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Element Cycling at Thermally Active Coal-Waste Dumps: A Case Study of *Calamagrostis epigejos* and *Solidago canadensis*

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Abstract: Coal-waste dumps in the Upper Silesian Coal Basin are usually colonized by tall grass *Calamagrostis epigejos* and *Solidago canadensis*, which influence the direction of vegetation formation and the soil chemistry. The aim of this study is to analyze and determine the content of major elements (Fe, Ca, P, Mg, Al, Na, K, S) and trace elements (Mo, Cu, Pb, Zn, Ni, Co, Mn, Sr, Cd, Cr) in aboveground and underground parts of the plants and the soil at the thermally active coal-waste dump. Analysis of the heavy metal concentrations reveals that they are higher in plant materials than in soil materials within the root zone of the plants. Environmental indicator analysis (geoaccumulation index, enrichment factor, translocation factor) shows that the studied species exhibit varying degrees of pollution, with cadmium and zinc showing the highest accumulation rates. The content of elements in the analyzed species, both in washed and unwashed specimens, does not show significant differences, which is confirmed by the enrichment factor. Statistical analysis shows a positive correlation between the amount of microelements in plants (roots, aerial part) and soil samples in both thermally active and inactive zones. These findings broaden the scientific inquiry and hold practical significance for the reclamation of post-industrial areas.

Keywords: land degradation; heavy metals; elemental composition; metal translocation; burning heap; wood small-reed; Canadian goldenrod

1. Introduction

The toxicity and real impact on the environment of coal-waste dumps constantly bring to light many contradictions [1–7]. Theoretically, such facilities—properly prepared and protected—should be neutral to the surroundings [8,9], which in Poland is regulated by legal provisions, including the Environmental Protection Law (Act of 27 April 2001). The law outlines the general principles of waste management, pollution prevention, and remediation. This Act is detailed in the Waste Act (Act of 14 December 2012), the Geological and Mining Law (Act of 9 June 2011) and the National Waste Management Plan. All these national regulations, adapted to EU directives, ensure that the currently created coal-waste dumps are properly designed, secured and monitored. An important difference between today's coal mining and the historical approach—from which most of the Silesian dumps come—is the sorting technologies. The solutions currently used allow for a significant reduction in the production of waste material, and the waste already produced goes directly to recovery (use in engineering construction, use in mining as backfill or sealing material) [10–13]. Disposal by landfill has become a last resort, not the first choice it once was. Environmental problems are most often caused by facilities built in the previous century, at a time when less attention was paid to environmental issues. Numerous studies from around the world have shown the negative impact of mining waste on the environment through the distribution of microelements in soil and groundwater [14,15].

Unfortunately, many coal-waste dumps still do not meet these standards and pose a threat to the environment. There are cases where extreme phenomena such as self-heating and uncontrolled smoldering underground fires occur in many older, long-existing

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coal-waste dumps [16]. These processes can completely change the bio- and geochemical situation in these objects and their vicinity [17–19]. High temperatures intensify, among others, element mobility, gas emissions, and dust [20–22]. Regardless of the thermal situation, plant succession also takes place in the burning coal-waste dumps. The fire generates the formation of specific plant zones (including the so-called death zone), vegetation streaks, and gigantism of plants [23,24]. The vegetation can even be an indicator of thermal phenomena in coal-waste dumps [24,25]. The species composition of the communities on the surface of the dumps oscillates around species native to the local flora; they are often invasive and ruderal and are mostly perennials and annuals.

An interesting issue is the connection of individual elements of the environment in the burning coal-waste dumps. Interactions between individual components of ecosystems have been studied for a long time. First of all, the interrelationships between vegetation and soil in natural conditions are sought [26–28]. The physicochemical properties of soil influence the viability of plant species, so the reflection of the chemical composition of plants is also the result of the chemistry of the soil material. Based on the chemical composition of plants, it is possible to at least indirectly predict the content of selected elements in the soil, which has been proven several times with the example of hyperaccumulators [29–31]. The chemical and physical properties of the soil (including the soil texture, structure, water retention and movement, soil pH, and total metal content) and the plant species and root structure are important factors influencing soil mineral uptake. Abiotic parameters of substrates in coal-waste dumps have a greater impact on soil enzymatic activity than species diversity and biomass associated with plants in the early phase of succession [32]. The relationship between abiotic factors and biomass levels provides the basis for planning the use of coal-waste dumps, taking into account the composition of the soil substrate, nutrient content and moisture level [7,10,12,13]. An important factor also seems to be the soil temperature, which influences root growth, water availability, and microbial activity, thereby affecting both nutrient cycling and soil respiration [33]. Previous research has shown that it can also affect the ability of plants to accumulate heavy elements [34–36]. The possibility of accumulation of toxic compounds and their transfer, e.g., as a result of biomass production, may intensify the contamination of subsequent areas and elements of the environment [37]. The impact of self-heating and underground fires on these interactions is poorly understood [38], and studies of the relationship between the chemical composition in the plant–soil system and newly formed ecological systems, often referred to as novel ecosystems, have not been conducted so far.

The ability to tolerate high concentrations and accumulations of toxic compounds in individual parts of plants makes it possible to use them in phytoremediation processes, especially in the forms of phytostabilization and phytoextraction. It is a low-cost and sustainable remediation method used worldwide to eliminate toxic substances from individual elements of the environment—soil, water and air—using selected plant species [39,40], which use different phytomechanisms when phytoremediating pollutants [41]. Also, some species appearing in burning coal-wasted dumps in Poland can accumulate concentrations of selected elements, which has been confirmed in numerous studies [42–44]. In the Upper Silesian Coal Basin, such plants include, e.g., *Solidago canadensis*—Canadian goldenrod [45,46] and *Calamagrostis epigejos*—wood small-reed [47,48]—dominant species in many dumps [24]. They are characterized by high ecological plasticity, a wide range of habitat and nutritional adaptations and the production of many light and volatile seeds that facilitate dispersal in extreme ecosystems such as smoldering coal-waste dumps [49]. Both species are considered good metal phytostabilizers in contaminated soils, particularly in the case of Cd, Pb, Cr, and Hg.

The aim of this article is to assess the suitability of *Solidago canadensis* and *Calamagrostis epigejos* for cycling elements and indirect phytoremediation of burning coal-waste dumps. This study is divided into three main tasks: assessing the thermal conditions within the dumps; analyzing the properties of technogenic soil; and investigating the relationships between soil and plants, focusing on the transfer of elements from soil to both underground and aboveground parts of the plants.

2. Materials and Methods

2.1. Study Area

The object of the research was a coal-waste dump located in Ruda Śląska, Czarny Las district (Upper Silesian Coal Basin, Poland), which was built in the early 1990s on the site of a former clay pit [24,50]. The dump is located in an urbanized area, close to large communication routes, residential estates and a service center (coordinates: 50°16′50.6″ N 18°51′08.6″ E). Waste from a nearby coal mine was transported there by rail and stored to level the area, so currently, this area is not geomorphologically diverse and has a flat anthropogenic character sloping toward the southwest. Despite the reclamation and protection of the facility, in 1995, subsurface smoldering fire phenomena were observed there, which continue to this day. In 2020, the surfaces of the fire hotspots were covered with a protective layer to suppress the phenomenon and, above all, its nuisance side effects (dust and gas emissions).

The selected facility is one of several hundred dumps of this type in the Upper Silesian Coal Basin, one of Europe's largest coal basins—located on the border of Poland and the Czech Republic. Coal has been mined in this area for over 200 years, and throughout this time, the area has been struggling with coal-waste problems. This particular heap was selected for this study for several reasons: it was a relatively representative feature, covered with vegetation, and thermally active. In the dump, 125 plant species were recognized, with the majority being native. The facility was primarily occupied by non-forest ecosystems, which emerged through the natural succession. These ecosystems featured *Calamagrostis epigejos*, *Erigeron annuus*, *Artemisia vulgaris*, *Rudbeckia laciniata*, *Solidago canadensis*, *S. gigantea*, and *Phragmites australis* among their prominent species.

2.2. Thermal Measurements

Surface and subsurface thermal measurements were carried out in the research area. The surface temperatures of the dump were measured using a RayTemp 28 pyrometer (accuracy ±2% or 2 °C, resolution 0.1 °C) with a 30 cm long K-type probe, which enabled measurements to be performed below the surface. In addition, a series of thermal images were taken with a handheld FLIR T640 infrared camera (with 640 × 480 matrix, 7.5–14 µm spectral range, and 13 mm lens, accuracy ±2% or 2 °C, sensitivity < 0.035 °C). The measuring equipment was used in accordance with the manufacturer's instructions and regularly maintained by specialists.

2.3. Plant and Soil Samplings

At the end of the growing season, at the turn of September and October 2022, samples of plant material (root and aerial part) from *Solidago canadensis* and *Calamagrostis epigejos* species in the ripening stage, growing in the coal-waste dump area, were taken (Figure 1). These are the dominant species that shape the physiognomy of the coal-waste dumps; hence, they were selected for analysis. Their share in the formation of soil levels and soil chemistry in anthropogenically transformed areas is quite high [49]. All the plant samples were of a similar size within species. *Calamagrostis epigejos* reached a height of 150–160 cm and a spread of 80 cm, and *Solidago canadensis* achieved a height of 140–150 cm and a spread of 100 cm. In both cases, the roots reached a maximum depth of 25 cm.

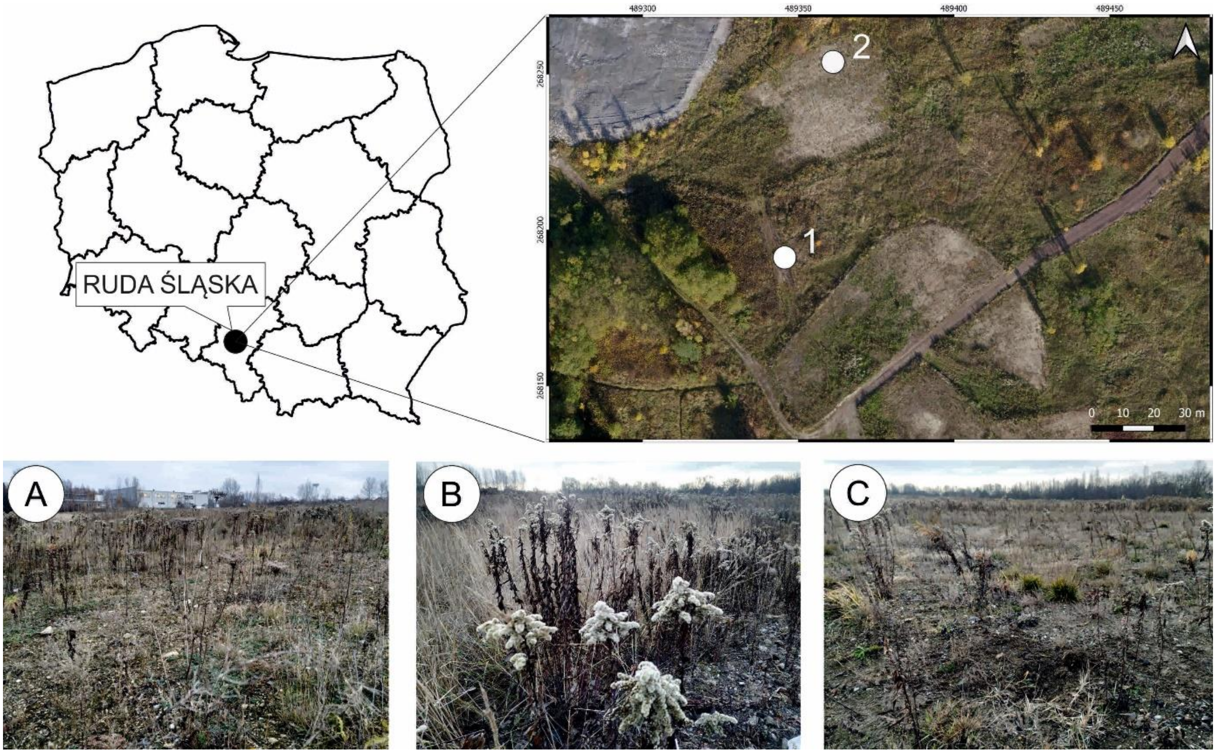

Figure 1. Research area: 1, 2—sampling points; (**A**)—view in the direction of the NE, (**B**)—view in the direction of the SE, *Solidago canadensis* (in the foreground) and *Calamagrostis epigejos* (in the background), (**C**)—view in the direction of the SW.

The samples were taken in places both affected and not affected by fire. In total, 16 plant samples for each species were taken (8 from each location). The plant samples were divided into three parts: the root part and two identical terrestrial parts (Figure 2). One of the ground samples was washed with de-mineralized water. The second was later analyzed without washing. After grinding, eight plants were combined into one sample and then analyzed. The soil samples were collected using a plastic spatula at points directly under the collected plant samples at the depth of the root zones of the analyzed species (up to the depth of 25 cm) in 8 repetitions for each location. The samples were transported to the laboratory in plastic string bags and stored in sterile conditions. The sampling procedures and material preparation for the laboratory analysis were performed according to the instructions given by MacNaeidhe [51] and Markert [52]. All the plant and soil samples were analyzed in dry weight in triplicate for all the investigated parameters and the mean values were calculated.

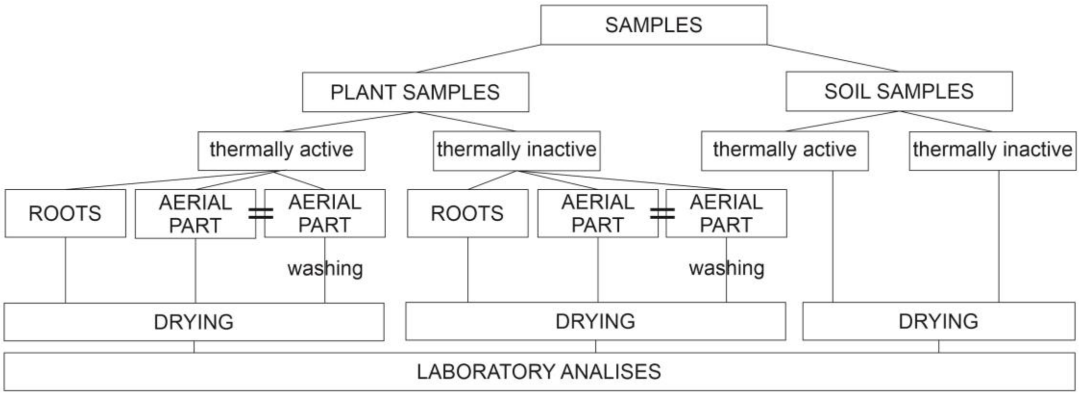

Figure 2. Sampling scheme for plants and soils.

2.4. Laboratory Analyses

ICP-MS analyses were performed for all the vegetation and soil samples to detect the content of macroelements (Fe, Ca, P, Mg, Al, Na, K, S) and trace elements (Mo, Cu, Pb, Zn, Ni, Co, Mn, Sr, Cd, Cr) [53]. Vegetation analyses were performed using a 1 g split digested in HNO_3, then Aqua Regia, and analyzed for the ultralow detection limits. The prepared soil samples were digested to complete dryness with an acid solution (H_2O-HF-$HClO_4$-HNO_3). HCl (50%) was added to the residue and heated using a mixing hot block. After cooling, the solutions were transferred and brought to volume using dilute HCl. Sample splits of 0.25 g were analyzed. The analyses were carried out in the Acme laboratory in Canada (www.bureauveritas.com, accessed on 10 May 2024) using the VG101 analytical package.

The basic physicochemical properties of the soils, such as the pH, TIC-TOC, and total nitrogen content, were examined in the collected samples. Particle size analysis of the soil samples was performed using the sieve method (using steel and woven sieves) and the total organic carbon (TOC) content was determined with an Eltra CS-500 analyzer. The total organic carbon was determined by subtracting the total inorganic carbon from the total carbon. The calibration was based on the means of the ELTRA standards. The analytical precision and accuracy were within ±2% for total carbon and ±3% for inorganic carbon. The total nitrogen content was detected by the Kjeldahl method. The pH measurement was performed using an Elmetron CP-401 pH meter (accuracy: ±0.002 pH, ±0.1 mV, ±0.1 °C). All these analyses were performed in the laboratories of the Institute of Earth Sciences of the University of Silesia in Katowice.

2.5. Analytical Studies

The content of the selected main and trace elements was analyzed. The following environmental indicators were used:

- Geoaccumulation index (I_{geo}): $I_{geo} = \log \frac{C_n}{1.5 \times B_n}$, where C_n is the content of the element in the sample, and B_n is the background value [54,55]. As background values, we used the content of elements in the Upper Continental Crust [56]. The geoaccumulation index allows the evaluation of the degree of metal contamination or pollution in the studied samples. The results are divided into seven classes: uncontaminated (0), uncontaminated to moderately contaminated (0–1), moderately contaminated (1–2), moderately to strongly contaminated (2–3), strongly contaminated (3–4), strongly to extremely strongly contaminated (4–5), and extremely contaminated (>5).
- Enrichment factor (EF): $EF = \frac{\left(\frac{C_x}{C_{ref}}\right)_{sample}}{\left(\frac{C_x}{C_{ref}}\right)_{background}}$, C_x is metal content and C_{ref} is the concentration of a reference element for normalization [57]. It is an indicator by which the relative concentrations of the analytes accumulated in a given specimen/object/environment are compared [55]. The enrichment factor is used to assess the degree of anthropogenic influence on ecosystems. The results determine five classes: deficiency to minimal enrichment (<2), moderate enrichment (2–5), significant enrichment (5–20), very high enrichment (20–40), and extremely high enrichment (>40).
- Translocation factor (TF): $TF = \frac{C_n}{R_n}$, where C_n is the element content in the aboveground parts of the plant, and B_n is the concentration of the same element in the roots [58,59]. The results distinguish four classes: low contamination factor (<1), moderate contamination factor (1–3), considerable contamination factor (3–6), and very high contamination factor (>6).

3. Results and Discussion

3.1. Thermal Situation in the Research Area

Several fire spots were identified on the surface of the coal-waste dump in Ruda Śląska. The area of the single heating zone was in the range of 20–45 m^2. The surface temperatures in the fire zones ranged from 10 to 14 °C at an air temperature of 6 °C. The temperature of the non-fire-free surfaces was close to the air temperature. Thermal fieldwork in the root zones at the fire spots showed that the soil temperature at a depth of 20 cm ranged from 20 to 40 °C. It is worth noting that the fire zones remained under only the protective layers (Figure 3).

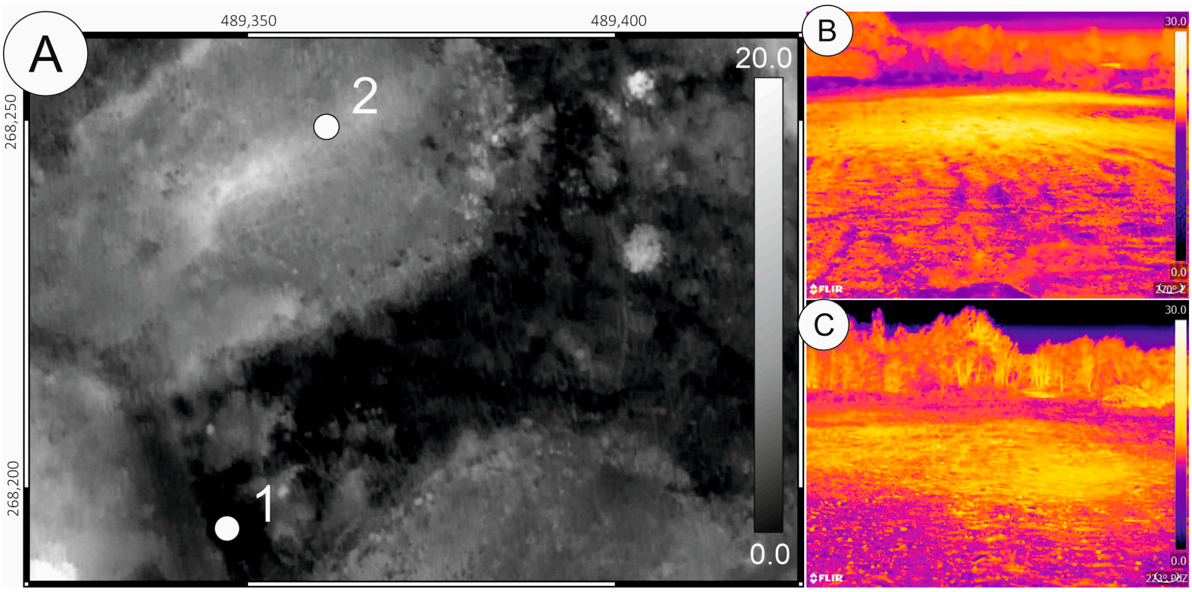

Figure 3. Thermal situation of the research area [°C]: (**A**) sampling points on the aerial thermal image, and (**B**,**C**) thermal images of the heating zone taken by the handheld IR camera.

3.2. Physicochemical Properties of Soil

The grain size analysis showed a significant difference in the grain size distribution above the fire (on the protective layer) and the areas not affected by the fire. In the case of soil in areas not affected by fire, coarse and medium gravel grains dominate (>20.0 mm to 5.0 mm), while in the case of fire-affected areas, which are covered with a protective layer, sand (0.5 to 0.1 mm) and silt fraction (<0.05 mm) dominate (Table 1). The differentiation of the grain size composition mainly results from the method of depositing post-mining waste. There is no doubt that some of the clay material will be burnt and transformed into silty clay, which in turn promotes water–air and soil sorption processes. Similar observations regarding the positive impact of fire on soil sorption were noticed by various authors [24,60,61].

Table 1. Soil grain sizes (mean values, $n = 8$) on the surface of the coal-waste dump (%).

Sample	**Grain Size [mm]**										
	>20.0 *	**20.0–10.0 ***	**10.0–5.0 ****	**5.0–2.0 *****	**2.0–1.0 ****	**1.0–0.8 *****	**0.8–0.5 *****	**0.5–0.25 ****	**0.25–0.1 ****	**0.1–0.05 *****	**<0.05 ****
Non-affected by fire	19.6	21.6	12.4	8.2	3.6	2.2	5.3	9.8	7.3	4.0	6.0
Affected by fire	3.8	3.4	1.6	3.6	10.5	5.0	9.4	21.6	17.2	6.4	17.5

Standard error (SE): * SE > 6.0, ** SE 3.0–6.0, *** SE < 3.0.

The content of carbon (TC, TIC, TOC) and sulfur (TS) fractions in the tested samples vary, and their high contents are unambiguously found on the surfaces where the fire did not take place. In areas with fire, the smaller contents are directly related to the burning of some organic parts as a result of a fire (Table 2). The soil reaction in the analyzed samples does not differ much. It ranges from 6.5 (KCl) to 7.1 (H_2O), i.e., from weak acid to neutral (Table 2). The content of total nitrogen (N_t) is similar and ranges from 1.11 to 1.14%.

Table 2. Organic part content in soil samples (mean values, n = 8).

Sample	TC *	TS ***	TIC ***	TOC *	pH **		Nt ***
			[%]		H_2O	KCl	[%]
Non-affected by fire	4.204	0.088	0.398	3.806	7.1	6.8	1.11
Affected by fire	1.146	0.047	0.355	0.790	6.6	6.5	1.14

TC—total carbon, TS—total sulfur, TIC—total inorganic carbon, TOC—total organic carbon. Standard error: * SE > 1.0, ** SE 0.1–1.0, *** SE < 0.1

3.3. Environmental Indicators

The I_{geo} index indicates that most of the vegetation does not accumulate heavy metals. In the case of *Solidago canadensis* and *Calamagrostis epigejos*, this was found both in the area affected by the fire and also without the fire (Table 3, Supplement S1). In both cases, an example may be cadmium, the content of which reached the strongly contaminated range (0.52–3.72). This is closely related to the cadmium content in the soil, which ranges from strongly to extremely contaminated (3.39–4.67). The results of other analyzed elements indicate that the study area is not contaminated. Insignificant Zn, Pb, and Cu contents are also not reflected in the index.

The enrichment factor for heavy metals in all the tested plant samples is mainly in the range of extremely high enrichment for the elements Cd, Zn, Mn, Mo and Cu. In turn, the main elements show a similar tendency: Ca (very high enrichment dominates), P (extremely high enrichment), K (extremely high enrichment), and S (extremely high enrichment). In the case of soil, only the analyzed samples in the case of K indicate the concentration—this is also related to the parent material. In the remaining main elements, the index falls within the range of deficiency to minimal enrichment (Table 4). Extremely high enrichment was found more frequently in the aboveground parts of *Solidago canadensis* than in its root parts. In general, the EF in the roots is lower than in the ground parts of these plants. These differences are related to the morphology and plasticity of plant roots, especially since the analyzed species are both invasive and expansive in Poland. In the areas of artificially stored materials, the fractions are heterogeneous—the distribution of the material is random, which is related to the absorbent surface of the soil material. Differences in the EF (>1) may result from, inter alia, the heterogeneity of the chemical composition of samples taken for testing but also from the very definition of the EF (bioaccumulation is influenced by the chemical nature of the compounds) [62].

In the fire-affected area, the translocation factor results from the washed and unwashed samples are more similar to each other than in an area not affected by fire (Table 5). The samples from areas not affected by fire differ slightly between the washed and unwashed (higher TF results in the washed). A plant is considered capable of moving metals from root to shoot when the TF is greater than one [63]. In the case of *Solidago canadensis*, we are dealing with the good transfer of elements from the root to the stem and the phytoextraction of Sr, Mn, Cd, and Zn (only non-affected by fire), while in the case of *Calamagrostis epigejos*, the phytoextraction was of Mo, Mn, K and S (Table 5). The remaining elements are accumulated in the roots; thus, phytostabilization takes place. This is confirmed by numerous previous studies presenting the type of *Solidago* as a Pb, Zn, Cu, and Cr bioaccumulator in polluted areas [45,64]. *Solidago* has interesting biogeochemical features expected in species used in environmental management—it can be a phytostabilizer in heavily contaminated soils [65].

Table 3. The geoaccumulation index (I_{geo}) within the studied samples.

		Affected by Fire							**Non-Affected by Fire**						
		***Solidago canadensis* L.**			***Calamagrostis epigejos* (L.) Roth.**			**Soil**	***Solidago canadensis* L.**			***Calamagrostis epigejos* (L.) Roth.**			**Soil**
		Root	**Washed**	**Unwashed**	**Root**	**Washed**	**Unwashed**		**Root**	**Washed**	**Unwashed**	**Root**	**Washed**	**Unwashed**	
Trace elements	Mo	−1.67	−2.43	−2.25	−2.63	−2.16	−1.81	−1.81	−3.91	−3.91	−4.54	−2.13	−2.43	−2.50	−0.58
	Cu	−0.99	−2.60	−2.24	−0.56	−3.22	−2.93	−0.39	−0.81	−1.66	−2.31	0.20	−2.33	−2.51	1.37
	Pb	−2.09	−4.06	−3.82	−2.13	−3.29	−3.10	1.64	−2.20	−3.50	−4.25	−0.93	−2.59	−2.40	2.83
	Zn	−0.78	−1.09	−1.01	0.93	−1.15	−0.89	1.99	−0.57	0.41	−0.19	1.72	−0.75	−0.70	3.26
	Ni	−4.12	−7.12	−5.54	−2.73	−5.80	−4.80	−0.26	−4.54	−6.54	−6.54	−3.17	−5.54	−5.12	0.44
	Co	−4.74	−6.68	−6.37	−3.73	−6.86	−5.91	−1.07	−5.44	−7.59	−7.76	−3.88	−6.37	−5.96	−0.27
	Mn	−3.58	−2.30	−2.12	−1.44	−0.12	−0.11	−0.57	−4.50	−3.77	−4.58	−2.23	−2.98	−3.04	0.61
	Sr	−3.95	−3.80	−3.85	−4.93	−5.38	−5.19	−2.27	−4.07	−3.72	−4.03	−4.98	−5.87	−6.02	−1.71
	Cd	1.85	2.02	2.04	1.35	0.52	0.65	4.67	2.19	2.78	2.57	3.72	1.68	1.49	3.39
	Cr	−4.58	−5.71	−5.58	−2.97	−5.23	−4.64	0.04	−4.87	−5.71	−5.58	−3.91	−5.23	−4.95	0.42
Macroelements	Fe	−5.72	−8.59	−7.79	−4.13	−7.65	−6.65	−1.18	−6.05	−8.37	−8.37	−4.83	−7.86	−6.72	−0.16
	Ca	−2.56	−2.33	−2.33	−2.74	−3.58	−3.30	−1.07	−3.14	−2.17	−2.76	−3.88	−4.54	−4.70	−0.81
	P	0.83	−0.43	0.40	−0.18	−1.21	−1.28	7.96	0.96	0.79	0.57	0.54	−0.45	−0.37	8.21
	Mg	−4.59	−5.10	−4.92	−4.59	−5.59	−5.49	−2.27	−4.41	−3.81	−4.58	−4.84	−5.34	−5.31	−1.34
	Al	−7.60	−10.18	−10.18	−5.86	−10.18	−8.60	−1.46	−7.86	−10.18	−10.18	−6.86	−10.18	−8.60	−0.94
	Na	−7.27	−7.66	−8.00	−10.33	−11.91	−10.91	−3.12	−9.91	−10.33	−10.91	−9.33	−10.91	−10.33	−3.80
	K	−1.45	−2.37	−2.30	−3.62	−3.16	−3.29	4.37	−1.90	−2.64	−2.34	−3.32	−3.39	−3.16	4.21
	S	−0.52	−1.52	−0.84	−0.84	−0.14	−0.14	−0.52	−0.84	−0.52	−1.52	0.41	−0.38	−0.38	0.48

I_{geo}: <0: uncontaminated; 0–1 : uncontaminated to moderately contaminated; 1–2 : moderately contaminated; 2–3 : moderately to strongly contaminated; 3–4 : strongly contaminated; 4–5 : strongly to extremely contaminated; and >5 : extremely contaminated.

Table 4. The enrichment factor (EF) within the studied samples.

		Affected by Fire							**Non-Affected by Fire**						
		***Solidago canadensis* L.**			***Calamagrostis epigejos* (L.) Roth.**			**Soil**	***Solidago canadensis* L.**			***Calamagrostis epigejos* (L.) Roth.**			**Soil**
		Root	**Washed**	**Unwashed**	**Root**	**Washed**	**Unwashed**		**Root**	**Washed**	**Unwashed**	**Root**	**Washed**	**Unwashed**	
Trace elements	Mo	16.55	71.71	46.23	2.84	45.09	28.78	0.65	4.41	22.06	14.18	6.50	43.03	18.55	0.74
	Cu	26.46	63.90	46.70	11.88	21.60	13.24	1.74	37.83	104.46	66.81	32.63	46.01	18.46	2.87
	Pb	12.37	23.17	15.66	4.02	20.62	11.73	7.10	14.43	29.20	17.39	14.89	38.43	19.95	7.94
	Zn	30.65	181.18	109.76	33.30	90.91	54.37	9.00	44.64	441.29	289.38	93.66	138.11	64.94	10.67
	Ni	3.02	2.77	4.75	2.64	3.61	3.61	1.90	2.85	3.56	3.56	3.16	4.98	3.02	1.51
	Co	1.97	3.77	2.66	1.32	1.74	1.68	1.08	1.52	1.71	1.52	1.93	2.80	1.69	0.92
	Mn	4.40	78.64	50.80	6.46	184.76	93.02	1.53	2.93	24.28	13.82	6.08	29.31	12.79	1.70
	Sr	3.40	27.70	15.31	0.57	4.85	2.76	0.47	3.95	25.14	20.25	0.90	3.96	1.62	0.34
	Cd	189.28	1564.69	908.53	44.74	289.68	158.01	23.75	302.84	2271.32	1968.48	375.30	741.97	295.96	28.39
	Cr	2.21	7.35	5.88	2.24	5.37	4.03	2.34	2.27	6.30	6.93	1.90	6.18	3.41	1.49
Macroelements	Fe	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Ca	8.94	76.92	43.95	2.62	16.87	10.26	1.08	7.49	73.42	48.70	1.93	9.96	4.05	0.64
	P	93.43	286.45	291.98	15.48	86.84	41.40	0.71	128.74	574.00	491.05	41.32	169.55	81.29	0.97
	Mg	2.18	11.24	7.29	0.73	4.18	2.24	0.47	3.10	23.52	13.88	1.00	5.72	2.65	0.44
	Al	0.27	0.33	0.19	0.30	0.17	0.26	0.83	0.28	0.28	0.28	0.24	0.20	0.27	0.58
	Na	0.34	1.91	0.86	0.01	0.05	0.05	0.26	0.07	0.26	0.17	0.04	0.12	0.08	0.08
	K	19.24	74.57	44.67	1.43	22.50	10.31	46.93	17.71	53.14	65.46	2.84	22.10	11.76	20.55
	S	36.83	135.06	123.48	9.82	183.21	91.60	1.59	37.04	231.52	115.76	37.78	178.27	81.03	1.56

EF: <2: deficiency to minimal enrichment; 2–5 : moderate enrichment; 5–20 : significant enrichment; 20–40 : very high enrichment; and >40 : extremely high enrichment.

Table 5. Translocation factor (TF) within the studied samples.

		Affected by Fire				**Non-Affected by Fire**			
		***Solidago canadensis* L.**		***Calamagrostis epigejos* (L.) Roth.**		***Solidago canadensis* L.**		***Calamagrostis epigejos* (L.) Roth.**	
		Washed	**Unwashed**	**Washed**	**Unwashed**	**Washed**	**Unwashed**	**Washed**	**Unwashed**
Trace elements	Mo	0.59	0.67	1.38	1.76	1.00	0.64	2.79	2.64
	Cu	0.33	0.42	0.16	0.19	0.55	0.35	0.35	0.31
	Pb	0.26	0.30	0.45	0.51	0.40	0.24	0.76	0.87
	Zn	0.81	0.85	0.24	0.28	1.97	1.30	0.88	0.91
	Ni	0.13	0.38	0.12	0.24	0.25	0.25	0.50	0.67
	Co	0.26	0.32	0.11	0.22	0.23	0.20	0.53	0.70
	Mn	2.44	2.76	2.49	2.51	1.66	0.94	2.86	2.74
	Sr	1.11	1.08	0.74	0.84	1.27	1.02	0.29	0.26
	Cd	1.13	1.15	0.56	0.62	1.50	1.30	0.70	0.61
	Cr	0.45	0.64	0.21	0.31	0.56	0.61	0.78	0.94
Macroelements	Fe	0.14	0.24	0.09	0.17	0.20	0.20	0.29	0.63
	Ca	1.17	1.17	0.56	0.68	1.96	1.30	0.38	0.34
	P	0.42	0.75	0.49	0.47	0.89	0.76	0.38	0.40
	Mg	0.70	0.80	0.50	0.54	1.52	0.89	0.53	0.54
	Al	0.17	0.17	0.05	0.15	0.20	0.20	0.20	0.60
	Na	0.76	0.60	0.33	0.67	0.75	0.50	0.50	0.75
	K	0.53	0.55	1.37	1.26	0.60	0.74	0.36	0.42
	S	0.50	0.80	1.63	1.63	1.25	0.63	1.38	1.38

TF: <1: low contamination; 1–3 : moderate contamination; 3–4 : considerable contamination; and >6 : very high contamination.

The areas subject to fires are characterized by favorable soil and water conditions. Clay materials are combusted as a result of the high temperatures, which increases the water infiltration. In such areas, plants put out extensive root systems. The plants resemble giant forms, distinguishing themselves from natural forms [23]. The analyzed species are characterized in dumps by an extensive root system, which favors the uptake of more nutrients. In other parts of the dump, in the areas not subject to measurements, the soil is characterized by high compaction and dryness, which has a negative effect on the water filtration [66], and the plants are poorly developed. It also influences the way the elements are taken up. In addition, the stored material is natural, comes from coal processing, and is theoretically completely free of or contains very few heavy metals. However, it is subject to transformation processes as a result of continuous changes in the cover and topography, as well as the processes of subsurface heating. Fires, the heat source of which is located inside the dump, increase the mobility of metals in the waste, as well as in the soil solution itself and plant roots. Moreover, the rate of root absorption may be increased as a result of greater evapotranspiration from the plant [67]. Hence, this leads to low levels of metals in the soil, which is reflected in the plant assimilation apparatus. The single exceeded indices may theoretically be related to the fact that the object is in the zone of anthropogenic impacts. However, the differences between the unwashed and washed samples are so small that the origin of the elements is more likely to be derived from the substrate (soil). The relations in the plant–soil and soil–plant system in the assimilation and root apparatus are actually comparable in two aspects: ultrapure and natural.

The concentration and statistical analysis of elements in both the soil and the plants for the results of both analyzed species reveal certain patterns. The concentrations of individual elements in the plant tissues are primarily strongly positively correlated with each other, both in thermally active and inactive areas (Table 6). These include correlations between Ni, Cr, Fe, Cd, Co, Zn, Mg, Mn, Cu and Pb, which were previously noticed by other authors in plants and soils of post-mining areas [68–70]. This suggests a coordinated uptake or assimilation mechanism within the plants, wherein the levels of various elements tend to fluctuate together. A positive correlation is also observed between the content of elements in vegetation and soil (Figure 4). This implies a dynamic exchange of elements between the plants and their surrounding soil environment, influenced by factors such as the root uptake, soil chemistry, and microbial activity [71–73]. The strong positive correlation among the element concentrations within the plant tissues suggests the presence of complex regulatory mechanisms governing nutrient uptake and transport [74,75]. Understanding these mechanisms could help with the development of targeted strategies for enhancing plant growth and remediation efforts in contaminated environments. Phytoremediation may involve the use of both analyzed species, as indicated by our results regarding the accumulation of elements by these species. However, *Calamagrostis epigejos* is much better suited for this purpose than *Solidago canadensis*. *C. epigejos* causes the area to be sodded and reduces the dust. It is a biennial plant, so after the phytoremediation process it can be easily replaced with other species. *S. canadensis* is an alien, invasive species, so there is a risk that it may lead to a reduction in the population of native plants around coal-waste dumps. Secondly, the positive correlation between the element content in the vegetation and soil underscores the interconnectedness of plant–soil interactions [76]. This highlights the potential for utilizing plants as bioindicators of soil quality and pollutant levels, as well as the importance of soil management practices in influencing plant health and productivity [7,49,77]. Overall, these observations contribute to a deeper understanding of the relationships between plants and their environment, offering valuable insights for ecological research and practical applications in agriculture, forestry, and environmental remediation.

Despite the relatively low content of trace elements (including heavy metals) in the tested samples, the area is not completely devoid of hazardous elements. According to the WHO standard [78] and the Regulation of the Minister of the Environment of Poland of 1 September 2016 [79], the target values (specified to indicate the desirable maximum levels of elements in unpolluted soils) in the case of soils are mostly higher than the content in the samples from the coal-waste dump. The situation is different in the case of the plant samples, where basically all the permissible values have been exceeded (Cd, Zn, Cu, Cr, Pb, Ni).

The smoldering of the coal-waste dumps causes the mobility of metals and their penetration into plant tissues, starting from the roots. This process, although occurring in a typically anthropogenic area, is very natural. Hyperaccumulative plants can be used to concentrate soil metals in harvestable parts of plants such as the roots and ground shoots. This biomass is incinerated so that the ash can then be disposed of or recycled [30]. The obtained results prove that the burning coal-waste dumps are areas where biological methods of reclamation of the contaminated environment can work very well. Phytoextraction in conditions of elevated temperature can get rid of contamination from the interior of the dump much faster than in areas with natural temperatures.

Table 6. The values of the Pearson rank correlation coefficients in the plant samples from the coal waste dump ($p < 0.05$).

Plant Samples from the Thermally Active Area

	Mo	Cu	Pb	Zn	Ni	Co	Mn	Sr	Cd	Cr	Fe	Ca	P	Mg	Al	Na	K	S
Mo	1																	
Cu	0.137	1																
Pb	0.379	0.677	1															
Zn	0.151	0.835	0.934	1														
Ni	0.318	0.739	0.993	0.969	1													
Co	0.331	0.731	0.996	0.962	0.999	1												
Mn	0.199	−0.231	0.223	0.167	0.211	0.199	1											
Sr	0.343	0.606	0.940	0.829	0.916	0.927	−0.047	1										
Cd	0.285	0.642	0.928	0.840	0.912	0.922	−0.102	0.996	1									
Cr	0.328	0.697	0.998	0.954	0.998	0.999	0.230	0.929	0.921	1								
Fe	0.326	0.713	0.997	0.958	0.999	1.000	0.218	0.927	0.921	1.000	1							
Ca	0.260	0.660	0.937	0.865	0.926	0.934	−0.079	0.993	0.998	0.933	0.933	1						
P	0.105	0.091	−0.405	−0.393	−0.404	−0.394	−0.831	−0.207	−0.173	−0.427	−0.415	−0.207	1					
Mg	0.352	0.716	0.996	0.941	0.993	0.996	0.140	0.956	0.951	0.995	0.995	0.958	−0.340	1				
Al	0.350	0.664	0.999	0.935	0.993	0.995	0.231	0.941	0.930	0.998	0.997	0.940	−0.427	0.995	1			
Na	0.379	0.641	0.997	0.911	0.983	0.988	0.191	0.961	0.949	0.991	0.990	0.954	−0.390	0.994	0.997	1		
K	0.371	0.637	0.998	0.918	0.987	0.990	0.231	0.949	0.936	0.995	0.993	0.943	−0.422	0.993	0.999	0.999	1	
S	0.574	−0.165	0.074	−0.025	0.051	0.042	0.789	−0.179	−0.239	0.056	0.050	−0.240	−0.330	0.003	0.059	0.034	0.063	1

Plant Samples from the Thermally Inactive Area

	Mo	Cu	Pb	Zn	Ni	Co	Mn	Sr	Cd	Cr	Fe	Ca	P	Mg	Al	Na	K	S
Mo	1																	
Cu	0.924	1																
Pb	0.956	0.939	1															
Zn	0.950	0.982	0.969	1														
Ni	0.956	0.943	1.000	0.972	1													
Co	0.957	0.944	1.000	0.973	1.000	1												
Mn	0.972	0.941	0.998	0.975	0.998	0.998	1											
Sr	0.854	0.894	0.966	0.930	0.966	0.966	0.951	1										
Cd	0.895	0.979	0.920	0.986	0.925	0.925	0.926	0.896	1									
Cr	0.951	0.931	1.000	0.964	0.999	0.999	0.996	0.970	0.913	1								
Fe	0.950	0.932	1.000	0.965	0.999	0.999	0.996	0.971	0.914	1.000	1							
Ca	0.796	0.846	0.927	0.897	0.927	0.926	0.911	0.989	0.870	0.933	0.934	1						
P	−0.546	−0.196	−0.369	−0.291	−0.362	−0.363	−0.411	−0.175	−0.176	−0.369	−0.365	−0.115	1					
Mg	0.911	0.914	0.989	0.953	0.989	0.988	0.981	0.992	0.908	0.991	0.992	0.971	−0.283	1				
Al	0.946	0.925	0.999	0.960	0.998	0.998	0.995	0.973	0.908	1.000	1.000	0.937	−0.367	0.993	1			
Na	0.946	0.925	0.999	0.960	0.998	0.998	0.995	0.973	0.908	1.000	1.000	0.938	−0.366	0.993	1.000	1		
K	0.941	0.919	0.998	0.956	0.997	0.997	0.993	0.975	0.903	0.999	0.999	0.940	−0.364	0.994	1.000	1.000	1	
S	0.819	0.819	0.677	0.794	0.681	0.683	0.714	0.537	0.804	0.658	0.658	0.487	−0.367	0.610	0.646	0.645	0.633	1

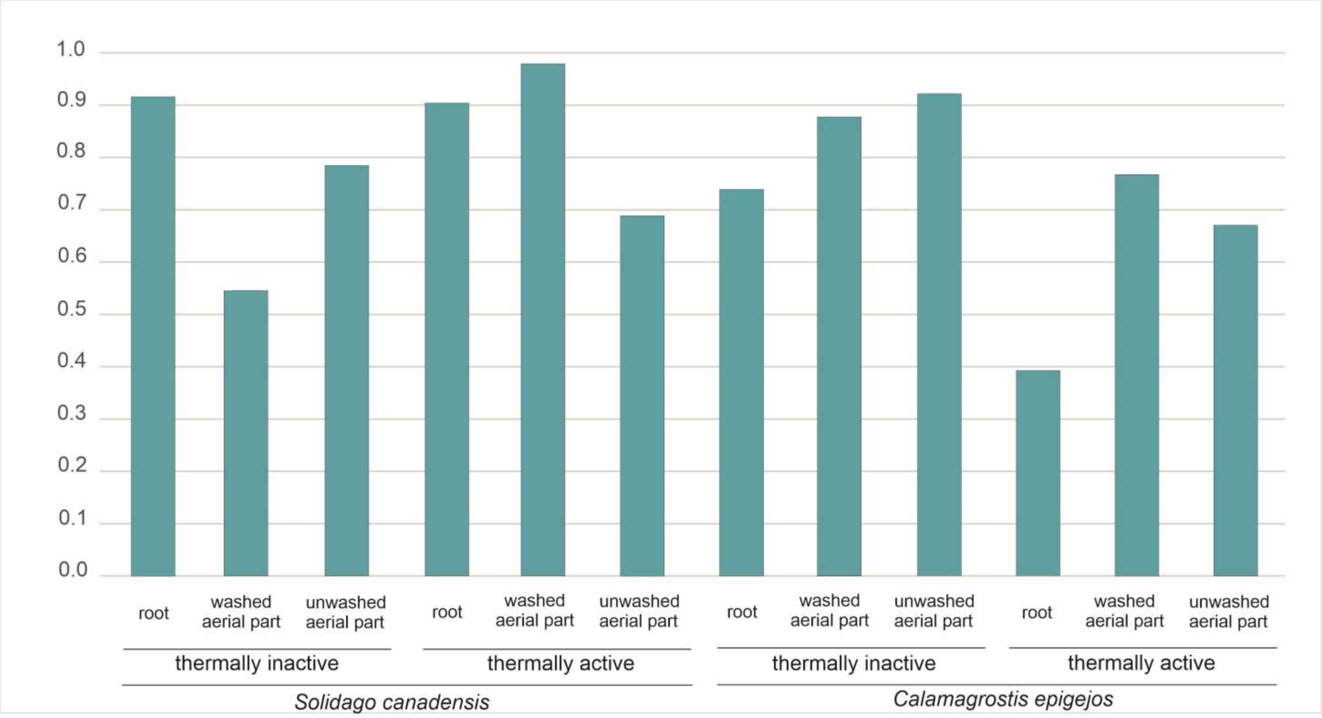

Figure 4. The values of the Pearson rank correlation coefficients between the amount of microelements in the plant (roots, washed aerial part, unwashed aerial part) and soil samples.

4. Conclusions

This study delved into the ecological dynamics of thermally active coal-waste dumps within the Upper Silesian Coal Basin, focusing on two selected species that spontaneously colonize the surface of the dumping sites. *Calamagrostis epigejos* and *Solidago canadensis* are suitable species for showing the circulation of trace elements in the plant–soil system resulting from their ecological features, allowing them to rapidly colonize coal-waste dumps. Their dead aboveground parts also significantly affect the variability of habitat conditions in terms of both the chemical and physical soil characteristics.

Our analysis revealed notable disparities in the concentrations of major and trace elements between the aerial and underground plant parts, as well as the surrounding soil. Particularly, the heavy metal concentrations were higher in the plant materials than in the soils within the root zone, indicating the potential for phytoremediation. Environmental indicators such as the geoaccumulation index, enrichment factor, and translocation factor provided insights into the varying degrees of pollution exhibited by the studied species, with cadmium and zinc exhibiting the highest accumulation rates. This underscores the importance of understanding pollutant uptake and translocation dynamics within plant species in coal-waste dump environments. The high accumulation of heavy metals also highlights the potential toxicity of these plants, which could pose risks to the environment and human health if not properly managed. The consistent element content observed in both the washed and unwashed plant specimens, as confirmed by the enrichment factor, highlights the robustness of our findings and suggests the minimal impact of external factors on the element concentrations.

The positive correlation observed between the microelement concentrations in the plants (both roots and aerial parts) and soil samples, regardless of the thermal activity zones, underscores the interconnectedness of the plant–soil relationships in these environments. This correlation reinforces the potential for utilizing indigenous plant species in the reclamation and remediation of post-industrial areas. Elementary analysis of the plant materials in terms of the content of macro- and microelements indicates their potential for enriching poor initial soils in post-mining areas, such as coal-waste dumps, after the death of the plants and the decomposition of their parts. This is one of the factors justifying the legitimacy of introducing vegetation to post-mining areas for their rehabilitation. Our study advances scientific inquiry into the ecological dynamics of coal-waste dumps and holds practical significance for informing strategies for the sustainable reclamation and management of post-industrial landscapes. The described study can be replicated in other thermally active facilities, not limited to the Upper Silesian Coal Basin but across different coal basins globally. Furthermore, conducting similar investigations on diverse plant species could offer insights into their behavior in burning coal-waste dumps for a comprehensive comparison.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/resources13060073/s1, Supplement S1: Elemental composition of the plant and soil samples; Supplement S2: Descriptive statistics of selected elements in the plant samples from the coal waste dump.

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