cr	104.2	35.4	66.4	100	380	72.28
Ni	8.8	9	24.2	35	210	84.72
Cu	365	336.4	218.6	36	190	38.37
Zn	94.1	96.5	74.6	140	720	79.43
As	16.6	47.5	31.2	29	55	14.69
Cd	0.5	0.64	0.52	0.8	12	-
Pb	34.6	40.1	46.2	85	530	69.34

Based on these results, it can be noticed that the soils are dominantly contaminated with copper and arsenic. Previous research [15] also confirmed that copper and arsenic are two of the common problem elements in contaminated soils. Thus, we will discuss here about copper and arsenic.

Although copper is an essential element for plants, with a role in photosynthesis, respiration, nitrogen and carbon metabolism, high copper concentrations lead to the reduced growth of plants. Copper occurs in the soil most often in sulfide compounds. Its mobility is extremely low. It is highly absorbed in the organic matter. Plants absorb it as Cu^{2+} in small quantities. As its concentration in the soil increases, the intensity of its absorption increases sharply. Copper is very toxic to plants if its concentration in the soil is

25–40 ppm and if the pH of the soil is below 5.5 [17,18]. It accumulates primarily in the roots of plants. Copper toxicity is rarely reported in humans. In animals that consume large quantities of copper, it accumulates in the tissues, primarily in the liver, and leads to impaired function [18]. The tolerance copper values are up to 190 ppm [51]. The concentrations of copper in all three initial locations increased. The high copper content in all locations is not surprising, since the geochemical source of copper dominates, i.e., this area consists of pyrite copper deposits [48].

The most common quantity of arsenic content in the soil ranges from 2 to 20 ppm. The permitted level in Serbia is 29 ppm and 20 ppm in Western Europe [17,18]. Arsenic content in the plants is usually much lower than in the soil.

Determining the background values of soil quality is a necessary measure when assessing soil pollution, given that the geological substrate already contains a certain amount of the investigated element. Values $Cfi < 1$ represent a low contamination factor, values $1 \leq Cfi < 3$ moderate, and values $3 \leq Cfi < 6$ significant, while values $Cfi \geq 6$ represent a high contamination factor [53]. The values of contamination factors of individual polluting and toxic metals for copper and arsenic are given in Table 9. The values of the contamination factors for copper are greater than 6, indicating significant contamination with this metal, while the obtained values of the contamination factor for arsenic confirmed that the contamination with this metal is mainly moderate. The results also confirmed that planting leads to a reduction of the contamination factor in comparison to the initial soils (zero state), especially in the case of copper.

Table 9. Contamination factors (Cfi) for copper and arsenic for the initial soils and soils after planting.

Location	Type of Plant	Cfi	
		Cu	As
1	Zero state	9.51	1.13
	Barley Hordeum sativum	6.17	2.28
	Sugar grazer Sorghum bicolor	6.96	1.61
	Hybrid BMR 333 Sudan grass	9.34	1.03
2	Zero state	8.76	3.23
	Barley Hordeum sativum	6.53	2.45
	Sugar grazer Sorghum bicolor	6.98	1.52
	Hybrid BMR 333 Sudan grass	7.82	2.98
3	Zero state	5.69	2.12
	Barley Hordeum sativum	8.21	3.16
	Sugar grazer Sorghum bicolor	6.67	2.49
	Hybrid BMR 333 Sudan grass	5.67	2.14

The results of the bioconcentration factor (BCF) for copper and arsenic for selected plants are given in Table 10.

Table 10. Bioconcentration factor (BCF) for copper and arsenic for selected plants.

Location	Type of Plant	BCF	
		Cu	As
1	Barley Hordeum sativum	0.54	0.10
	Sugar grazer Sorghum bicolor	0.97	0.23
	Hybrid BMR 333 Sudan grass	0.37	0.22
2	Barley Hordeum sativum	0.70	0.16
	Sugar grazer Sorghum bicolor	0.51	0.65
	Hybrid BMR 333 Sudan grass	0.28	0.06
3	Barley Hordeum sativum	0.83	0.16

Sugar grazer <i>Sorghum bicolor</i>	1.16	0.44
Hybrid BMR 333 Sudan grass	0.69	0.13

Generally, the greater the BCF, the stronger the accumulation of the heavy metals in the plant, and a BCF of more than 1 indicates the ability of the species to remediate. A BCF above 1 for some of these species suggests that they could be potential species for remediation. These plants were capable of growing and accumulating copper after growing in copper mines and metallurgy sites. Thus, remediation with these species with moderate copper-accumulation potential represents a suitable remediation strategy. Given that *sugar grazer Sorghum bicolor* have a BCF factor close to or above 1 which means that this species could accumulate copper, especially at locations 1 and 3. *Sugar grazer* was found to have the greatest bioconcentration factor among the three species, followed by *barley* (Table 10).

Analyzing the papers dealing with this problem, it can be concluded that the BCF factor has different values. Li and Yang [54] used *Prunus persica* in a manganese mine land and found a BCF value for copper of 0.16, while Antonijević et al. [35] pointed out that some plant species such as *Prunus persica* can be considered as potential hyperaccumulators with a BCF value of 1.20 for copper. This value agrees with the BCF value (1.16) found in this study for *sugar grazer Sorghum bicolor* (Location 3). Khan et al. [55] revealed that *D. sanguinalis* has the highest BCF (54%), and *C. dactylon* has the lowest BCF for copper (36,9%). Gautam and Agrawal [56] conducted a study on identifying metal-tolerant plants for phyto management of red mud and found that the BCF results of copper (7.5%) for *C. dactylon* were much less than the present results. Similarly, in a study by Campillo-Cora et al., the BCF of copper (14%) was reported [57].

According to [14], hyperaccumulation of copper is a very rare phenomenon in the plant world. So, due to the relatively low metal content in copper hyperaccumulators, laboratory tests have not been carried out to a greater extent.

Copper-tolerant plants are essentially excluders. Most copper-tolerant plants respond eco-physiologically as excluders with very limited copper translocation from the roots to the shoots [58]. Generally, most copper-tolerant plants behave as excluders, and the tolerance level appears to be controlled by several modifiers [5].

Further, phytoextraction of copper can be enhanced using high-biomass and fast-growing plants, an alternative to hyperaccumulating plants [58]. Phytoextraction can be more efficient when the entire plant is harvested. Abnormally high plant tissue copper concentrations occur only when plants are exposed to high soil copper with a low root-to-shoot translocation factor.

Also, for arsenic, the best results were obtained using *sugar grazer Sorghum bicolor*, considering BCF. Since the three investigated species did not accumulate sufficient concentrations of arsenic in their harvestable aboveground tissues, they cannot be classified as hyperaccumulators.

Similarly to copper, the bioconcentration factor (BCF) for arsenic reported in the literature varies considerably. As stated in [35], BCF values for arsenic ranged from 0.05 in *Saponaria officinalis* to 0.54 in *Prunus persica*.

In general, BCF values are strongly influenced by soil characteristics, metal concentrations and speciation, as well as by plant species used in the phytoremediation process. Variability in these factors can lead to substantial differences in metal uptake efficiency and accumulation patterns among species.

Although the BCF value is a very important indicator of phytoextraction potential, other factors such as translocation factor, root accumulation, biomass growth and total metal removal are important too.

Also, *sugar grazer Sorghum bicolor* is well known as an energetic plant, which could be used in biomass energy production. Renewable biofuels are imperative to meet long-term

energy needs [59]. *Sorghum bicolor* is globally recognized as an energy source because it creates more energy with fewer inputs. Energy *sorghum* is among the most economical and climate-smart agricultural crops because it can grow with less input on poor lands in challenging climates. Aside from being utilized for food and energy, *sorghum*'s lignocellulose biomass is also employed in the production of biomaterials like bioplastics and biocomposites [12]. Certainly, prior to their use, several important parameters should be considered, including the composition of the resulting combustion products and ash, as well as the economic viability of the energy generated. This will be used in further research.

The tolerance of three selected agricultural plant species to metals was tested in this research. This means the possibility of metal accumulation in the roots of the plants and further in the leaves. Most plant species that are tolerant of metals in concentrations that are toxic to other species act as excluders. Depending on the accumulated concentration of metal in the roots of plants and leaves, the ability to accumulate or the tolerance of the tested plant species to the accumulation of a certain metal is determined, and in this regard, this plant can be used for phytoremediation.

There are naturally distributed plants that actively absorb one or more metals from the soil in significant quantities and translocate them to aboveground organs, whereby accumulation occurs in foliar parts without the appearance of symptoms of phytotoxicity. This can be seen through toxic metal concentration tests in this research. All three agricultural plants used in this study showed the ability of phytoremediation. All plants have managed to accumulate polluting metals from the soil.

Thus, the results showed that these plants have potential for copper accumulation and, to some extent, arsenic, as well as for the revegetation of soil contaminated with these metals.

5. Conclusions

This study analyzed the content of polluting metals in soil surrounding the mining and metallurgical complex. Soil pollution at three different locations was assessed based on the measured concentration of these metals and the contamination factor (Cf). Three species: *barley Hordeum sativum*, *sugar grazer Sorghum bicolor*, and *hybrid BMR 333 Sudan grass* were used for growing in the copper mine and metallurgy areas. These species showed potential abilities for remediation on contaminated soil.

Phytoremediation is recognized as an eco-friendly technology because it does not produce secondary pollutants. Besides that, phytoremediation provides an environmentally sustainable option for restoring natural ecosystems, offering long-term ecological benefits beyond pollutant removal.

Another potential application of the three species is for the revegetation of copper mine and metallurgy areas, which is a real challenge. The three species of pseudo-metallophytes that were observed to grow and reproduce in such areas are good ground cover for the build-up of organic matter. The biomass of the aerial parts of these plants can also provide biofuel resources for biomass energy production, i.e., obtaining thermal and/or electrical energy.

Phytoremediation provides a sustainable and cost-effective approach for addressing soil contamination, particularly in environments affected by heavy metals. Thus, phytoremediation could be a viable option to decontaminate heavy metal-polluted sites, particularly when the biomass produced during the process could be economically utilized in the form of bioenergy. Efforts should be made to find species that produce greater biomass, as well as to find technologies for their cultivation, which will be further considered through further research.

Healthy soils are crucial to reaching climate neutrality goals and contribute to stopping desertification and land degradation, while preserving biodiversity and human health at the same time. Thus, the problem of land pollution, which is gaining importance and standing side by side with the problems resulting from air, water, and soil pollution,

it is necessary to establish the systematic monitoring of land quality, primarily in areas degraded by the expansion of the mining and metallurgy industries, considering large mining complexes such as the mining and metallurgical complex Bor.

Selected and used agricultural plants give a good base for furthering their application and represent a key instrument for the reduction of toxic metal content in contaminated mining and metallurgy land and for making decisions and plans related to sustainable land and soil, which will be used in environmental conditions.

Data obtained through this research represent a basis for further investigations in this area and lead to phytoremediation and remediation of contaminated mining and metallurgy soil pollution, not only in the territory of the city of Bor and Timok region but also in the entire Danube region, and could be useful for all European and non-European countries with this problem. Such research is important because it not only improves the environment but also contributes to sustainable development.

6. Future Investigation

Given that the study was conducted under controlled laboratory conditions over a six-month period, it provides valuable preliminary information but does not necessarily reflect field performance.

Therefore, future research should include:

- Validation under field conditions over longer periods of time;
- Monitoring plant growth monthly, rather than only at the beginning and after six months, to enable assessment of uptake kinetics;
- Identification of active biomass growth phases;
- Long-term monitoring over multiple growing seasons;
- Repeated planting and harvesting cycles;
- Assessment of total metal removal per unit area, rather than concentration alone;
- Evaluation under different climatic and soil conditions;
- Assessment of metal accumulation and translocation from roots to shoots;
- Evaluation of the economic feasibility of using these plants for large-scale phytoremediation;
- Evaluation of the economic feasibility of bioenergy production, taking into account the generation of new waste streams.

Future efforts also should focus on enhancing plant resilience through genetic engineering and optimizing pollutant metal uptake for enhancing pollutant metal removal and accelerating soil restoration.

Author Contributions: A.K., conceptualization; A.K., H.W. and N.S., methodology; A.K. and V.N., validation; I.J., investigation; A.K., I.J. and V.N., data curation; I.J., writing—original draft preparation; A.K., H.W., V.N. and N.S. writing—review and editing; A.K., I.J. and V.N., visualization; A.K., H.W. and N.S., supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Teng, Y.; Liu, L.; Zheng, N.; Liu, H.; Wu, L.; Yue, W. Application of Different Indices for Soil Heavy Metal Pollution Risk Assessment Comparison and Uncertainty: A Case Study of a Copper Mine Tailing Site. *Minerals* **2022**, *12*, 1074.
2. Paunkovic, M. Analysis of the State of the Environment from Damage Caused by Previous Work RTB-Bor. Master's Thesis, University of Niš, Faculty of Science, Department of Geography, Niš, Serbia, 2017. (In Serbian)
3. Kikis, C.; Thalassinos, G.; Antoniadis, V. Soil Phytomining: Recent Developments—A Review. *Soil Syst.* **2024**, *8*, 8.
4. Baker, A.J.M.; Ernst, W.H.O.; van der Ent, A.; Malaisse, F.; Ginocchio, R. Metallophytes: The Unique Biological Resource, Its Ecology and Conservational Status in Europe, central Africa and Latin America. In *Ecology of Industrial Pollution*; Batty, L.C., Halberg, K.B., Eds.; Cambridge University Press: Cambridge, UK, 2010; pp. 7–40.
5. Lange, B.; van der Ent, A.; Baker, A.J.M.; Echevarria, G.; Mahy, G.; Malaisse, F.; Meerts, P.; Pourret, O.; Verbruggen, N.; Faucon, M.P. Copper and cobalt accumulation in plants: A critical assessment of the current state of knowledge. *New Phytol.* **2017**, *213*, 537–551.
6. Brooks, R.R.; Reeves, R.D.; Morrison, R.S.; Malaisse, F. Hyperaccumulation of copper and cobalt: A review. *Bull. Soc. R. Bot. Belg.* **1980**, *113*, 166–172.
7. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of Heavy Metals—Concepts and Applications. *Chemosphere* **2013**, *91*, 869–881.
8. Alengebawy, A.; Abdelkhalek, S.T.; Qureshi, S.R.; Wang, M.Q. Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics* **2021**, *9*, 42.
9. Shah, V.; Daverey, A. Phytoremediation: A Multidisciplinary Approach to Clean Up Heavy Metal Contaminated Soil. *Environ. Technol. Innov.* **2020**, *18*, 100774.
10. Nedjimi, B. Phytoremediation: A Sustainable Environmental Technology for Heavy Metals Decontamination. *SN Appl. Sci.* **2021**, *3*, 286.
11. Baker, A.J.M. Accumulators and Excluders Strategies in Response of Plants to Heavy Metals. *J. Plant Nutr.* **1981**, *3*, 643–654.
12. Ameen, M.; Mahmood, A.; Shahzad, A.N.; Zia, M.A.; Javaid, M.M. Sorghum's potential unleashed: A comprehensive exploration of bio-energy production strategies and innovations. *Bioresour. Technol. Rep.* **2024**, *27*, 101906.
13. Jakovljević, K.; Tomović, G.; Baker, A.J.; Đurović, S.; Mihailović, N.; Lazarević, P.; Lazarević, M. Strategies of Accumulation of Potentially Toxic Elements in *Minuartia recurva* and *M. bulgarica*. *Environ. Sci. Pollut. Res.* **2022**, *29*, 43421–43434.
14. Jovanović, G.; Randelović, D.D.; Marković, B.R.; Sokić, M.D. Review of Extraction Technologies and Application Possibilities for Metals from Balkan Hyperaccumulators. *Teh. — Rud. Geol. i Metal.* **2022**, *73*, 5.
15. Nikolić, V.; Staletović, N.; Presburger-Ulniković, V.; Jovanović, I. Soil Pollution and Risk Assessment in Bor Using Different Indices. *Bakar* **2025**, *50*, 33–44.
16. Wang, C.; Xu, D.; Li, Y.; Zhou, W.; Bian, P.; Zhang, S. Source and Migration Pathways of Heavy Metals in Soils from an Iron Mine in Baotou City, China. *Minerals* **2024**, *14*, 506.
17. Technical Faculty in Bor, University of Belgrade. *Local Environmental Action Plan (LEAP) of Bor Municipality for 2013–2022*; Municipality of Bor: Bor, Serbia, 2013 (In Serbian)
18. Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020, “Living Well, Within the Limits of Our Planet”. Available online: <http://data.europa.eu/eli/dec/2013/1386/oj> (accessed on 1 March 2024).
19. Kramer, U. Metal Hyperaccumulation in Plants. *Annu. Rev. Plant Biol.* **2010**, *61*, 517–534.
20. Chipeng, K.; Hermans, C.; Colinet, G.; Faucon, M. Copper Tolerance in *Haumaniastrum katangense*. *Plant Soil* **2009**, *328*, 235–244.
21. Faucon, M.P.; Chipeng, F.; Verbruggen, N.; Mahy, G.; Colinet, G.; Shutcha, M.; Pourret, O.; Meerts, P. Copper Tolerance and Accumulation in Two Cuprophytes of South Central Africa. *Environ. Exp. Bot.* **2012**, *84*, 11–16.
22. Clavé, G.; Garel, C.; Poullain, C.; Renard, B.L.; Olszewski, T.K.; Lange, B.; Shutcha, M.; Faucon, M.P.; Grison, C. Ullmann reaction through ecocatalysis: Insights from bioresource and synthetic potential. *RSC Adv.* **2016**, *6*, 59550–59564.
23. De La Torre, J.B.B.; Claveria, R.J.R.; Perez, R.E.C.; Perez, T.R.; Doronila, A.I. Copper Uptake by *Pteris melanocaulon* from a Copper-Gold Mine. *Int. J. Phytoremediat.* **2015**, *18*, 435–441.
24. Shu, W.S.; Ye, Z.H.; Lan, C.Y.; Zhang, Z.Q.; Wong, M.H. Lead, Zinc and Copper Accumulation and Tolerance in *Paspalum distichum* and *Cynodon dactylon*. *Environ. Pollut.* **2002**, *120*, 445–453.
25. Wang, J.; Zhao, F.J.; Meharg, A.A.; Raab, A.; Feldmann, J.; McGrath, S.P. Mechanisms of Arsenic Hyperaccumulation in *Pteris vittata*. Uptake Kinetics, Interactions with Phosphate, and Arsenic Speciation. *Plant Physiol.* **2002**, *130*, 1552–1561.
26. Gonzaga, M.I.S.; Santos, J.A.G.; Ma, L.Q. Arsenic Chemistry in the Rhizosphere of *Pteris vittata* and *Nephrolepis exaltata* L. *Environ. Pollut.* **2006**, *143*, 254–260.

27. da Silva, E.B.; de Oliveira, L.M.; Wilkie, A.C.; Liu, Y.; Ma, L.Q. Arsenic removal from As-hyperaccumulator *Pteris vittata* biomass: Coupling extraction with precipitation. *Chemosphere* **2018**, *193*, 288–294.
28. Yan, X.L.; Chen, T.B.; Liao, X.Y.; Huangh, Z.C.; Pan, J.R.; Hu, T.D.; Nie, C.J.; Xie, H. Arsenic transformation and volatilization during incineration of the hyperaccumulator *Pteris vittata* L. *Environ. Sci. Technol.* **2008**, *42*, 1479–1484.
29. Ma, L.Q.; Komar, K.M.; Tu, C. A Fern That Hyperaccumulates Arsenic. *Nature* **2001**, *409*, 579.
30. Francesconi, K.; Visoottiviseth, P.; Sridokchan, W.; Goessler, W. Arsenic species in an arsenic hyperaccumulating fern, *Pityrogramma calomelanos*: A potential phytoremediator of arsenic-contaminated soils. *Sci. Total Environ.* **2002**, *284*, 27–35.
31. Niazi, N.; Singh, B.; Zwieten, L.; Kachenko, A. Phytoremediation of an Arsenic-Contaminated Site Using *Pteris vittata* and *Pityrogramma calomelanos* var. *austroamericana*. *Environ. Sci. Pollut. Res.* **2012**, *19*, 3506–3515.
32. Bačeva, K.; Stafilov, T.; Matevski, V. Bioaccumulation of Heavy Metals by Endemic *Viola* Species. *Int. J. Phytoremediat.* **2014**, *16*, 347–365.
33. Maric, M.; Mladenovic, D.; Milutinovic, S.; Petrovic, R. Content of arsenic, copper, lead and zinc in the soils of Bor region. In *Proceedings “Ecological Truth”, Sokobanja, Serbia, 4–7 June 2000*; Technical Faculty Bor, University of Belgrade: Belgrade, Serbia, 2000; pp. 186–191.
34. Milutinovic, S.; Maric, M.; Mladenovic, D. Influence of the RTB mining complex on the content of nutrients and heavy metals in soil and plant material. In *Proceedings “Ecological Truth”, XIV Expert Meeting of Preventive Medicine in Timok Region, Donji Milanovac, 3–6 June 2001*; Technical Faculty Bor, University of Belgrade: Belgrade, Serbia, 2001.
35. Antonijevic, M.M.; Dimitrijevic, M.D.; Milic, S.M.; Nujkic, M.M. Metal concentrations in the soils and native plants surrounding the old flotation tailings pond of the Copper mining and smelting complex Bor (Serbia). *J. Environ. Monit.* **2012**, *14*, 866–877.
36. Cho-Ruk, K.; Kurukote, J.; Supprung, P.; Vetayasuporn, S. Perennial plants in the phytoremediation of lead-contaminated soils. *Biotechnology* **2006**, *5*, 1–4.
37. Baudha, K.; Singha, K.; Singha, B.; Singha, R.P. *Ricinus communis*: A robust plant for bio-energy and phytoremediation of toxic metals from contaminated soil. *Ecol. Eng.* **2015**, *84*, 640–652.
38. Cheng, S.F.; Huang, C.Y.; Lin, Y.C.; Lin, S.C.; Chen, K.L. Phytoremediation of lead using corn in contaminated agricultural land—An in-situ study and benefit assessment. *Ecotoxicol. Environ. Saf.* **2015**, *111*, 72–77.
39. 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. *Ecotoxicol. Environ. Saf.* **2016**, *126*, 111–121.
40. Steliga, T.; Kluk, D. Application of *Festuca arundinacea* in phytoremediation of soils contaminated with Pb, Ni, Cd and petroleum hydrocarbons. *Ecotoxicol. Environ. Saf.* **2020**, *194*, 110409.
41. Salehi, N.; Azhdarpoor, A.; Shirdarreh, M. The effect of different levels of leachate on phytoremediation of pyrene-contaminated soil and simultaneous extraction of lead and cadmium. *Chemosphere* **2020**, *246*, 125845.
42. Wu, L.H.; Luo, Y.M.; Xing, X.R.; Christie, P. EDTA-enhanced phytoremediation of heavy metal contaminated soil with Indian mustard and associated potential leaching risk. *Agric. Ecosyst. Environ.* **2004**, *102*, 307–318.
43. Steingraber, L.F.; Knolle, F.; Kierdorf, H.; Ludolph, C.; Kierdorf, U. Toxic Legacy—Environmental Impacts of Historic Metal Mining and Metallurgy in the Harz Region (Germany) at Local, Regional and Supra-Regional Levels. *Environments* **2025**, *12*, 215. <https://doi.org/10.3390/environments12070215>.
44. Zhakypbek, Y.; Kossalbayev, B.D.; Belkozhaev, A.M.; Murat, T.; Tursbekov, S.; Abdalimov, E.; Pashkovskiy, P.; Kreslavski, V.; Kuznetsov, V.; Allakhverdiev, S.I. Reducing Heavy Metal Contamination in Soil and Water Using Phytoremediation. *Plants* **2024**, *13*, 1534. <https://doi.org/10.3390/plants13111534>.
45. Radu, V.M.; Vijdea, A.M.; Ivanov, A.A.; Alexe, V.E.; Dincă, G.; Filiuță, A.E. Research on the Closure and Remediation Processes of Mining Areas in Romania and Approaches to the Strategy for Heavy Metal Pollution Remediation. *Sustainability* **2023**, *15*, 15293. <https://doi.org/10.3390/su152115293>.
46. Zheng, X.; Lin, H.; Du, D.; Li, G.; Alam, O.; Cheng, Z.; Liu, X.; Jiang, S.; Li, J. Remediation of heavy metals polluted soil environment: A critical review on biological approaches. *Ecotoxicol. Environ. Saf.* **2024**, *284*, 116883. <https://doi.org/10.1016/j.ecoenv.2024.116883>.
47. Rouhani, A.; Skousen, J.; Tack, F.M.G. An Overview of Soil Pollution and Remediation Strategies in Coal Mining Regions. *Minerals* **2023**, *13*, 1064. <https://doi.org/10.3390/min13081064>.
48. Dimitrijević, M.; Kostov, A.; Tasić, V.; Milošević, N. Influence of Pyrometallurgical Copper Production on the Environment. *J. Hazard. Mater.* **2009**, *164*, 892–899.
49. Hakanson, L. Ecological Risk Index for Aquatic Pollution Control. *Water Res.* **1980**, *14*, 975–1001.

50. Pachura, P.; Ociepa-Kubicka, A.; Skowron-Grabowska, B. Assessment of Heavy Metal Availability to Plants. *Desalin. Water Treat.* **2015**, *57*, 1469–1477.
51. Official Gazette of RS, 30/18 and 64/19. Regulation on Limit Values of Polluting, Harmful and Dangerous Substances in the Soil. Available online: <https://leap.unep.org/en/countries/rs/national-legislation/regulation-limit-values-polluting-harmful-and-dangerous> (accessed on 1 March 2020).
52. Mrvić, V.; Sikirić, B.; Jaramaz, D.; Koković, N.; Nikoloski, M. Soil Characteristics Study. *Ratar. Povrt.* **2019**, *56*, 1–6.
53. Lam, E.J.; Urrutia, J.; Bech, J.; Herrera, C.; Montofré, I.L.; Zetola, V.; Álvarez, F.A.; Cánovas, M. Environmental Geochemistry Study. *Environ. Geochem. Health* **2023**, *45*, 409–426.
54. Li, M.S.; Yang, S.X. Heavy metal contamination in soils and phytoaccumulation in a manganese mine wasteland, South China. *Air Soil Water Res.* **2008**, *1*, 31–41.
55. Khan, S.; Dilawar, S.; Hassan, S.; Ullah, A.; Yasmin, H.; Ayaz, T.; Akhtar, F.; Gaafar, A.-R.Z.; Sekar, S.; Butt, S. Phytoremediation of Cu and Mn from Industrially Polluted Soil: An Eco-Friendly and Sustainable Approach. *Water* **2023**, *15*, 3439.
56. Gautam, M.; Agrawal, M. Identification of metal tolerant plant species for sustainable phytomanagement of abandoned red mud dumps. *Appl. Geochem.* **2019**, *104*, 83–92.
57. Campillo-Cora, C.; Fernández-Calviño, D.; Pérez-Rodríguez, P.; Fernández-Sanjurjo, M.; Núñez-Delgado, A.; Álvarez-Rodríguez, E.; Arias-Estévez, M.; Nóvoa-Muñoz, J. Copper and zinc in rhizospheric soil of wild plants growing in long-term acid vineyard soils. Insights on availability and metal remediation. *Sci. Total. Environ.* **2019**, *672*, 389–399.
58. Ancheta, M.H.; Quimado, M.O.; Tiburan, C.L., Jr.; Doronila, A.; Fernando, E.S. Copper and arsenic accumulation of *Pityrogramma calomelanos*, *Nephrolepis biserrata*, and *Cynodon dactylon* in Cu- and As mine tailings. *J. Degrad. Min. Lands Manag.* **2020**, *7*, 2201–2208.
59. Dar, R.A.; Dar, E.A.; Kaur, A.; Phutela, U.G. Sweet Sorghum—A promising alternative feedstock for biofuel Production. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4070–4090.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.