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Statistical Analysis of Soil Contamination in Vicinity of Coal-Processing Plant: Implications for Ecosystem Stability

Abstract: The extensive generation of waste and intensified geological processes that result from hard coal mining and active operations within mining regions have led to increases in the pollution levels of ecosystems. Most coal-mining wastes contain significant amounts of heavy metals and are, therefore, particularly hazardous to the environment. The soils around waste heaps can be contaminated with various pollutants. This article presents the results of a study of soils that were sampled in the impact zone of the waste heap of the Chervonohradska CPP of the Chervonohrad Mining District. Using statistical methods (including variogram modeling and spatial interpolation), we analyzed the spatial distributions of heavy metals in the affected soil zones. This approach allowed for an enhanced understanding of contamination-dispersion patterns and potential risk areas. The authors collected soil samples from the depth of the biotically active humus-accumulative horizon from the lower tier of the slope of the waste heap at distances of 20 m, 40 m, and 100 m from the spoil tip. We measured the contents of the studied elements in the soil using X-ray fluorescence analysis and assessed the quality of the soil by phytotesting using the *Triticum aestivum* L. and *Lepidium sativum* L. test species. It was found that the average concentrations of certain heavy metals in multiple samples exceeded the background values for the region and affected the inhibition of the development and growth of the test objects.

Keywords: environmental safety, coal mining, environmental monitoring, bioindication, heavy metals, statistical models, soil quality

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1. Introduction

The long-term development of the large-scale mining and energy sector has led to a high level of anthropogenic load in industrialized regions. However, the use of methods for the bioindication of soil contamination with heavy metals in the Lviv-Volyn coal-mining region remains insufficiently studied – particularly in terms of low-cost and statistically justified approaches. Previous studies have primarily focused on point-based assessments rather than spatially continuous models; the latter can provide a more comprehensive picture of contamination dispersal. Specifically, soil pollution (including heavy metals) has become a serious environmental problem [1, 2]. Specifically, the soils that were formed in the coal dumps of the Szczygłowice Coal Mine in the Upper Silesian Coal Basin in southern Poland are rich in Zn, Pb, Ni, and Cu [3]. Another soil study at five sites of self-heated coal waste in the Upper Silesian Basin revealed soils that were contaminated with Pb, Cd, Zn, Hg, and As [4]. The soils of Shanxi Province (the coal base in China) were contaminated by Mn, Cu, Zn, Cr, and Ni [5]. Coal mining and preparation lead to the increased mobility of heavy metals in the environment and disruptions of their biogeochemical cycles [6–8] as well as higher carcinogenic risks for humans [9].

In Ukraine, the coal industry is concentrated in the Donetsk, Lviv-Volyn, and Dnipro coal basins. The environmental situation in the Chervonohrad district of the Lviv region is one of the worst in the region. The main environmental problems of this region include the geomechanical impact and subsidence of the Earth's surface [10], flooding [11], changes in hydrochemical fields and soil contamination [12], and the formations of technogenic landscapes and phytogenic fields [13]. A significant part of the district's land is occupied by waste rock, which is stored in dumps and other places (spoil tips) and is a source of geochemical pollution of three media – soils, surface/groundwater, and the air [14, 15]. The environmental safety of spoil tips depends on many factors: the chemical and mineralogical composition of the rocks, peculiarities of the physical and chemical internal and external transformations in combination with climatic and hydrogeological conditions, susceptibility to degradation processes, etc.

In the territory of the Chervonohrad Mining Industrial District (CMID), there are 22 waste mine dumps; these cover areas from 9–10 ha to 29–30 ha [16] and can be divided into isometric or sectoral shapes and conical or prismatic sections. The total area of all of the waste heaps in the district is about 170 ha, and their heights range from 25 m to 40 m. In total, more than 78.8 million m^3 of waste rock is concentrated in the spoil tips of the Chervonohrad mines. The largest amount of waste rock is concentrated in the waste heap of the Chervonohrad Central Coal-Processing Plant (CPP), which covers an area of more than 85 ha [17]. The hazardous impact of the spoil tips is also caused by the washing away of anthropogenic soil from their surfaces as a result of water erosion and the pitting of fine soil due to wind erosion. These technogenic soils are toxic because they contain elevated levels of heavy metals that have become mobile due to the oxidation of the pyrite in the waste rock (which forms sulfuric acid) and its destructive effect on metal compounds [17].

The water erosion of spoil tips and waste heaps is caused by storms, melts, and irrigation water runoffs (which are generally considered to be the movements of water over the surface and near-surface soil layer). Spoil tips that are prone to significant water erosion release substantial volumes of rock mass into the environment, which results in changes in the soil cover of the surrounding area. Since chemicals and mechanical pollutants are removed from the dumps and spread across the landscape (mainly with surface runoff from atmospheric precipitation – cascading), the distributions of the pollutants and rock particles largely depend on the topography of the territory; its pollution is not uniform. Local wind erosion (which primarily affects the exposed slopes and elevated terrain) also significantly degrades the soil cover. When rock particles are carried away by the wind, the contamination of the territory is diffuse; this involves the transfer of pollutants through the air-land-water system and can occur at rather large distances from its source. The adjacent territory to which the flows from the landfill enter is already another geosystem (which, in the case of a slope, can be classified as being transaccumulative); so, the study of the ecological states of the soils in this location is relevant and important [18, 19]. The significant anthropogenic load that occurs in the areas of mining operations inevitably leads to soil that is contaminated with sulfur, nitrogen, and other pollutants [20].

Coal-mining wastes that come to the surface undergo physical and chemical transformations in order to adapt to new thermal conditions. As a result, parts of the solid waste are dispersed (along with toxic elements) around spoil tips in zones according to the individual rates of the substance spreading. The removal of components from the surfaces of the spoil tips contributes to the transition of salts of alkaline and alkaline earth elements, sulfides, and heavy metals such as Ni, Cu, Pb, Cd, Zn, Fe, and Mn into solutions. Other negative processes that are initiated by the disposals of spoil tips include the high migration activities of toxicants, the formations of geochemical anomalies, the destruction of crystal lattices of the clay minerals in the soils, salinization, the inhibition of the soil's biological activity, the degradation of humus, and the loss of fertility [4, 9, 13, 14].

It is well-known that excessive concentrations of pollutants that are anthropogenically released into the environment have a negative impact on the environment; they cause the disruptions of physiological and biochemical processes in living organisms [21, 22]. Excessive amounts of heavy metals in various components of the biosphere (including those with biogenic properties) have an inhibitory toxic effect on the biota [6, 13]. Various test cultures are widely used to assess the toxicity of mining wastes and soils [23–25]. According to [26], only three vascular plant toxicity tests that had been developed by the USEPA were currently approved for laboratory use, including the seed germination/root elongation toxicity test. Since seeds possess certain sensory mechanisms that allow them to germinate under favorable environmental conditions and complete the development process, it has been established that being exposed to metals negatively affects the seed germination, growth, and productivity of many plants [27]. The toxic effects of pollutants that are contained in the soil on the germination and the early stages of the growth and development of terrestrial plants can be assessed using the biotesting method, which is based on biota responses to anthropogenic pressure. Due to its simplicity, efficiency, and accessibility, biotesting is widely used [28–30]. Biological test systems indicate the overall toxicity index of a sample; the main criterion for assessing environmental pollution is not the concentration of a pollutant but the response of a living indicator organism to its toxic effect.

The most commonly used plants for phytotesting are garden cress (*Lepidium sativum* L.) [31–34] and common wheat (*Triticum aestivum* L.) [35–37]. These crops significantly differ in a wide range of parameters, thus allowing researchers to compare their effectiveness as indicator plants under the conditions of coal mine technogenesis and, additionally, obtain comprehensive research results. *Lepidium sativum* L. (cress) is a highly sensitive indicator of soil contamination with heavy metals and high soil acidity. *Triticum aestivum* L. (wheat) is a moderately sensitive indicator for the heavy-metal contamination of the soil as well as for excessive salt contents and nutrient deficiencies. These plants also differ in their growth rates; *Lepidium sativum* L. is a faster-growing plant when compared to *Triticum aestivum* L. According to the literature analysis, both plants give good results for phytoindication at the same time during one growing season, and they are widely available and unpretentious in their germination [38]. Therefore, the use of two different plant species may allow for a wider range of data and the higher accuracy of phytoindication; the cress will provide quick results, while the wheat will provide long-term monitoring. The combination of different plant species helps to account for various environmental factors and offers a comprehensive approach to assessing soil health.

This study focuses on the ecological and geochemical characteristics of the soils that have formed in the dumps of the Chervonohrad Central Coal-Processing Plant in the Lviv-Volyn coal basin (Ukraine).

The aim of the study is to substantiate the most optimal bioindicators of soil pollution based on a statistical model of the parameters of the ecological and geochemical system of the soils that have formed on the spoil tip of a coal-preparation plant by statistical analysis.

The basic premise of this study is that the heavy-metal contamination of soils in the impact zone of the Chervonohrad Central Coal-Processing Plant spoil tip in the Lviv-Volyn coal basin, Ukraine, significantly inhibits the development and growth of vegetation; this should be reflected in the growth parameters of the selected phytoindicators. At the same time, certain parameters of the geochemical field are likely to affect the growth parameters of the phytoindicators. Establishing such relationships will be of practical interest for improving the phytomonitoring's accuracy and developing cost-effective tools for environmental assessment and land-rehabilitation planning in coal-mining areas.

2. Materials and Methods

2.1. Soil sampling

Soil samples were collected in from adjacent areas at depths that corresponded to the biotically active humus-accumulating horizon (0–20 cm) from the lower tier of the spoil tip slope and at distances of 20 m, 40 m, and 100 m from the spoil tip (Fig. 1).

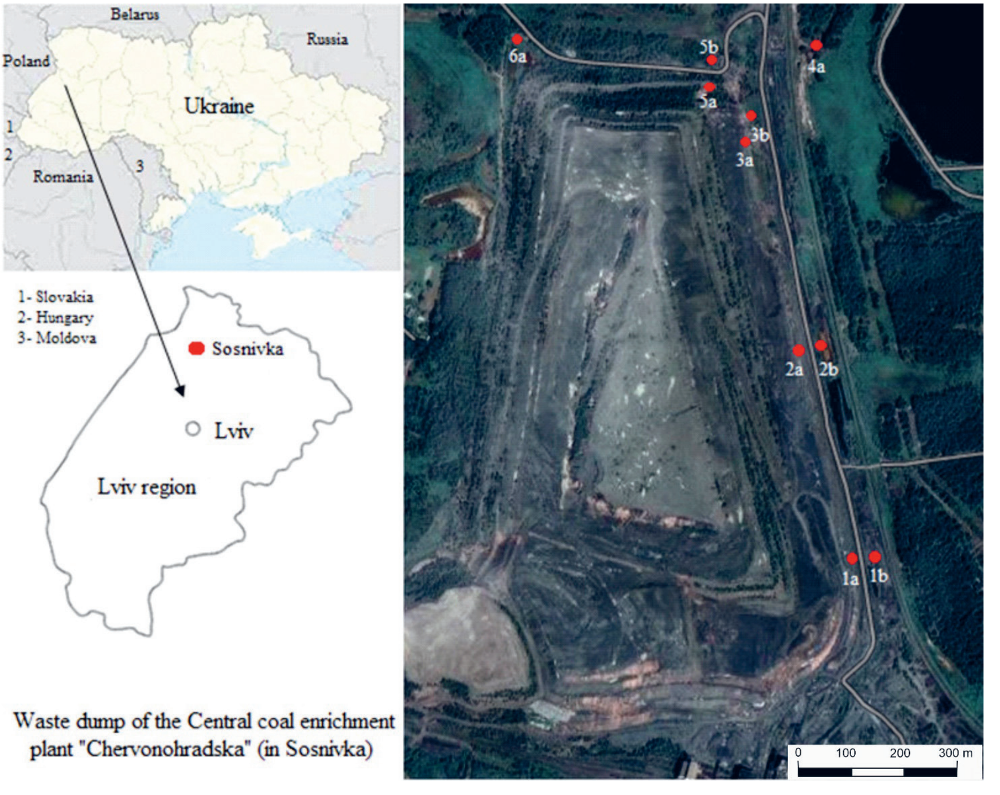

Fig. 1. Location of study area and distribution of soil-sampling sites within waste heap of Chervonohrad Central Coal-Processing Plant: 1a – slope of spoil tip; 1b – 20 m from spoil tip; 2a – slope of spoil tip; 2b – 20 m from spoil tip; 3a – slope of spoil tip; 3b – 20 m from spoil tip; 4a – 100 m from spoil tip; 5a – slope of spoil tip; 5b – 40 m from spoil tip; 6a – 40 from spoil tip

The sampling points were selected due to their locations on the eastern side of the Western Bug River spoil tip, which is in the impact zone of the Chervonograd CPP. The latitude and longitude of each sampling point were recorded using GPS with an accuracy of ±1.5 m, thus ensuring the precise spatial mapping of the contamination. A total of ten soil samples were collected using the envelope method; these consisted of five samples at the corners of a 1 m × 1 m envelope and in the central part of a representative plot at the test site. The combined sample was made by mixing the five point samples that were taken from one site. The weight of the combined sample was at least 1 kg, and the samples were air-dried at room temperature in a laboratory. The soil sample was placed on a clean sheet of paper; then, small pebbles, plant particles, and other inclusions were removed, while the larger clods of soil were ground in a porcelain mortar, mixed with the main soil, and passed through a sieve with a pore diameter of 4 mm; the processed samples were then packed in plastic bags.

2.2. X-Ray Fluorescence Elemental Determination

For measuring the contents of the studied elements, the soil samples were prepared for analysis in accordance with DSTU ISO 11464:2007. The thoroughly mixed soil was placed on clean square paper and divided into four equal parts with a spatula. Two opposite parts were discarded, and the remaining two were combined, mixed, and taken for further analysis. This middle sample was further sieved (a 0.25 mm pore size), and any larger particles were crushed as needed. The element content in the soil was measured by X-ray fluorescence analysis using an Elvax Light SDD analyzer; this could detect chemical elements within a range of ^{11}Na to ^{92}U with high accuracy (0.01%). The data-acquisition time was 2 × 180 s for all of the samples. The limits of the measurement absolute error were ca. 0.05–0.20% (the time of one measurement was 180 s). For each sample, three parallel measurements were made. The contents of the studied elements in the soil samples were determined in milligrams per kilogram. For the soil analysis, the samples (ca. 2 g) were placed on an ultra-thin (4 μm) polypropylene film that was transparent to X-rays (these were included in the delivery package) and carefully transferred to the device where the measurements were made. A more detailed methodology can be found in [39].

The assessment of the environmental conditions in the soil that was adjacent to the spoil tip of the Chervonohradska CPP involved a comparative analysis. This entailed comparing the actual contents of the studied soil samples with both the maximum permissible concentration (MPC) limits in accordance with [40] and the background concentrations (clarke) that were established for the Western Polissia region according to [41] (as outlined in the official regulations).

Phytotesting was carried out following the guidelines of DSTU ISO 11269-2:2002. The evaluation of the soil state was undertaken by examining its impact on the germinations and growths of different terrestrial plant species by comparing the soils of unknown quality to the control soil.

This evaluation was based on statistically significant differences in the germinations and growths of the seedlings within the test medium in comparison to the control. In this context, the control substrate consisted of soil that was taken from a relatively clean area such as a nature reserve, sanctuary, or resort zone. Two plant species were chosen for the test: Category 1 encompassed monocotyledonous plants, and Category 2 involved dicotyledonous plants. The specific selections for testing included soft wheat (*Triticum aestivum* L.) (representing Category 1) and garden cress (*Lepidium sativum* L.) (representing Category 2).

When assessing the toxicity of the soil samples, a sheet of filter paper was placed in a Petri dish; on this, a dried and crushed soil sample was placed and evenly distributed over the container, and the required humidity was achieved with deionized water. The soil was planted with ten homogeneous untreated seeds of the selected plant species. The experiment was conducted at room temperature (20°C) in a place that was protected from direct sunlight. At the end of the experiment, the plants were carefully removed from the Petri dishes, and the lengths of the roots and stem systems of the sprouts were measured. The sprouts were then placed in paper bags and dried for several days; after this, their dry weights were determined.

2.3. Processing of Growth Test Results

After measuring each of the studied variants, the average length of the aerial and root parts $\overline{x} \pm m$ (*m* was the arithmetic mean error) was calculated using the following formula:

$$m = \sqrt{\frac{\sigma^2}{N}} \quad (1)$$

where *N* was the number of results, and σ^2 was the variance (average variation per unit of population); the latter was determined by the following equation:

$$\sigma^2 = \frac{\sum_{i=n}^{N} (x - \overline{x})^2}{N} \quad (2)$$

The reliability of the difference of arithmetic means *t* was calculated by the Student-test:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{m_1^2 + m_2^2}} \quad (3)$$

where $\overline{x}_1$ was the arithmetic mean of the indicator in the control experiment, $\overline{x}_2$ was the arithmetic mean of the indicator in the experimental variant, m_1 was the error of the arithmetic mean in the control experiment, and m_2 was the error of the arithmetic mean in the experimental variant.

The phytotoxic effect (PE) was determined as a percentage of any bioparameter: the plant weight, the length of the root or stem system, the number of damaged plants, the number of seedlings, etc. The phytotoxic effect was calculated by the following formula:

$$PE = \frac{M_0 - M_x}{M_0} \cdot 100 \tag{4}$$

where M_0 was the value of the bioparameter (plant weight, sprout height, root length, etc.) in the dishes with the control substrate, and M_x was the value of the same bioparameter in the dishes with the test substrate.

To assess the toxicity of the soils by the growth test of the *Triticum aestivum* L. and *Lepidium sativum* L. phytoindicators, the following scale of the toxicity levels was proposed (Table 1) [42].

Table 1. Scale for assessing soil-toxicity levels

Level of growth inhibition PE [%]	Toxicity level
0.0–20.0	no or low toxicity
20.1–40.0	average
40.1–60.0	above average
60.1–80.0	high
80.1–100.0	maximum

The statistical analysis of the experimental data was also performed using the Statistica software package. First, the data was standardized; at the next stage, a factor analysis was performed to determine the factors that affected the various parameters of the bioindicators and to reduce the number of variables for the canonical correlation analysis. The factor analysis was performed without vector rotation. According to the results of the canonical correlation analysis, only the first canonical function was taken into account. The level of significance was taken as $p < 0.05$.

3. Results

3.1. Soil-Chemical Compositions

Analyzing the contents of typical biogenic elements such as Si, Al, Mg, S, K, and Ca (Table 2) is essential for assessing the overall conditions of soils. Fe, Al, Ca, Mg, and K are typically classified as major elements in soils, whereas Ti, Mn, P, and S belong to a transitional group between macro- and microelements.

Table 2. Content of biogenic elements in soils in impact area of Chervonogradska CPP [mg/kg]

Element	1a	1b	2a	2b	3a	3b	4a	5a	5b	6a
Mg	12,022.05 (±1,098.56)	7,877.82 (±1,562.17)	11,533.94 (±1,118.10)	9,158.42 (±1,693.26)	8,822.70 (±1,138.47)	9,416.09 (±1,305.09)	4,172.67 (±806.30)	7,861.39 (±1,323.70)	7,028.73 (±1,316.73)	1,601.26 (±1,097.39)
Al	63,571.65 (±658.58)	125,356.30 (±882.70)	70,623.31 (±676.94)	123,981.20 (±929.99)	65,482.62 (±671.33)	126,978.50 (±805.18)	47,287.53 (±525.73)	121,836.80 (±779.87)	114,273.90 (±803.53)	56,171.19 (±662.26)
Si	333,129.60 (±915.58)	258,627.90 (±868.52)	329,732.40 (±872.56)	246,494.30 (±878.05)	334,421.80 (±897.81)	264,397.5 (±745.80)	406,428.90 (±708.82)	275,053.40 (±767.13)	287,415.60 (±794.11)	364,865.90 (±814.67)
S	745.55 (±36.56)	15,315.90 (±104.94)	2,903.38 (±49.98)	26,097.30 (±143.20)	3,642.90 (±54.11)	7,181.50 (±66.15)	1,371.42 (±35.20)	9,848.02 (±75.30)	7,909.37 (±69.88)	1,3768.18 (±89.07)
K	21,596.05 (±1,641.82)	27,486.68 (±2,284.62)	19,668.58 (±1,682.89)	23,379.51 (±2,348.38)	21,057.48 (±1,717.10)	22,243.18 (±1,479.15)	11,085.80 (±2,487.80)	23,747.43 (±1,730.98)	25,266.33 (±1,828.57)	18,328.11 (±2,597.43)
Ca	50,893.17 (±1,053.46)	6,326.44 (±1,113.67)	35,897.82 (±1,012.58)	12,804.50 (±1,204.51)	39,805.59 (±1,075.21)	1,284.48 (±710.79)	0 (±1,144.03)*	1,056.56 (±811.21)	2,063.77 (±875.21)	1,533.94 (±1,180.16)

Notes:
* Element was absent in sample under study.
Sampling point positions and their distances from spoil tip can be interpreted based on Figure 1, which includes linear scale.

The study revealed that the Mg content in the soils that were collected from the slope of the spoil tip exceeded the average regional background values by 1.83–1.90 times; however, most of the samples showed deviations of 1.10–1.49 times from the average content. It should be noted that the Mg content decreased with increasing distances from the spoil tip. Among the other chemical elements, Al ranked third in abundance; this is classified as a typical macronutrient, and it plays a key structural role in soils; its contents in the samples ranged from 47.28 g/kg to 126.98 g/kg, and increased at a distance of 20 m from the spoil tip. Phosphorus was only detected in three samples, where its concentration exceeded the regional background by 1.74–1.87 times. The K content increased with distance, while Ca decreased in the vast majority of the cases. With increasing distances from the spoil tip, K concentrations rose, whereas Ca concentrations tended to decrease.

The studied soils were characterized by an increased sulfur content relative to the maximum permissible concentration MPC = 160 mg/kg [40] and exceeded the permissible content by 4.66–163.1 times. With increasing distances, its content increased in almost all of the cases – reaching 26,097.3 mg/kg. This could be explained by the fact that, during the mining of coal, a large amount of sulfur is released into waste heaps (spoil tips) (from low-sulfur [0.1%] to high-sulfur [4.1%] compounds); also, the mined rocks contained sulfide and free sulfur, with an average of 2.2% sulfur (including 2% sulfide sulfur). The pyrite (FeS_2) content in the waste from the Chervonohradska CPP reached as high as 1% [43] – the oxidation of which leads to the formation of sulfuric acid and easily soluble iron sulfates.

The analyses of metals such as Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr, Cd, Pb, Ti, Rb, Y, and Sr (Table 3) at different distances was essential for assessing the chemical pollution and its impact on the soil quality in the technogenically affected areas. Our laboratory analysis of the heavy metal concentrations and biogenic element content in soils that were affected by the Chervonohradska CPP provided essential data for evaluating the ecological conditions and functional transformations of technogenically altered landscapes.

The distribution of the chemical elements – primarily Mn, Ni, Cu, Zn, and Pb – showed elevated concentrations relative to the typical background levels for the study area (Table 4). These elements demonstrate distinct geochemical behaviors relevant to their environmental impacts. Ni and Mn are relatively mobile under acidic or reducing conditions – often migrating in ionic form or as complexes. Cu, Zn, and Pb tend to accumulate in the upper soil horizons due to their strong sorption by organic matter and clay minerals. Despite Cu and Zn being mobile under hypergenic conditions, they are easily immobilized in soils through precipitation or adsorption processes [44, 45]. Characterized by low mobility, Pb is retained in surface layers near pollution sources due to its high affinity for solid soil components [46]; these properties helped explain their spatial distributions and potential bioavailability in the studied area. According to [47], Pb(II) is well adsorbed by rapeseed biomass, and Cu(II), Pb(II) are adsorbed by chaff; these plants are grown in abundance in Ukraine.

Table 3. Metal content in soils in impact area of Chervonohradska CPP [mg/kg]

Element	1a	1b	2a	2b	3a	3b	4a	5a	5b	6a
Ti	4,787.28 (±268.53)	8,564.05 (±390.06)	5,254.35 (±287.12)	7,507.99 (±397.19)	5,411.60 (±287.42)	7,091.43 (±280.76)	2,156.90 (±285.49)	7,230.54 (±310.19)	6,759.47 (±305.55)	3,901.53 (±348.55)
Cr	71.25 (±65.45)	278.07 (±97.39)	103.04 (±68.05)	266.32 (±102.01)	130.98 (±67.41)	218.83 (±68.88)	49.44 (±75.22)**	205.65 (±72.80)	177.62 (±75.93)	98.94 (±88.30)
Mn	597.11 (±47.67)	789.84 (±73.73)	571.77 (±48.47)	1,645.74 (±83.87)	728.90 (±52.89)	1,395.00 (±57.56)	40.25 (±43.58)	365.19 (±52.07)	495.67 (±52.77)	1,954.12 (±78.64)
Fe	27,435.70 (±159.44)	85,347.40 (±345.60)	37,965.86 (±189.04)	93,584.17 (±379.27)	34,678.30 (±184.70)	86,927.81 (±294.15)	8,425.26 (±90.05)	80,010.97 (±286.81)	72,110.50 (±277.22)	44,007.48 (±220.25)
Ni	11.99 (±12.86)	105.96 (±28.94)	25.07 (±15.40)	171.14 (±31.08)	32.37 (±14.58)	89.36 (±19.63)	13.79 (±11.93)	46.06 (±21.67)	51.17 (±20.24)	21.00 (±20.20)
Cu	25.04 (±8.42)	116.54 (±16.85)	28.37 (±8.78)	199.56 (±19.97)	31.10 (±9.08)	144.47 (±12.52)	16.51 (±8.11)	42.12 (±11.74)	56.02 (±11.69)	18.02 (±11.48)
Zn	43.59 (±6.12)	147.15 (±12.58)	45.97 (±6.53)	287.91 (±15.7)	53.15 (±6.85)	128.07 (±9.13)	19.77 (±5.89)	45.75 (±7.85)	68.97 (±8.54)	32.93 (±8.12)
Rb	107.58 (±2.52)	208.12 (±4.85)	106.20 (±2.61)	184.45 (±5.12)	107.30 (±2.69)	137.84 (±3.42)	23.22 (±1.55)	155.57 (±3.49)	141.43 (±3.45)	48.00 (±2.46)
Sr	200.10 (±2.99)	458.83 (±6.00)	195.26 (±3.05)	525.34 (±6.87)	200.59 (±3.16)	473.54 (±4.90)	37.63 (±1.64)	241.02 (±3.69)	205.39 (±3.57)	102.47 (±2.80)
Y	31.23 (±2.12)	48.37 (±3.76)	32.05 (±2.24)	62.12 (±4.09)	33.83 (±2.31)	40.91 (±2.56)	3.25 (±1.50)	35.59 (±2.63)	28.74 (±2.59)	13.99 (±2.27)
Zr	512.36 (±4.66)	267.34 (±5.71)	520.62 (±4.79)	251.35 (±6.15)	566.73 (±5.09)	213.65 (±4.17)	119.05 (±2.59)	286.02 (±4.31)	215.11 (±4.01)	179.29 (±3.80)
Cd	0 (±9.06)*	3.61 (±16.30)	4.01 (±9.58)	0 (±18.17)*	4.03 (±9.87)	9.67 (±9.56)**	8.56 (±10.47)	0 (±11.09)*	2.18 (±11.72)	0 (±14.20)*
Pb	25.30 (±4.13)	103.74 (±9.26)	41.36 (±4.95)	127.32 (±10.75)	35.01 (±4.89)	115.33 (±7.49)	0 (±3.77)*	101.61 (±7.94)	86.78 (±7.20)	26.58 (±5.72)

* Element was absent in sample.
** The metal concentration in the sample is below the detectable minimum (the error is greater than the value).

Table 4. Comparison of measured heavy metal concentrations in study area with reference values

Element	Average content in soil-forming rocks of Ukraine [mg/kg]	Regional clarke for Western Polissia [mg/kg]	Maximum excess over regional clarke
Mn	850	185 (75–700)	10.56
Ni	40	13 (9–21)	8.15
Cu	20	6 (1.4–17)	33.26
Zn	50	38 (8–15)	7.57
Pb	12	11 (8–15)	14.12
Fe	38,000	12,055 (8,000–27,000)	7.76
Ti	4,600	3,585 (2,000–6,000)	2.38
Sr	300	141 (80–520)	3.72
Cr	200	48 (23–67)	5.79

Source: based on data from sources and [41]

Beyond the elemental compositions, it is crucial to evaluate the biological impacts of soil contamination through bioassays.

3.2. Results of Biotesting

The toxicity of the environment was determined by using test objects that signaled danger regardless of the substances and their combinations that caused changes in vital functions. The results of the soil phytotoxicity tests based on the inhibitions of the growths of the test objects of garden cress (*Lepidium sativum* L.) and common wheat (*Triticum aestivum* L.) are presented in Tables 5 and 6, respectively.

An inhibition of *Lepidium sativum* L.'s growth as compared to the control could be observed in Soils 2b, 1b (collected 20 m from the spoil tip), and 5a (collected from the slope of the spoil tip). The best growth rates of the ground and root parts could be found in Samples 2a, 3a (taken from the slope of the spoil tip), and 6a (taken 40 m from the spoil tip). An inhibition of *Triticum aestivum* L.'s growth as compared to the control could be observed in the soil from Points 2b, 1b, 3b (located 20 m from the spoil tip), and 5a (located on the slope of the spoil tip). The best growth rates of the ground and root parts could be found in Samples 6a, 3a, 1a (soils from the slope of the waste heap), and 4a (100 m from the waste heap).

Table 5. Arithmetic means of plant heights and root lengths, their errors, and their variances for each soil sample; test object – garden cress (*Lepidium sativum* L.)

Variant	Indicator [cm]	*Lepidium sativum* L.				
		Plant germination [pcs]	Variance, σ^2	Mean, $\overline{x} \pm m$	*t*-test	Dry sprout weight [mg]
Monitoring	HS	9	0.30	4.82 (±0.18)	–	16.2
	LR		5.82	6.24 (±0.80)	–	
1a	HS	9	0.25	4.66 (±0.17)	0.62	16.1
	LR		1.53	3.30 (±0.41)	3.25	
1b	HS	7	0.13	1.44 (±0.13)	14.73	7.6
	LR		0.14	0.74 (±0.14)	6.73	
2a	HS	10	1.79	4.44 (±0.42)	0.82	12.2
	LR		4.85	5.15 (±0.69)	1.03	
2b	HS	*	–	–	–	–
	LR		–	–	–	
3a	HS	10	1.12	4.63 (±0.33)	0.50	14.3
	LR		6.31	5.65 (±0.79)	0.52	
3b	HS	9	0.26	3.31 (±0.17)	6.02	11.1
	LR		4.81	5.88 (±0.73)	0.32	
4a	HS	6	0.08	2.02 (±0.12)	12.86	4.0
	LR		0.02	1.41 (±0.05)	5.98	
5a	HS	5	3.30	1.72 (±0.81)	3.72	5.8
	LR		0.92	2.14 (±0.43)	4.50	
5b	HS	8	0.42	2.36 (±0.23)	8.34	8.5
	LR		3.24	6.03 (±0.63)	0.21	
6a	HS	9	0.34	3.65 (±0.19)	4.37	13.1
	LR		4.04	5.87 (±0.67)	0.35	

Notes: σ^2 – variance; $\overline{x} \pm m$ – arithmetic mean ± standard error; *t*-test – Student's *t*-test value; pcs – numbers of germinated seeds (pieces); HS – heights of sprouts; LR – lengths of roots; * seeds did not germinate.

Tables 6. Arithmetic means of plant heights and root lengths, their errors, and their variances for each soil sample; test object – common wheat (*Triticum aestivum* L.)

Variant	Indicator [cm]	*Triticum aestivum* L.				
		Plant germination [pcs]	Dispersion, σ^2	Mean, $\overline{x} \pm m$	*t*-test	Dry sprout weight [mg]
Monitoring	HS	10	1.82	8.70 (±0.42)	–	77.4
	LR		8.06	14.95 (±0.89)	–	
1a	HS	9	4.53	8.18 (±0.71)	0.37	66.7
	LR		8.78	12.65 (±0.98)	5.47	
1b	HS	10	0.03	0.68 (±0.06)	18.49	20.1
	LR		0.05	0.95 (±0.07)	15.64	
2a	HS	9	7.63	4.82 (±0.92)	3.62	44.1
	LR		6.89	8.70 (±0.87)	4.98	
2b	HS	10	0.0025	0.15 (±0.015)	19.52	8.4
	LR		0.0002	0.105 (±0.004)	16.53	
3a	HS	10	3.40	7.73 (±0.58)	1.06	66.4
	LR		4.89	14.14 (±0.69)	0.71	
3b	HS	7	1.82	1.84 (±0.51)	10.01	15.2
	LR		5.94	6.75 (±0.92)	6.36	
4a	HS	10	0.94	8.33 (±0.31)	0.32	65.9
	LR		0.98	14.75 (±0.31)	0.21	
5a	HS	10	1.26	0.90 (±0.35)	13.67	19.7
	LR		1.32	3.74 (±0.36)	11.57	
5b	HS	10	2.97	4.95 (±0.54)	5.12	50.3
	LR		4.71	8.82 (±0.68)	5.42	
6a	HS	10	0.88	7.50 (±0.29)	1.92	66.3
	LR		4.76	14.87 (±0.69)	0.07	

Notes: HS – heights of sprouts; LR – lengths of roots.

Based on the measurements, the phytotoxic effect could be calculated (Figs. 2, 3); we also calculated the average phytotoxic effect for the selected soil samples. From these, it followed that the maximum phytotoxic effects of the *Lepidium sativum* L. test crop could be observed at Point 2b (100%), high levels of toxicity could be observed at Points 1b (70.44%), 4a (70.26%), and 5a (64.73%), and no (or low) levels of toxicity could be observed in Samples 1a (17.01%), 2a (16.67%), 6a (16.44%), and 3a (8.37%). The maximum phytotoxic effects in the *Triticum aestivum* L. test crop could be found in the soils from Points 2b (95.56%) and 1b (86.61%), high levels of toxicity could be observed at Points 5a (79.72%) and 3b (71.35%), and no (or low) toxicity levels could be found in Soil Samples 1a (11.72%), 3a (10.26%), 4a (6.81%), and 6a (9.55%). Based on these results, it could be concluded that the most contaminated soil samples were those from Points 2b, 1b, 5a, and 3b, and the least phytotoxic effects could be observed in Samples 1a, 6a, and 3a.

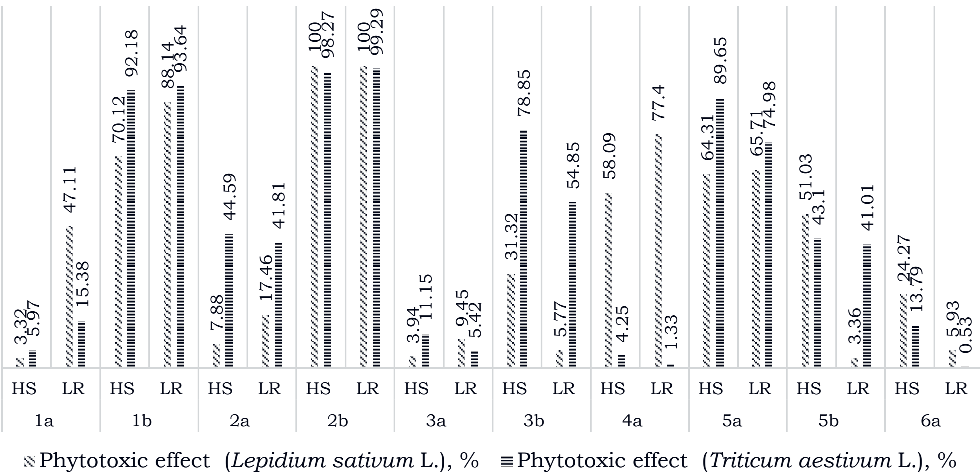

Fig. 2. Phytotoxic effects by sprout height (HS) and root length (LR) [%]

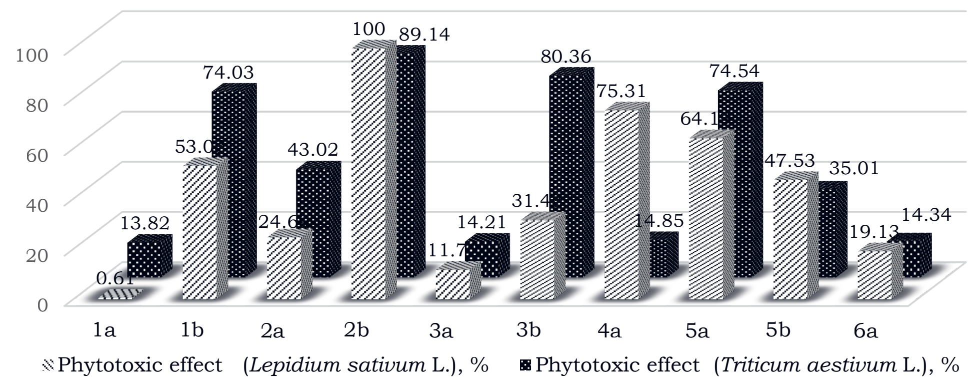

Fig. 3. Phytotoxic effect by dry weights of seedlings [%]

Significant differences in the growths of the test objects in Sample 4a should be noted, as the average phytotoxic effects were 70.26% in the case of the *Lepidium sativum* L. test culture and 6.81% with *Triticum aestivum* L. This may have been due to the fact that the soil was sandy, low contents of biogenic elements could be detected, and the individual sensitivities of the test objects were high regarding their contents.

Based on the biotesting, it could be concluded that the most contaminated soils were those from Points 2b, 1b, 5a, and 3b; this fully confirmed the results that were obtained by studying the elements in the soil via X-ray fluorescence analysis. The lowest phytotoxic effects could be observed in Samples 3a, 1a, and 6a due to the low contents (or absence) of pollutants in the soil samples (see Section 3.1).

3.3. Statistical Analysis of Experimental Data

According to the results of the factor analysis by the principal components method, the distribution of the features of the geochemical and environmental parameters was obtained in the fields of Factors F1–F2 (Fig. 4).

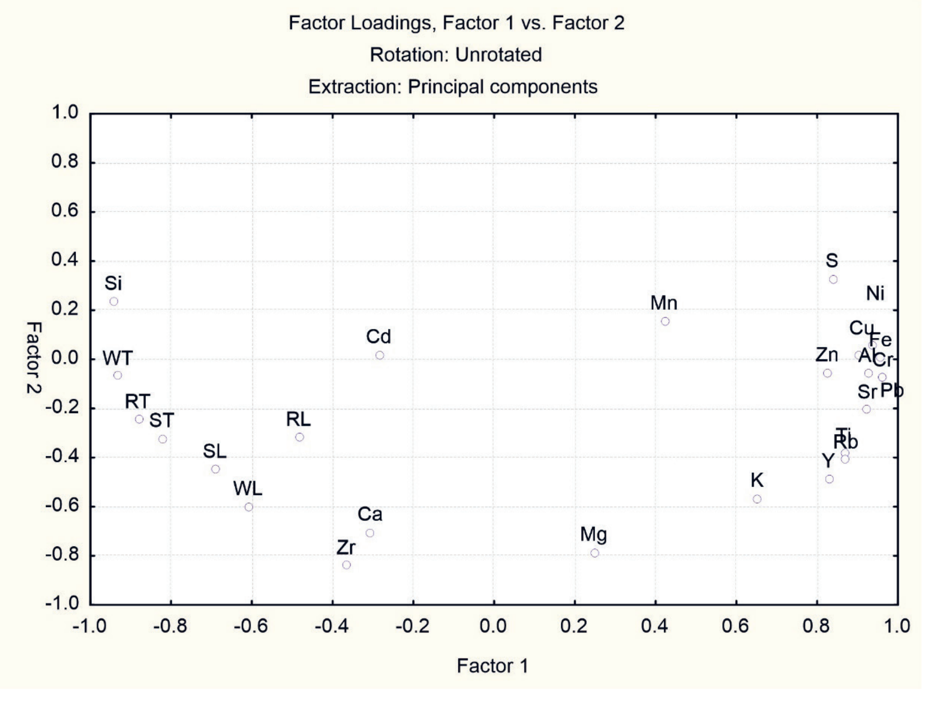

Fig. 4. Overview of factor analysis for all obtained biological and geochemical variables, where WT was weight of dry sprout of *Triticum aestivum* L.: RT – length of root of *Triticum aestivum* L., ST – height of sprout of *Triticum aestivum* L., SL – height of sprout of *Lepidium sativum* L., WL – weight of dry sprout of *Lepidium sativum* L., RL – length of root of *Lepidium sativum* L.

In the field of Factor F1, two statistically significant associations of indicators could be clearly distinguished. The positive part of the F1 factor concentrated on most of the chemical elements that can be found in soils (Al, S, Ti, Cr, Fe, Ni, Cu, Zn, Rb, Sr, Y, and Pb); we denoted this association of chemical elements as Association 1. In the negative part of the F2 factor, we distinguished Association 2 – a group of biological indicators (ST, RT, and WT) plus silicon, which is a rock-forming chemical element that dominates all rock elements. Other biological indicators (SL and WL) also tend toward this association; that is, the higher the concentration of chemical elements of Association 1, the lower the sprout height, root length, and weight of *Triticum aestivum* L. The germination parameters of *Lepidium sativum* L. (SL, RL, WL) tended toward Association 2 but did not reach statistical significance; therefore, their reliability as ecological indicators for soils of this type is lower.

In the field of Factor F2, a statistically significant association of chemical elements (Mg, Ca, Zr) could be identified in the negative part. Magnesium and calcium are typical representatives of carbonate minerals: calcite ($CaCO_3$), and dolomite ($MgCaCO_3$). Together with calcium, zirconium is included in the silicates (eudialyte, vlasovite, and gittinsite); this can form carbonate-containing zirconium hydroxide and is included in the carbonates as an isomorphic impurity [48–50]. Although the WL index shows a weak tendency toward this association, this tendency has not been statistically confirmed; therefore, any conclusions regarding the WL index should be treated as being hypothetical and requiring further verification. According to the results of our research, such a relationship was not statistically proven; this created ideas and a field for future research.

For the ecological assessments of the states of soils in mining areas, it is worth using indicators of the sprout height, root length, and weight of *Triticum aestivum* L. The effect of metal pollution on the growth of *Lepidium sativum* L. has not been statistically proven.

Using the factor score coefficients, we identified the metals that contributed most to the formation of the F1 factor: Pb, Cr, Fe, and Ni. This allowed us to substantiate a set of metals for establishing relationships with sets of effective growth indicators of *Triticum aestivum* L. (ST, RT, and WT) and *Lepidium sativum* L. (AL, SL, and WL) using the canonical correlation analysis. According to the results of the canonical correlation analysis (Table 7), the conclusions that were drawn from the results of the factor analysis were confirmed.

Table 7. Results of canonical correlation analysis of sets of indicators of phytoindication and heavy metals in soils that were formed on dumps of coal-processing plant

Groups of variables	Canonical *R*	Canonical R^2	Chi-sqr.	*df*	*p*	Lambda Prime
ST, RT, WT – Pb, Cr, Fe, Ni	0.942	0.886	24,439	12	0.0178	0.017
SL, RL, WL – Pb, Cr, Fe, Ni	0.913	0.834	11,520	12	0.485	0.147

Notes: For second group (SL, RL, WL – Pb, Cr, Fe, Ni), *p*-value was above 0.05 significance threshold, thus indicating that observed correlation was not statistically significant despite high canonical *R*. Explanations: canonical *R* – canonical correlation coefficient; canonical R^2 – squared canonical correlation; Chi-sqr. – chi-square statistic; *df* – degrees of freedom associated with chi-square test; *p* – *p*-value, indicating significance level of canonical correlation; Lambda Prime – Wilks' lambda, multivariate test statistic.

The canonical correlation coefficient (canonical R) indicates the strength of the relationship between two sets of variables. The values of canonical R between both sets of variables (0.942, 0.913) were very high, thus indicating a strong correlation between the sets of variables.

The canonical R^2 value shows the percentage of the variation in the dependent variables that can be explained by the independent variables. The R^2 – of ST, RT, WT – Pb, Cr, Fe, Ni (0.886) was slightly higher than the R^2 – of SL, RL, WL – Pb, Cr, Fe, Ni (0.834); this indicated that the first set of indicators had a slightly higher explanatory power as compared to the second set. Meanwhile, the values of both indicators were very high; however, it is important to emphasize that a high canonical correlation coefficient (canonical R) alone is insufficient for drawing reliable conclusions if the corresponding p-value does not reach statistical significance. A non-significant p-value indicates that the observed relationship may be due to random variations or multicollinearity in the data, and the model's explanatory power in this case should be interpreted with caution. The p-value indicates the probability that the observed results could be obtained if the null hypothesis were true. In this study, the results for the ST, RT, WT – Pb, Cr, Fe, Ni group were statistically reliable, as the $p < 0.05$ condition was met. This meant there was less than a 5% chance that the observed strong relationship occurred by chance. In the AL, SL, WL – Pb, Cr, Fe, Ni group of variables, the p-value was significantly higher than 0.05, which meant that the results of the canonical correlation analysis for this group were not statistically significant at the selected significance level ($p < 0.05$). It should be noted that the second canonical function showed a large p-value ($p > 0.05$) despite its high canonical correlation. This suggested that the result may have been due to chance or multicollinearity. Therefore, further studies with larger sample sizes and repeated experiments are recommended to confirm this relationship.

In addition, Lambda Prime (λ') is a statistical indicator that is used in canonical correlation analysis to assess the overall fit of a model to data. Lambda Prime shows the proportion of the variance that is not explained by the model; therefore, a smaller λ' value indicates a better fit of the model to the data. It also serves as a generalized test of the statistical significance of all of the canonical functions taken together. The Lambda Prime for the second group of variables was higher than for the first, thus indicating a weaker correlation and lower model fit to the data. At the same time, the results of our research indicated that the use of *Lepidium sativum* L. as a bioindicator remained a subject of further investigation due to its high canonical correlation values and potential selectivity. Therefore, more-extensive research should be conducted to identify its advantages, limitations, and optimal application conditions. It should be emphasized that, although the WL index shows some tendency toward a possible relationship with the concentrations of heavy metals, this observation was not statistically confirmed in this study. Therefore, any conclusions that were based on the WL index should be regarded as hypothetical and should be tested in future studies using larger data sets.

4. Discussion

The integration of principal components analysis (PCA) and canonical correlation analysis (CCA) allowed for a rigorous validation of plant-based indicators in our technogenically altered soils. PCA revealed two main groups: one that was dominated by metals (F1), and the other by plant traits and carbonate elements (F2); this guided the selection of the indicator parameters. By isolating these latent structures, PCA guided our selection of the four-most-contributory metals (Pb, Cr, Fe, and Ni) and two bioindicator suites (wheat parameters vs. cress parameters) for the subsequent CCA. This two-step approach ensured that the CCA focused on the most informative variable combinations rather than all raw measurements, thus reducing the noise from weak or redundant variables.

The canonical correlation analysis quantified the strengths of the relationships between the soils' metal contents and the plant responses. For *Triticum aestivum* L. (ST, RT, WT), a strong and statistically significant canonical correlation could be observed ($R = 0.942$, $p = 0.0178$); this confirmed its value as a reliable bioindicator. In contrast, the correlation for *Lepidium sativum* L. (SL, WL, RL) was also high ($R = 0.913$), but it was not statistically significant ($p = 0.485$); this indicated that its apparent sensitivity may have been affected by variability or other uncontrolled factors. This may have been partially attributed to the known sensitivity of *Lepidium sativum* L. to soil pH and abiotic stress factors [51].

Neither the germination rates of *Triticum aestivum* L. nor the root lengths of *Lepidium sativum* L. showed significant sensitivities to heavy metal contamination. This suggested that these variables were either too stable to reflect subtle toxic effects or were influenced by other confounding soil factors, thus making them unreliable for metal-specific bioindication in technogenic environments.

One exception was Sample 4a, where *Lepidium sativum* L. exhibited high phytotoxicity (PE ≈ 70%), while *Triticum aestivum* L. remained largely unaffected (PE ≈ 6.8%). This anomaly likely reflected site-specific soil conditions – such as low nutrient content and sandy texture – that impaired the cress growth independently from the metal toxicity.

As was shown in Section 3.1, the sulfur concentrations exceeded 26,000 mg/kg in several samples; this likely contributed to acidification and enhanced heavy metal mobility. Sulfur-driven acidification is well-documented in enhancing heavy metal solubility and mobility, thus leading to phytotoxicity and biomass suppression in both above- and belowground plant tissues [52]. Although magnesium is an essential nutrient, excessive Mg can interfere with calcium uptake and modulate metal–plant interactions [53]. In our study, those samples with high Mg and S contents exhibited disproportionately strong phytotoxic effects that were relative to the metal concentrations alone, thus indicating that the nutrient imbalance coupled with the acidification likely amplified the contaminant stress in the coal-affected soils.

Although not statistically confirmed in this study, the observed tendency of the WL index to align with the carbonate-associated elements (Mg, Ca, and Zr) suggested a potential physiological response to the soil-buffering capacity. Further investigation is warranted to assess whether *Lepidium sativum* L.'s dry biomass could reflect the carbonate-related modulation of stress factors in technogenic soils. Such non-specific reactivity may compromise its selectivity as a metal-specific indicator – especially in technogenically altered acidic soils.

Thus, PCA and CCA acted synergistically: PCA uncovered the dominant contamination and plant-response patterns, while CCA rigorously tested and quantified those patterns' predictive power. This combined framework provides a clear data-driven path to select and validate bioindicators in complex multivariate environmental data sets.

The canonical correlation analysis revealed that certain plant-growth parameters were strongly associated with the soils' heavy metal levels, thus indicating their potentials as bioindicators in coal-dump environments. In particular, the *Lepidium sativum* L. (garden cress) metrics (e.g., seedling/shoot length and biomass) showed strong correlations with heavy metal concentrations. While the *Triticum aestivum* L. (wheat) parameters were statistically reliable in our study, their sensitivity to individual metals may be lower; this has been supported by phytotoxicity studies, Bożym and Rybak [51] demonstrated that *L. sativum* L. root and shoot growths were strongly inhibited by metals like Se, As, and Hg and even stimulated by Pb. By contrast, Rashid et al. [54] noted that wheat tolerated high Cd levels and could serve as Cd indicators, thus implying that *Triticum aestivum* L.'s utility may be limited to specific metals.

Lepidium sativum L. is strongly sensitive to heavy metals and correlated with the soils' metal levels in our CCA; this is consistent with its known phytotoxic response [51].

Triticum aestivum L. tolerates some metals (e.g., Cd), and it showed weaker canonical correlations in our data; this suggested limited sensitivity [54].

Our findings echoed recent bioindicator surveys; for example, Cakaj et al. [55] found that common weeds varied in their metal uptakes (e.g., *Plantago lanceolata* L. contained very high levels of Zn and Cd, while *Lolium* spp. had high Ni levels in its roots) under controlled metal exposure. This variation underscored the need to choose one's indicators carefully.

The use of canonical correlation analysis (CCA) was pivotal for uncovering these multivariate relationships. CCA simultaneously links sets of plant and soil variables and identifies which combinations co-vary most strongly. This approach goes beyond simple pair-wise correlations by revealing collective patterns. Multivariate analyses have proven to be valuable in related environmental studies [56]. In our case, CCA highlighted that *L. sativum* L.'s shoot/root parameters and certain metal groups formed a strong canonical axis, thus guiding us to the most reliable biological markers. Thus, CCA offers practical applied value: it distills complex data into clear bioindicator signals that can inform monitoring strategies. For instance, Kučer et al. [57] used canonical-like analyses in coal-spoil contexts to show how topsoil metals decreased with increased distances from spoil tips, pointing to specific metals (e.g., Pb) that tend to migrate and, ergo, should be monitored. Similarly, our CCA isolated which plant traits best reflected contamination in coal-derived soils. Comparisons with other recent studies reinforced and contextualized our results. Studies in coal-mining areas have reported similar metal profiles and plant responses. Zhu et al. [58] found that soils near a Chinese coal mine contained elevated Ni, As, Cr, Cu, Pb, Cd, and Zn levels (above the regional background levels). Lu et al. [59] reported an extremely high pollution index (especially Hg, Cd, Co, and Ni) in the soils of a Gansu coal mine and identified native wild plants that hyperaccumulated these metals. Zhang et al. [60] studied the soils around a coal-gangue dump in Southwest China and found moderate-to-high Cu and Cd contamination (with significant health risks also being identified for local communities). These findings paralleled our context: coal-basin soils often contain multiple heavy metals at elevated levels. Unlike typical agricultural soils, coal dumps can include unusual contaminants (e.g., mercury, nickel) as well as highly acidic conditions. Kučer et al. [57] noted that the Donbas coal spoil contained abundant pyritic minerals, so the pyrite oxidation and erosion led to toxic substances and metal mobilization. While the exact metal mixes varied, a common theme was that coal-derived soils posed complex contamination challenges; our results fit this pattern of multi-element stress.

Taken together, the results of the multivariate statistical analysis clearly indicated that the shoot height (ST), root length (RT), and dry biomass (WT) of *Triticum aestivum* L. were statistically validated and ecologically meaningful indicators of soil contamination with heavy metals (particularly, Pb, Cr, Fe, and Ni). In contrast, the corresponding parameters for *Lepidium sativum* L. showed high but statistically unreliable correlations, while the germination and root length proved to be insensitive to the contamination levels. Therefore, *T. aestivum* L.'s growth parameters should be prioritized in future phytomonitoring strategies for coal-affected soils, with *L. sativum* L. being used with caution or only for exploratory purposes under controlled conditions.

Despite these findings, several limitations of the present study should be acknowledged in order to contextualize the conclusions and guide future research efforts. This study's scope was limited by its sample size (a single region with two plant species) and by focusing on morphological traits. Future work should expand to more indicator species (e.g., known metal accumulators or native flora) and include biochemical markers (e.g., stress enzymes, metallothioneins) to corroborate plant stress. Incorporating soil physicochemical factors into the analysis (pH, organic matter, etc.) would refine the understanding of metal bioavailability and plant uptake. Longitudinal sampling could reveal seasonal dynamics of uptake. Lastly, validating these markers in other coal-dump sites would test their generality. Since

Lu et al. [59] emphasized the potential of native hyperaccumulators for remediation, parallel studies might explore the use of identified bioindicator species for phytostabilization or remediation. In all, our CCA-driven approach provided a foundation; however, broader surveys and experimental validations will be needed to fully establish reliable bioindicators.

5. Conclusions

According to the results of our soil studies in the impact zone of the Chervonogradska CPP spoil tip, the maximum-permissible-concentration limits for a soil's sulfur content were exceeded by up to 163.1 times, lead – 3.98 times, and manganese – 1.3 times. There were also distinct excesses of the contents of the studied elements in relation to the clarke (times): Ti – 2.39, Sr – 3.73, Cr – 5.79, Zn – 7.57, Fe – 10.56, Ni – 13.09, and Cu – 33.26. It was found that environmental acidification enhanced the mobility of heavy metals, thus facilitating their entry into the biological cycle. The land plots in the area of the Chervonogradska CPP waste heap were depleted by technogenic processes and may be adversely affecting the natural flora and fauna in the area of the waste heap.

Based on the results of the statistical procedures, two statistically significant associations of indicators were identified by factor analysis: the contents of Al, S, Ti, Cr, Fe, Ni, Cu, Zn, Rb, Sr, Y, and Pb (Factor 1); the growth parameters of *Triticum aestivum* L. (ST, RT, WT); and the Si content (Factor 2). The established associations contributed to the understanding of the processes of metal accumulation and dispersion in the soil and their impact on the phytocoenocenotic parameters of the ecological and geochemical system. The results of the factor analysis and canonical correlation analysis proved the reliability of the use of the sprout height, root length, and dry sprout weight of *Triticum aestivum* L. as indicators of soil pollution by heavy metals in the soils of coal mining areas. The effectiveness of *Lepidium sativum* L. as an indicator of pollution requires further research. Neither the germination rates of *Triticum aestivum* L. nor the root lengths of *Lepidium sativum* L. showed sensitivity to heavy metal concentrations in the soils that were affected by the coal-preparation plant's spoil tip.

The results of the research can be used to assess the ecological state of soils and damage from coal mining, build waste-management systems for coal mines, reclaim degraded areas, and develop schemes for the phytostabilization of degraded landscapes. Future research should integrate remote-sensing data with ground-based geostatistical models to improve prediction accuracy for contamination spread. Additionally, the implementation of phytoremediation techniques that are tailored to the specific heavy metal loads that have been identified should be further explored in order to mitigate environmental impacts.

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CRediT Author Contribution

I. K.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision.

V. K.: methodology, software, validation, formal analysis, investigation, data curation, writing – review and editing, visualization, supervision.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests nor personal relationships that could have appeared to influence the work that is reported in this paper.

Data Availability

The original contributions that were presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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