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Geoecological aspects of chemical element migration in soils of the waste heap impact zone at the Bogdanka Mine, Lublin Coal Basin

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Abstract

Purpose. This research aims to explore the peculiarities of chemical soil pollution and analyse the patterns of chemical element migration in the waste heap impact zone of the Bogdanka Mine in the Lublin Coal Basin compared to the control area. To achieve the purpose set, soil samples were taken from various ecotopes at depths of 0-5, 5-10, and 10-15 cm, the ecological state of the territories was assessed, and a statistical analysis of the chemical element content was performed.

Methods. The research was based on methods of statistical data processing, correlation and cluster analysis, multidimensional ecotope ordination using Principal Component Analysis (PCA) and canonical discriminant analysis. Sampling was conducted in accordance with the ISO 10381-8:2006 standard. Analytical determinations of elemental composition were performed using X-ray fluorescence spectrometry on an ElvaX Light SDD device.

Findings. Significant spatial heterogeneity in the distribution of macro- and microelements in soils of the waste heap impact zone has been identified. Increased concentrations of Mg, Al, S, K, Ti, V, Fe, Ni, Cu, Zn, Sr, Y, and Pb were recorded at the foot of the waste heap. The maximum values of individual elements are typical for specific ecotopes, in particular Mn and Zr for coastal and forest areas. The highest exceedance of maximum permissible concentrations was found for Cu, Ni, and Zn (up to 22.3, 20.1, and 30 times, respectively).

Originality. The scientific novelty of the research consists in determining the spatial gradients of chemical soil pollution in the impact zone of coalmine waste heap based on multidimensional ordination of ecotopes. 2D graphic visualization of geochemical indicators, the axes of which are chemical element concentrations or integral gradients of the environment, provides a clear representation of the migration processes of elements in soils of various ecotopes.

Practical implications. The practical significance of the results obtained lies in the possibility of using the identified patterns of chemical element distribution to assess the level of soil pollution in the impact zone of the waste rock dump. The data obtained can be used to predict local changes in soil cover quality and to substantiate measures to reduce the negative impact of heavy metals on the soil environment of adjacent territories.

Keywords: *waste rock dump; mine waste heap; chemical pollution; complex environmental gradient; environmental safety; human health*

1. Introduction

The mining industry plays a key role in ensuring raw material security, the development of industry and the energy sector in most countries around the world. It is an integral component of economic development, but it is accompanied by the formation of complex production infrastructure and significant technogenic environmental impacts. Modern research in the field of mining covers not only direct mining technologies, but also issues of safety of mining transport systems, energy efficiency of production, use of digital and information technologies for monitoring and managing processes, as well as aspects of innovative development of the industry [1]-[4]. In particular, attention is paid to controlling technogenic risks at mining infrastructure facilities, improving energy-efficient technologies, and applying modern visualization methods, remote sensing, and automated observation systems to analyse the state of production and natural components of mining areas [5]-[8].

In turn, waste rock dumps of coal mines are an indispensable component of the mining industry. Almost all countries in the world face problems of placement, processing and utilization of waste rock mass [9], [10]. There is often an increase in background radiation level in the impact zone of coalmine waste dumps [11]. Developed countries have long since reformed or eliminated their waste rock dumps [12]-[14]. This phenomenon is also characteristic of countries

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with a small land area [15]. In many countries around the world, waste rock dumps are reclaimed [16]. In countries with insufficient financing of the mining industry, waste rock dumps are left untouched and subjected to natural self-growth in order to reduce environmental burden [16]-[20]. Such waste rock dumps often burn [21]-[23], causing secondary technogenic environmental pollution from the mining industry and adversely affecting human health [24]-[27]. This causes chronic diseases in humans, particularly of the endocrine system [28], [29] and the gastrointestinal tract [30].

As a result of the functioning of waste rock dumps, surface and underground water bodies, air, and soils are polluted [31]-[34]. In the world, many scientific works are devoted to various and diverse studies of waste rock dumps, in particular, mathematical modelling of the spread of pollutants [35].

In addition to direct environmental pollution, coalmine waste rock dumps are regarded as complex technogenic facilities requiring systematic management and long-term monitoring. Scientific research emphasizes the need for an integrated approach to ensuring the sustainability of such facilities, which includes analysis of their spatial structure, technical state and environmental risks [36]. To solve these problems, geoinformation systems and 3D modelling are increasingly used, allowing for detailed assessment of the geometry of waste dumps, the specifics of their formation, and potential hazard zones [37]. Some studies show that physical-chemical processes in technogenic masses, particularly in the conditions of activated and oxidizing solutions, significantly affect the migration of chemical elements and may increase their entry into the soil and aquatic environment [38], [39].

An important area of current research is also the search for ways to reduce the negative impact of dump mass by reusing it or processing it technologically. Interactive 3D models are used to visually represent the spatial structure of technogenic facilities and the results of environmental studies, facilitating data interpretation and the identification of potential environmental hazard zones [40]. In particular, the prospects of involving waste from the fuel and energy complex as secondary raw materials for the production of building and thermal insulation materials are shown, which allows simultaneously reducing the area of waste dumps and the environmental impact on the surrounding ecosystem [41]. At the same time, in the context of sustainable development and rehabilitation of disturbed areas, increasing attention is paid to the ecosystem approach and legal aspects of environmental protection activities, particularly in terms of reclamation and ecological rehabilitation of technogenically-transformed landscapes [42]. The effectiveness of environmental monitoring of technogenic territories is improved through the use of automated information systems, spatial analysis methods, and algorithms for processing large data sets, which provides a more reasonable assessment of the geological environment state [43]-[45].

To date, a typology of impacts resulting from ore mining and waste disposal in coal-mining regions has been successfully developed based on five indicators: air pollution, fire hazard, soil deformation, water pollution and depletion of water resources. The application of this developed typology is illustrated in the case of the Shilbottle Coal Basin (Northumberland, Great Britain) [46]. Research finding [46] indicate that mining activities have the greatest impact on air, soil, water, topography, and vegetation quality. There are two main approaches to the problem of assessing the susceptibility of mining waste to spontaneous combustion. The first relies on so-called expert methods, consisting in assessing fire hazards based on a number of criteria specific to the particular location and the nature of waste stored there. The second approach is based on experimental methods, with which the tendency of waste to spontaneous combustion is assessed through testing or observation of mining waste on installations or research benches under laboratory conditions [47]. Study [48] examines the self-heating mechanism, self-ignition zones, various factors affecting self-heating, and various experimental studies for predicting its occurrence.

An extremely dangerous phenomenon associated with waste rock dumps is the presence of arsenic in their composition. In particular, the total arsenic concentration in samples from the Los Rueldos mercury mine dump (Spain) ranges from 4746 to 62196 mg/kg. Pb and Zn are present in average concentrations of 3680 and 45 mg/kg, respectively. The filtrate from this dump goes to the El Batán coal dump along with acidic effluents from the old underground workings of the Los Rueldos mine, which has a very low pH (2.5), with a content of up to 2900 mg^{-1} SO_4 and from 5.3 to 8.3 mg^{-1} As [50]. The concentration of As in waste samples from the surface of the dump reaches a maximum value of 72153 mg/kg, and the average value is 15967 mg/kg; analysis of deeper samples (trenches on the waste rock dump) exceeds 99999 mg/kg. The total flow of polluted water from its circulation through the dump is estimated at 3465 m^3/hour.

Weathering processes facilitate the dissolution and leaching of As and heavy metals in ore and waste [51]. The arsenic content in surface waters (San Tirso River) immediately downstream from the dump reaches 7.9 mg/l [51]. It has been found that arsenic is effectively removed from drained solutions by adsorption onto soil particles, with the final effect that arsenic concentrations in groundwater do not rise above baseline levels. The drainage rate measured for the Daisy Dump (Nevada) continues to decline each year, and is approaching steady state conditions [53].

Thus, the issue of geoecological aspects of chemical element migration in soils of the impact zones of a mine waste heap requires comprehensive research to study the impact on human health in mining regions.

The purpose of this research is to explore the peculiarities of chemical soil pollution and to analyse general trends in the spread of chemical elements, in comparison with the control area, within the impact zone of the Bogdanka Mine waste heap in the Lublin Coal Basin. According to the purpose, the main tasks are set: sampling of soil substrates in the waste heap impact zone (depths are 5, 10, 15 cm), assessment of the ecological state of the test sites, transfer of samples to the laboratory for studying the content of chemical elements in the samples, statistical analysis of the identified chemical element concentrations.

2. Methods

The research uses the following methods: statistical processing of soil chemical pollution parameters; Data Mining method; correlation analysis; assessment of ecotope similarity and grouping of chemical elements based on cluster analysis; multidimensional ordination of ecotopes in the space of geochemical indicators based on Principle Component Analysis and Canonical Discriminant Analysis.

Sampling was performed in accordance with ISO 10381-8:2006 Soil quality. Sampling. Part 8: Guidance on sampling of stockpiles. The samples for analysis were prepared at the Scientific Research Laboratory for Environmental Safety at Lviv State University of Life Safety. The selected samples were analyzed in the laboratory of Lviv Polytechnic National University using an ElvaX Light SDD spectrometer.

The level of chemical soil pollution in the waste heap impact zone was assessed using indicators developed based on geochemical and hygienic studies of the environment. These indicators include concentration coefficient *Kc*, total pollution index *Zc*, soil pollution index [54].

The concentration coefficient Kc is determined as the ratio of the actual content of a chemical substance *C* (mg/kg) to its maximum permissible concentration C_{MPK} or background concentration value C_{BV}:

$$Kc_i = \frac{C_i}{C_{MPKi}}; \tag{1}$$

$$Kc_i = \frac{C_i}{C_{BVi}}, \tag{2}$$

where:

i – sequence number of the chemical element.

Background concentration values of chemical elements were determined based on analysis of literature sources on background content of microelements.

The soil pollution index (*PI*) is determined as the arithmetic mean of the concentration coefficient *Kc*:

$$PI = \frac{\sum_{1}^{n} Kc_i}{n}, \tag{3}$$

where:

n – number of chemical elements.

Total pollution index *Zc* is expressed by the formula:

$$Zc = \sum_{1}^{m} Kc_i - (m-1), \tag{4}$$

where:

m – number of concentration coefficients exceeding 1.

For the total pollution index *Zc*, the following pollution categories were determined empirically [55]: permissible – $Zc < 16$; moderately hazardous – $Zc = 16\text{-}32$; hazardous – $Zc = 32\text{-}128$; extremely hazardous – $Zc > 128$.

Standardized values for chemical element concentrations were calculated using the formula:

$$z_i = \frac{(x_i - M)}{\sigma}, \tag{5}$$

were:

z_i – standardized value of chemical element concentration in soil;

x_i – actual chemical element concentration;

M – arithmetic mean value;

σ – standard deviation.

Peculiarities of the spatial chemical element distribution in the waste heap impact zone were studied using Data Mining method [56]. The research involved three main stages: studying the structure of the mutual arrangement of elementary sections in a multidimensional space of chemical element content characteristics, mathematical modelling of the structure and verification of the mathematical model. The geochemical information is based on data on the concentration of 18 chemical elements (Mg, Al, Si, P, S, K, Ca, Ti, Fe, Y, Zr, Cu, Zn, Pb, Ni, V, Mn, Sr) in the soil at six sites within the waste heap impact zone (Table 1).

Table 1. Ecological characteristics of the test sites

No.	Sample numbers/ sampling depth	Coordinates	Brief description
I	1 – 5 cm 2 – 10 cm 3 – 15 cm	51.31778575688911, 23.012731096861867	The site is located on the eastern side of the waste heap. Natural soil, dominated by ruderal vegetation, mainly cereal vegetation.
II	4 – 5 cm 5 – 10 cm 6 – 15 cm	51.31762042405169, 23.011931307755727	The site is located on the eastern side of the waste heap at a distance of 30 m from the No. 1 site. Natural soil, dominated by tree-shrub vegetation.
III	7 – 5 cm 8 – 10 cm 9 – 15 cm	51.31320207046712, 23.01540194199676	The site is located on the southeastern side of the waste heap. Remediated, based on crushed stone and bulk soil mixtures. Grassy vegetation, artificially sown.
IV	10 – 5 cm 11 – 10 cm 12 – 15 cm	51.31339527691599, 23.015279852293546	The site is located on the southeastern side of the waste heap, 30 m from the No. 3 site. Remediated, based on crushed stone and bulk soil mixtures. Grassy vegetation, artificially sown. It is the bank of a drainage ditch.
V	13 – 5 cm 14 – 10 cm 15 – 15 cm	51.314226521259755, 22.979188081936005	The site is located on the western side of the waste heap, approximately 1000 m away. Remediated, based on bulk soil mixtures. Birch forest and grass vegetation, artificially sown.
VI	16 – 5 cm 17 – 10 cm 18 – 15 cm	51.27510718029608, 22.957167448517048	The site is located on the southern side of the waste heap at a distance of approximately 4000 m. Pine forest. Natural soil. Forest vegetation.

Mathematical modelling was performed by identifying systematic relationships between the chemical element concentrations. Each site can be represented as a point in a multidimensional space of characteristics, the coordinates of which correspond to chemical element concentrations. In this case, the similarity of sites in terms of a combination of ecological parameters of environmental pollution can be determined based on the distances between points. The essence of the subsequent mathematical procedure is to identify the axes of maximum variation, determine their number, and evaluate the contribution of each chemical element to the variation based on principal component analysis [57].

The differences between ecotope parameters in the waste heap impact zone were assessed using variance analysis. The construction of a typological scheme of mine ecotopes and graphical visualization of the mathematical modeling results were based on canonical discriminant analysis. The mathematical model was verified based on a comparative assessment of the position of sites on the axes of maximum variation (multidimensional ordination) with the results of soil and vegetation cover studies [58].

The Bogdanka coal mine (Lubelski Węgiel "Bogdanka" SA) is located in the Lublin Coal Basin in the village of Bogdanka near Łęczna, close to Lublin and 197 km south-east of Warsaw. The Bogdanka Mine is administratively located in the Lublin Province, in the Puchaczów municipality. It is the only coal mine in the Lublin Coal Basin. The Lublin Upland, centred around the Lublin Coal Basin, has one of the most valuable natural environments in Poland (Fig. 1).

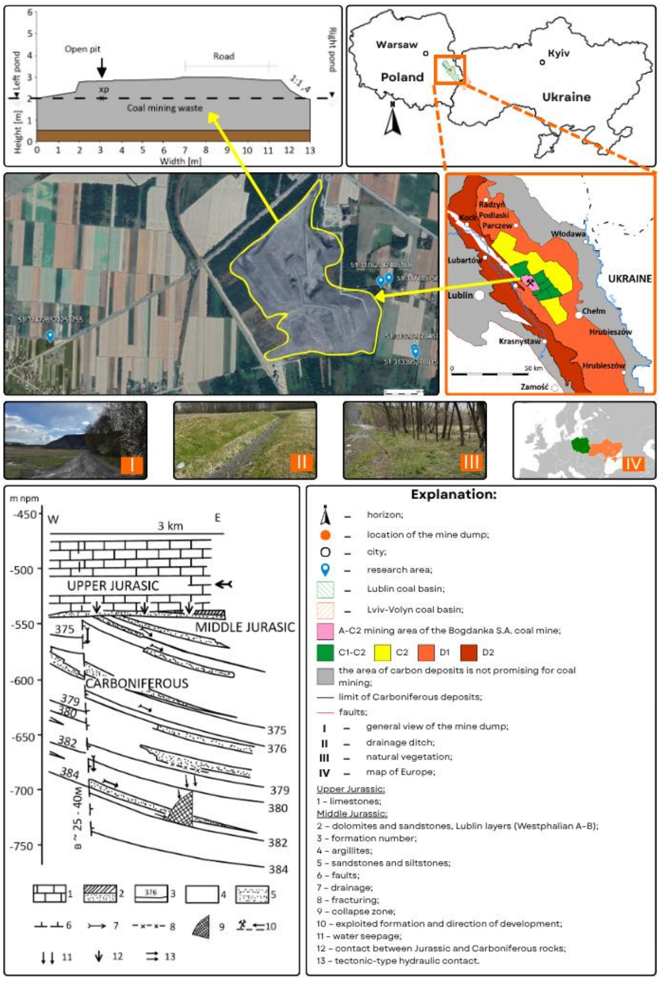


Figure 1. Layout of test sites in the impact zone of the Bogdanka mine waste heap (developed using data available in scientific publications) [59]-[61]

There are nature reserves, Polissya National Park and Natura 2000 territory operating in the mine impact zone. The process of intensive hard coal mining leads to surface subsidence, which is irreversible [62]. Mining coal reserves in the Lublin Basin amount to approximately 243 million tons. The mining depth ranges from 860 to 1100 m. The total sulphur content in the seams averages 1.27% in seam 382 and 0.99% in seam 385/2. The total sulphur content in the studied zone ranges from 0.82 to 2.16% in seam 382 and from 0.58 to 1.83% in seam 385/2 [63]. The study [64] shows significant differences within individual seams and the relationship between mercury and iron sulphides. High variability in mercury content indicates local areas of beneficiation, possibly related to tectonic phenomena. The characteristic peculiarities of quantitative variation in these coal seams may correlate with changes in glacial-interglacial periods and climatic humidity, and may also be interpreted as a response to variable volcanogenic CO_2 upwelling [65].

The variability of rare earth elements (Ce, La, Sc, and Y) content in bituminous coal is high. The lowest variability was measured for scandium, and the highest for lanthanum and cerium, while in the case of yttrium the variability was average. The scandium asymmetry coefficient indicates a positive quasi-asymmetry of distribution, while the probability distribution of the remaining elements is characterized by weak asymmetry. Correlation analysis revealed highly statistically significant relationships between the following pairs of elements Ce – La, Ce – Y and La – Y [66]. The granulometric structure of 5-year-old waste from the Lublin Coal Basin was similar to that of 3-15-year-old waste from the Upper Silesian Coal Basin. The content of silt, clay and sand fractions in the latter was significantly higher than in 7-year waste from the Lublin Coal Basin [61].

Coal waste dumps can be considered important secondary deposits of chemical elements. Feasibility studies and past coal mining experiences show the need for new sites to recover [67]. Sustainable coal mining is not only economically viable, but also environmentally sound. It is also important for local communities to reuse and manage reclaimed landfill sites [68], [69].

3. Results and discussion

The content of chemical elements in the soil depends on many factors, primarily on their content in the parent rock. Macroelements – Si, Al, Fe, Ca, Mg, and K – are usually characterised by maximum concentration in the soil. These elements are almost entirely inherited from the soil-forming rock and in the process of soil formation are redistributed into the soil profile. Based on the absolute content in the soils of the test sites (Tables 2-3), the following groups of elements can be distinguished:

1 – Si (concentration is 294349-420581 mg/kg, or 29.4-42.1%);

2 – Al (concentration is 29589-136253 mg/kg, or 2.9-13.6%);

3 – K, Fe (average concentration value is 12742-18663 mg/kg, or 1.3-1.9%);

4.1 – Ca, Ti, Mg (average concentration value is 4594-5055 mg/kg, or 0.46-0.51%);

4.2 – S (average concentration value is 804 mg/kg);

4.3 – P, Mn, Zr (average concentration value is 353-590 mg/kg);

4.4 – V, Sr, Zn (average concentration value is 86-145 mg/kg);

4.5 – Pb, Y, Ni, Cu (average concentration value is 21-26 mg/kg).

Compared to the average values at site No. 4, increased concentrations of 13 out of 18 chemical elements are observed, namely: Mg, Al, S, K, Ti, V, Fe, Ni, Cu, Zn, Sr, Y, Pb (Tables 2-3).

Table 2. Level of chemical element concentration in ecotopes of the waste heap impact zone

No.	*h*	Chemical element concentration, mg/kg										
		Mg	Al	Si	P	S	K	Ca	Ti	Fe	Y	Zr
1	5	2837.2	37854.5	410668.7	598.2	141.9	15515.4	5251.7	3663.2	8394.1	15.2	376.0
	10	4519.5	37678.7	408817.0	577.1	159.9	17694.1	5402.0	3061.0	8292.1	2.2	254.6
	15	3127.2	36402.7	408502.5	593.5	123.0	13424.1	13283.5	2572.7	8535.8	13.8	238.8
2	5	3711.7	44252.8	398605.9	617.6	974.6	19083.0	4646.3	4231.2	12936.7	22.5	335.7
	10	3265.6	51764.4	389102.5	634.5	1940.7	19258.2	3873.3	5881.9	15803.7	27.7	335.4
	15	3049.2	43403.8	402451.8	610.2	1372.8	17265.2	874.1	4610.5	14701.4	25.2	325.4
3	5	3204.1	39918.1	400515.7	603.1	114.5	20944.1	6925.2	5202.1	11893.9	35.4	606.6
	10	2905.6	38582.9	405178.0	588.1	66.9	19182.1	5168.7	5006.6	10689.7	28.7	505.2
	15	4658.2	39276.1	405381.5	553.5	39.8	19173.7	4354.5	4060.4	9519.0	21.4	378.2
4	5	13513.6	136253.4	294349.1	524.0	2867.0	22146.5	6298.3	8095.4	25455.4	56.9	219.0
	10	12311.7	135368.6	295983.3	524.4	2229.3	22113.4	7276.0	7986.7	24943.7	56.7	220.7
	15	12289.1	134337.3	297473.9	511.7	1993.6	22316.5	6589.0	7910.8	24637.6	52.9	219.5
5	5	2338.9	36582.0	408660.5	608.2	135.6	18923.1	3513.5	4782.1	10610.9	25.8	513.3
	10	3093.1	35878.5	410050.8	571.2	46.6	18925.6	3133.6	4101.1	9984.3	26.2	491.1
	15	2480.1	38706.5	408607.3	577.8	43.1	18306.1	2757.7	4264.2	9777.0	27.0	498.6
6	5	1868.5	29589.6	420581.3	652.1	951.0	14070.4	4627.9	3969.2	6622.5	2.4	185.5
	10	1679.5	36543.2	409593.7	639.8	766.1	20055.9	3880.9	4665.7	8931.1	16.4	403.7
	15	1835.0	37648.7	412485.8	632.3	507.5	17542.0	3138.7	3302.3	7631.6	2.5	249.3
M		4593.8	55002.3	388167.2	589.9	804.1	18663.3	5055.3	4853.7	12742.2	25.5	353.1
σ		3824.36	37225.79	42937.13	41.05	906.76	2525.77	2615.83	1643.63	6116.58	16.77	126.81
BV		7900	38200	289000	1200	1200	13400	53800	4600	22300	23.4	255.6
Concentration coefficient *Kc*, the exceedance of background values, times												
1	5	0.36	0.99	1.42	0.50	0.12	1.16	0.10	0.80	0.38	0.65	1.47
	10	0.57	0.99	1.41	0.48	0.13	1.32	0.10	0.67	0.37	0.09	1.00
	15	0.40	0.95	1.41	0.49	0.10	1.00	0.25	0.56	0.38	0.59	0.93
2	5	0.47	1.16	1.38	0.51	0.81	1.42	0.09	0.92	0.58	0.96	1.31
	10	0.41	1.36	1.35	0.53	1.62	1.44	0.07	1.28	0.71	1.18	1.31
	15	0.39	1.14	1.39	0.51	1.14	1.29	0.02	1.00	0.66	1.08	1.27
3	5	0.41	1.04	1.39	0.50	0.10	1.56	0.13	1.13	0.53	1.51	2.37
	10	0.37	1.01	1.40	0.49	0.06	1.43	0.10	1.09	0.48	1.23	1.98
	15	0.59	1.03	1.40	0.46	0.03	1.43	0.08	0.88	0.43	0.91	1.48
4	5	1.71	3.57	1.02	0.44	2.39	1.65	0.12	1.76	1.14	2.43	0.86
	10	1.56	3.54	1.02	0.44	1.86	1.65	0.14	1.74	1.12	2.42	0.86
	15	1.56	3.52	1.03	0.43	1.66	1.67	0.12	1.72	1.10	2.26	0.86
5	5	0.30	0.96	1.41	0.51	0.11	1.41	0.07	1.04	0.48	1.10	2.01
	10	0.39	0.94	1.42	0.48	0.04	1.41	0.06	0.89	0.45	1.12	1.92
	15	0.31	1.01	1.41	0.48	0.04	1.37	0.05	0.93	0.44	1.15	1.95
6	5	0.24	0.77	1.46	0.54	0.79	1.05	0.09	0.86	0.30	0.10	0.73
	10	0.21	0.96	1.42	0.53	0.64	1.50	0.07	1.01	0.40	0.70	1.58
	15	0.23	0.99	1.43	0.53	0.42	1.31	0.06	0.72	0.34	0.11	0.98

Legend:
No. – site sequence number:
1 – natural soil;
2 – Robinia pseudoacacia plantation;
3 – lake shore;
4 – waste heap foot, drainage sludge;
5 – birch forest;
6 – pine forest;
h – depth of soil sampling, cm;
M – average value, mg/kg;
σ – standard deviation, mg/kg;
BV – background concentration value, mg/kg.

Only Si, P have low concentrations here. At site No. 2, increased concentrations are characteristic of P, S, K, Mn, and Pb. The maximum concentrations of Mn and Zr are characteristic of sites No. 3 and 5, Ca – site No. 1, P – site No. 6. In general, three groups of sites can be distinguished by the absolute chemical element content in the soil:

1 – No. 4 site;

2 – No. 2 site;

3 – No. 3, 6, 1, 5 sites.

The study [70] should be noted, where Pb and As were found in higher concentrations in the tested mine waste (Pb_{max} = 15000 mg/kg, As_{max} = 114 mg/kg), making them the most common potentially toxic elements. Cluster analysis and Pearson correlation showed that Pb, Cu, and As are grouped together, indicating a common source in mine waste. In alkaline conditions, Pb precipitates in solution, while As exhibits high mobility, leading to pollution of the environment, surface water, groundwater, cultivated soil, and posing a risk to human health. The content of certain chemical elements in the soil may be low, but their toxic effect may exceed the permissible standards [21], [71]. This primarily concerns heavy metals [35], [72], [73].

Table 3. Level of soil pollution with heavy metals in ecotopes of the waste heap impact zone

No.	*h*	Chemical element concentration, mg/kg							*PI*	*Zc*
		Cu	Zn	Pb	Ni	V	Mn	Sr		
1	5	8.2	25.4	11.7	12.3	125.8	203.9	50.1	–	–
	10	11.6	7.5	15.7	11.5	126.8	213.4	50.5	–	–
	15	7.9	30.0	12.0	15.6	126.0	207.7	46.0	–	–
2	5	23.1	36.1	22.4	19.2	73.8	487.7	80.6	–	–
	10	26.0	34.4	37.0	20.8	60.1	402.5	112.9	–	–
	15	23.4	6.8	35.9	11.7	130.2	323.3	89.2	–	–
3	5	10.5	34.9	20.2	12.1	153.5	491.2	97.9	–	–
	10	12.6	23.5	17.8	12.6	147.5	405.8	88.7	–	–
	15	7.5	18.6	14.0	12.0	127.0	417.5	65.3	–	–
4	5	66.9	170.1	53.0	72.0	199.5	318.1	284.5	–	–
	10	63.8	340.2	49.7	80.5	247.0	375.8	273.7	–	–
	15	58.7	690.6	50.0	74.5	209.2	379.1	267.8	–	–
5	5	9.4	35.7	21.0	12.3	144.7	547.2	70.8	–	–
	10	7.5	31.0	18.1	11.0	127.3	498.7	67.7	–	–
	15	8.5	24.8	19.1	11.5	126.7	450.4	67.1	–	–
6	5	10.3	26.6	21.0	14.2	160.9	296.6	36.0	–	–
	10	9.8	8.7	21.4	16.0	164.4	260.8	46.2	–	–
	15	9.0	8.1	24.5	13.4	152.9	377.0	44.7	–	–
M		20.8	86.3	25.8	24.1	144.6	369.8	102.2	–	–
σ		20.35	171.09	13.36	23.94	43.92	105.26	82.30	–	–
MPC		3	23	32	4	150	1500	458*	–	–
Concentration coefficient *Kc*, the exceedance of maximum permissible concentration (MPC), times										
1	5	2.72	1.10	0.37	3.07	0.84	0.14	0.11	1.19	5.08
1	10	3.86	0.33	0.49	2.88	0.85	0.14	0.11	1.24	5.98
1	15	2.64	1.30	0.38	3.90	0.84	0.14	0.10	1.33	6.17
2	5	7.68	1.57	0.70	4.81	0.49	0.33	0.18	2.25	13.31
2	10	8.67	1.50	1.16	5.20	0.40	0.27	0.25	2.49	15.02
2	15	7.79	0.29	1.12	2.93	0.87	0.22	0.19	1.92	10.76
3	5	3.52	1.52	0.63	3.01	1.02	0.33	0.21	1.46	6.53
3	10	4.19	1.02	0.55	3.16	0.98	0.27	0.19	1.48	6.85
3	15	2.49	0.81	0.44	3.01	0.85	0.28	0.14	1.14	4.64
4	5	22.31	7.40	1.66	17.99	1.33	0.21	0.62	7.36	53.05
4	10	21.27	14.79	1.55	20.13	1.65	0.25	0.60	8.60	62.99
4	15	19.57	30.03	1.56	18.63	1.39	0.25	0.58	10.29	76.47
5	5	3.13	1.55	0.66	3.09	0.96	0.36	0.15	1.42	6.19
5	10	2.49	1.35	0.56	2.75	0.85	0.33	0.15	1.21	4.8
5	15	2.84	1.08	0.60	2.87	0.84	0.30	0.15	1.24	5.03
6	5	3.44	1.16	0.66	3.54	1.07	0.20	0.08	1.45	6.66
6	10	3.25	0.38	0.67	4.00	1.10	0.17	0.10	1.38	10.89
6	15	3.01	0.35	0.77	3.35	1.02	0.25	0.10	1.26	5.64

Legend:
No. – site sequence number:
1 – natural soil; 2 – Robinia pseudoacacia plantation; 3 – lake shore; 4 – waste heap foot, drainage sludge; 5 – birch forest; 6 – pine forest; *h* – depth of soil sampling, cm; *M* – average value, mg/kg; *σ* – standard deviation, mg/kg; MPC – maximum permissible concentration, mg/kg; *PI* – soil pollution index, times; *Zc* – total pollution index, times.

In this regard, an important peculiarity of chemical elements is the concentration coefficient values, which characterize the exceedance of maximum permissible concentrations (MPC) for heavy metals and background values for macroelements [74], [75]. The maximum exceedance of MPC at the test sites is characteristic of three chemical elements (Table 2): Cu (exceedance of MPC within 2.5-22.3 times), Ni (exceedance of MPC within 2.8-20.1 times), Zn (exceedance of MPC within 0.3-30.0 times).

The spatial distribution of Cu in the 0-5 cm horizon is shown in Figure 2. It should be noted that the test site No. 4 is characterized by the most polluted substrate, with a Cu value of 66.9 mg/kg in the corresponding horizon.

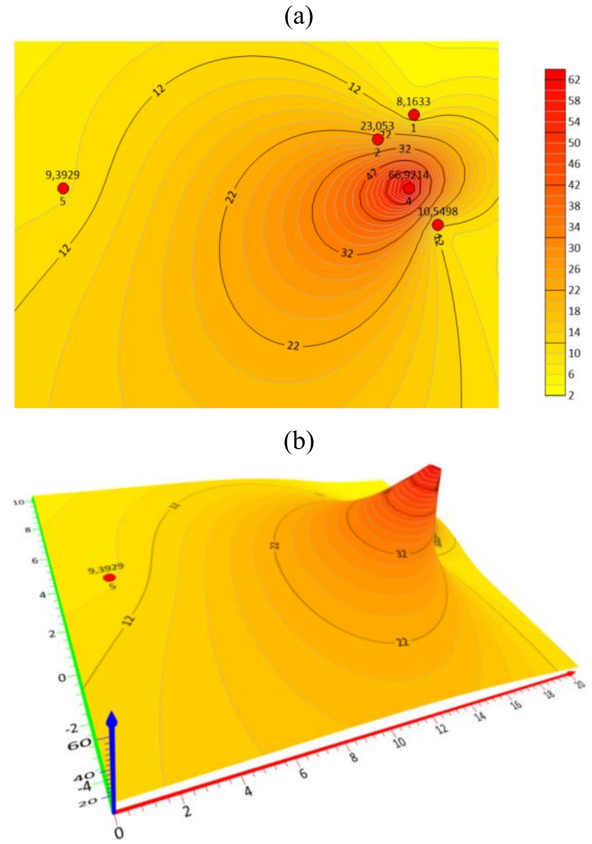


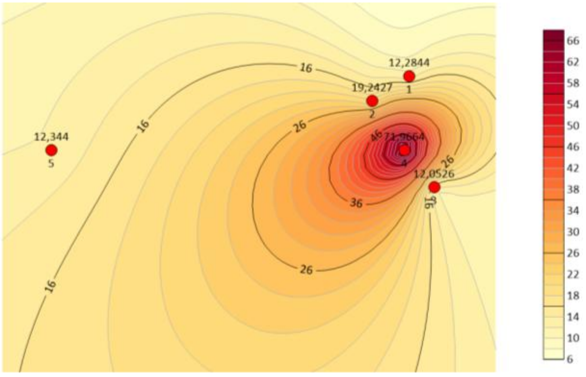
Figure 2. Spatial distribution of Cu in the 0-5 cm horizon in the waste heap impact zone: (a) 2D-visualization; (b) 3D- spatial distribution model

Similarly, research results in [76] showed a high Cu concentration in the Musina copper mine tailings (Limpopo Province, South Africa), indicating bioavailability and posing an environmental hazard, as well as potential risk to human health. The spatial distribution of Ni in the 0-5 cm horizon is shown in Figure 3. It should be noted that, as in the previous case, the test site No. 4 is characterized by the most polluted substrate, with Ni value of 72 mg/kg in the corresponding horizon.

Studies [77] showed very high content of toxic metals Pb, Zn, Cd, Cr and Hg in all samples, indicating the need to take corrective measures to reduce the spread of these hazardous elements into the environment. The results obtained indicate two main sources of metal pollution: Cu, Mn, Hg and Pb originate from anthropogenic sources of mine waste from tailings, while Ni, Zn, Cr and even Fe originate from lithogenic and anthropogenic sources. Chemical analysis of tailings (lead-zinc flotation factory at the Boquira Mine, Brazil) shows that the main components are Fe, Si, Mg and Ca. The content of toxic metals is Pb – 1.3%, Zn – 1.3%, Cu – 135 mg/kg, Cd – 127 mg/kg and As – 5 mg/kg. Strong leaching of Cd, Pb and Zn indicates that they may be a source of toxic metals [78].

In our case, site No. 4 has the highest soil pollution index (*PI* = 7.36-10.29 times), followed by site No. 2 (*PI* = 1.92-2.49 times). For the remaining sites, the soil pollution index does not exceed 1.5 times.

(a)



(b)

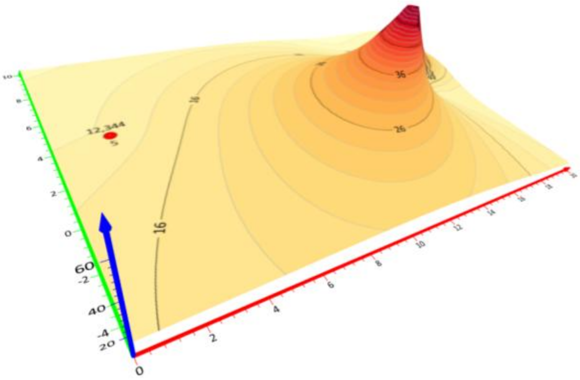
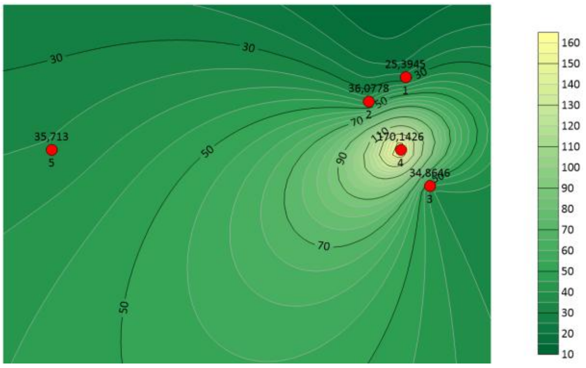


Figure 3. Spatial distribution of Ni in the 0-5 cm horizon in the waste heap impact zone: (a) 2D-visualization; (b) 3D-spatial distribution model

(a)



(b)

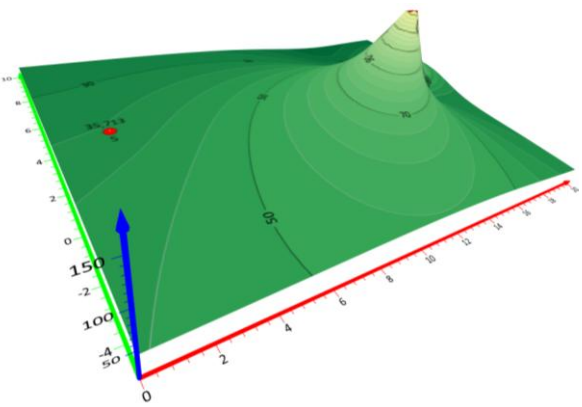


Figure 4. Spatial distribution of Zn in the 0-5 cm horizon in the waste heap impact zone: (a) 2D-visualization; (b) 3D-spatial distribution model

Site No. 4 is characterized by hazardous soil pollution level (Zc = 53.1-76.5), site No. 2 is at the upper limit of the permissible pollution level, transitioning into a moderately hazardous zone (Zc = 10.8-15.1). Other sites differ in terms of permissible pollution level (Table 3).

Based on the concentration coefficient values (Tables 2-3), the following groups of chemical elements can be distinguished (Fig. 5a):

1) Cu, Ni, Zn (average concentration coefficient values by 3.8-6.9 times);

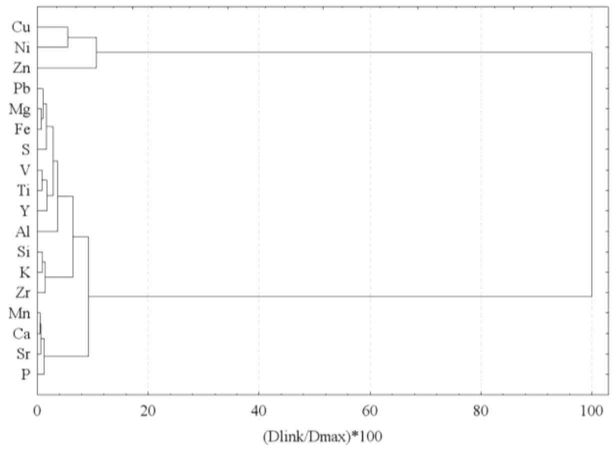
2) Al, K, Zr, Si (average concentration coefficient values by 1.3-1.4 times);

3.1) Y, Ti, V (average concentration coefficient values by 1.0-1.1 times);

3.2) Pb, S, Mg, Fe (average concentration coefficient values by 0.6-0.8 times);

4) P, Mn, Sr, Ca (average concentration coefficient values by 0.1-0.5 times).

(a)



(b)

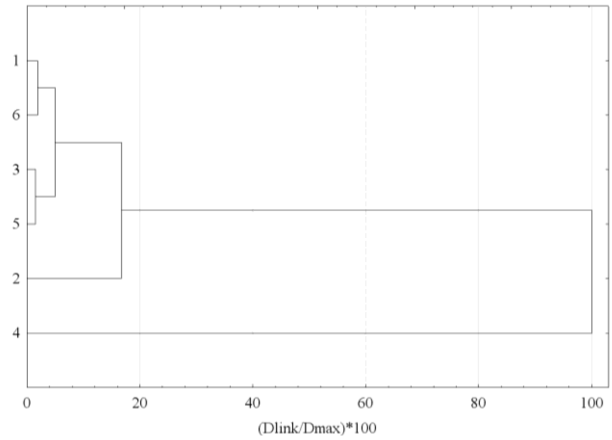


Figure 5. Dendrogram of similarity of chemical elements (a) and sites (b) based on spatial distribution of their soil content (sequence numbers of sites are given in Table 2)

The maximum Euclidean distance is observed between Cu and Ca (DE = 23.3) and Cu and Mn (DE = 23.0). The difference between chemical elements based on Euclidean distances in 2D space can be represented as a triangle, in the corners of which are: Zn, Cu, Ni, Ca, Mn and the remaining chemical elements. In 3D space, Cu is located at the top of a 3D pyramid, at the base of which is a triangle with Zn, Ni, Ca^{+} Mn^{+} remaining elements.

Based on the concentration coefficient values (Tables 2-3), 3 groups of sites can be similarly distinguished (Fig. 5b): 1 – No. 4 site; 2 – No. 2 site; 3 – No. 1, 6, 3, 5 sites.

The difference between sites based on Euclidean distances in 2D space can be represented as a triangle, in the corners of which the sites 4, 2, 1 + 3 + 5 + 6 are located. The greatest Euclidean distance relative to other ecotopes is characteristic of site No. 4 (DE = 25.7-29.4), while for other sites it averages DE = 6.4-7.8.

Analysis of the dependence between chemical element concentrations in soil indicates a close correlation between them. Correlation coefficients are characterized by high values for many pairs of chemical elements. Thus, for concentrations Mg and Al $r = 0.98$, Mg and Si $r = -0.98$, Cu and Fe $r = 0.98$, Ni and Al $r = 0.99$, Cu and Pb $r = 0.94$. Only Ca, Mn and, to some extent, Zr have weak bonds with other chemical elements. High correlation coefficients can be a consequence of pseudo-correlation caused by the high concentration of most chemical elements at site No. 4. Diagrams of the dependence between the element concentrations also indicate this. The idea of our further research was to mathematically model the location structure of the test sites in the multidimensional space, characterized by the chemical element content in the soil.

Since the chemical element concentrations in the soils of the test sites are correlated with each other, it can be concluded that the observation data can be explained by a small number of new variables that are not directly measured but can be obtained by a linear combination of the initial data. This makes it possible to reduce the dimensionality of the observation space. Graphically, the calculation procedure is reduced to moving the origin to the data center and rotating the coordinate axes so that the abscissa passes in the direction of maximum data set variance.

The results of the principal component analysis based on the correlation matrix are as follows (Fig. 6):

$$Factor_1 = 0.274 \cdot Mg + 0.281 \cdot Al - 0.282 \cdot Si - 0.215 \cdot P + 0.237 \cdot S + 0.205 \cdot K + 0.064 \cdot Ca + 0.265 \cdot Ti + 0.276 \cdot Fe + 0.251 \cdot Y - 0.116 \cdot Zr + 0.277 \cdot Cu + 0.236 \cdot Zn + 0.260 \cdot Pb + 0.278 \cdot Ni + 0.197 \cdot V + 0.012 \cdot Mn + 0.281 \cdot Sr, \lambda_1 = 12.51; \quad (6)$$

$$Factor_2 = -0.073 \cdot Mg - 0.052 \cdot Al \; 0.036 \cdot Si - 0.030 \cdot P - 0.096 \cdot S + 0.374 \cdot K - 0.356 \cdot Ca + 0.157 \cdot Ti + 0.054 \cdot Fe + 0.229 \cdot Y + 0.524 \cdot Zr - 0.051 \cdot Cu - 0.043 \cdot Zn + 0.018 \cdot Pb - 0.087 \cdot Ni - 0.091 \cdot V + 0.581 \cdot Mn + 0.031 \cdot Sr, \lambda_2 = 2.31, \quad (7)$$

where:

$Factor_i$ – component coordinates, complex environmental gradients;

Mg, Al, Si, P, S, K, Ca, Ti, Fe, Y, Zr, Cu, Zn, Pb, Ni, V, Mn, Sr – standardized values of chemical element concentrations in the soil;

λ_i – eigenvalues of vectors.

The statistical parameters of the chemical element content in the soil of the test sites for the subsequent calculations of z_i are given in Tables 2-3. An analysis of the characteristics of eigenvalues λ_i shows that the two principal components provide 82.4% of the total variance, so for many purposes of analysis it Is sufficient to use the 2D projection of the original data matrix. The eigenvectors of the correlation matrix (6), (7) make it possible to distinguish combinations of chemical element concentrations that determine the axes of maximum variation of sites in the waste heap impact zone. The main pattern of the ecological state formation at the sites (the first principal component, $Factor_1$) has the following structure of bonds between chemical elements (Fig. 6): with an increase in concentration of Sr in soil (correlation coefficient $r = 0.99$), Al ($r = 0.99$), Ni ($r = 0.98$), Cu ($r = 0.98$), Fe ($r = 0.98$), Mg ($r = 0.97$), Ti ($r = 0.94$), Pb ($r = 0.92$), Y ($r = 0.89$), S ($r = 0.84$), Zn ($r = 0.84$), K ($r = 0.73$), V ($r = 0.70$), the concentrations of Si ($r = -1.00$), P ($r = -0.76$) decrease. The first principal component explains 69.5% of the total variance, therefore, based on its values, the main pattern of chemical element content in the waste heap impact zone can be clearly observed. Thus, high values of the first principal component $Factor_1$ are characteristic of site No. 4 (waste heap foot, drainage sludge) (Fig. 6), which are distinguished by high concentration coefficient values K_c of 13 out of 18 chemical elements, especially Cu, Zn and Ni (Tables 2-3). The minimum values of the first principal component are characteristic of sites No. 1 and No. 6 (pine forest), where high concentration coefficient values K_c for Si and low content of heavy metals Cu, Zn and Ni were observed (Tables 2-3).

The second maximum variation axis, $Factor_2$, additionally explains 12.9% of the total data variance (Fig. 6). The value of the $Factor_2$ function mainly depends on the content of Mn ($r = 0.88$), Zr ($r = 0.80$). The minimum values of the $Factor_2$ function are characteristic of site No. 1, which is distinguished by minimum concentrations of Zr and Mn in the soil, and compared to other sites, a higher concentration of Ca (Tables 2-3). The maximum value of the second principal component is found at sites No. 5 (birch forest) and No. 3 (lake shore), which are characterized by the opposite tendency in the content of these chemical elements. The third axis of maximum variation, $Factor_3$, which additionally explains 7.0% of the total data variance, is mainly dependent on the content of Ca ($r = -0.63$), S ($r = 0.49$), P ($r = 0.47$). The maximum $Factor_3$ function values are characteristic of site No. 2 (Robinia pseudoacacia plantation). Thus, in 2D space of complex environmental gradients, ecotopes can be represented as a triangle, in the middle of which there is site No. 2, and in the corners of which there are sites No. 4, 1 and 5 (Fig. 6). In 3D space, the site No. 2 is at the top of a triangular pyramid.

The dimensionality of the observation space can be reduced not only by calculating the principal components of the correlation matrix, but also by excluding individual chemical elements from the analysis, taking into account their close bonds with each other (high correlation coefficient values). The variance analysis results can be used as a basis for further conclusions (Table 4).

Univariate variance analysis is based on the calculation of Fisher's criterion, which is the ratio between intergroup and intragroup variances. Intergroup variance shows how much the sites in the waste heap impact zone differ from each other in terms of chemical element concentration levels. Intergroup variance is zero when the average concentration values of chemical elements are equal. Intragroup variance characterizes the difference in chemical element concentrations within the same site. The maximum Fisher's criterion value is characteristic of the chemical elements Al, Si, Cu, Ni, Sr, Fe, Mg, Pb, which are the main factor in the ecological differentiation of sites by chemical element concentration (Table 4).

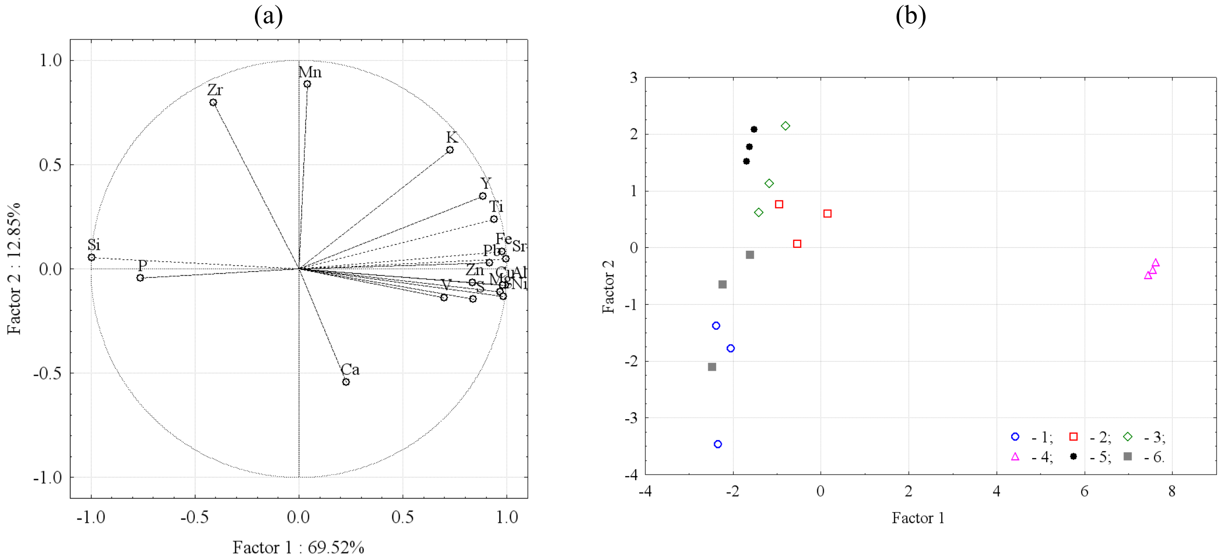


Figure 6. Results of the analysis of the principal components of chemical element content in soil: (a) correlations system between chemical element concentrations and complex environmental gradients; (b) location of sites in the coordinate system of complex environmental gradients ($Factor_{1-2}$ – principal components, complex environmental gradients; sequence numbers of sites are given in Table 2)

Table 4. Variance analysis results of chemical element concentrations by spatial location of sites

Element	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Mg	2.437E + 08	5	4.874E + 07	4927491	12	410624	118.70	0.000000
Al	2.347E + 10	5	4.694E + 09	88845000	12	7403750	633.98	0.000000
Si	3.116E + 10	5	6.232E + 09	183429064	12	15285755	407.67	0.000000
P	2.571E + 04	5	5.142E + 03	2935	12	245	21.02	0.000015
S	1.299E + 07	5	2.598E + 06	988100	12	82342	31.55	0.000002
K	7.647E + 07	5	1.529E + 07	31978129	12	2664844	5.74	0.006230
Ca	6.081E + 07	5	1.216E + 07	55508487	12	4625707	2.63	0.078947
Ti	4.189E + 07	5	8.378E + 06	4036990	12	336416	24.90	0.000006
V	2.811E + 04	5	5.622E + 03	4686	12	391	14.40	0.000103
Mn	1.564E + 05	5	3.128E + 04	31983	12	2665	11.73	0.000278
Fe	6.256E + 08	5	1.251E + 08	10430509	12	869209	143.94	0.000000
Ni	9.644E + 03	5	1.929E + 03	99	12	8	232.72	0.000000
Cu	6.977E + 03	5	1.395E + 03	64	12	5	261.78	0.000000
Zn	3.555E + 05	5	7.110E + 04	142105	12	11842	6.00	0.005224
Sr	1.138E + 05	5	2.276E + 04	1351	12	113	202.11	0.000000
Y	4.424E + 03	5	8.848E + 02	355	12	30	29.89	0.000002
Zr	2.104E + 05	5	4.208E + 04	62935	12	5245	8.02	0.001571
Pb	2.853E + 03	5	5.706E + 02	180	12	15	37.97	0.000001

Legend:
SS Effect and SS Error – intergroup and intragroup sums of deviation squares;
MS Effect and MS Error – intergroup (factor) and intragroup (residual) variances;
df – degrees of freedom; F – Fisher's criterion;
p – significance level

Only for Ca, the significance level is $p>0.05$, indicating its low differential ability. Regarding the depth of sampling, one-dimensional variance analysis did not allow the identification of chemical elements that would have reliable differential ability.

A detailed analysis based on the least significant difference test (LSD test) shows that Si demonstrates a difference only for sites No. 2 and 4, while for the remaining sites, the difference in the concentration of this chemical element is not significant. Similar results were obtained for Al, Cu, and Ni. In this regard, the next stage of our research consis-ted in constructing a typological scheme of sites in the waste heap impact zone only for heavy metals. For this purpose, we calculated the optimal combinations of concentrations of seven chemical elements, which can be used to determine the peculiarities of anthropogenic load on ecotopes in the waste heap impact zone. A typological scheme of sites in the waste heap impact zone is presented in Figure 7.

Mathematical modeling results (Fig. 7) can be represented by the equations (8) and (9).

The first typological scheme axis $Root_1$ (Fig. 7) explains 91.8% of the total variance. The minimum values of the canonical discriminant $Root_1$ function characterize the location of site No. 4 (waste heap foot), where the edaphotope was formed by drainage sludge. The maximum $Root_1$ values are characteristic of the ecotopes of sites No. 5 (birch forest), No. 3 (lake shore), No. 5 (birch forest), No. 6 (pine forest), and No. 1 (natural soil).

$$Root_1 = -0.5740 \cdot Cu - 0.0095 \cdot Zn + 0.0650 \cdot Pb - 0.1469 \cdot Ni - 0.0104 \cdot V + 0.0044 \cdot Mn - 0.0049 \cdot Sr + 15.0074; \quad (8)$$

$$Root_2 = 0.3999 \cdot Cu + 0.0018 \cdot Zn + 0.4039 \cdot Pb + 0.1171 \cdot Ni - 0.0286 \cdot V + 0.0044 \cdot Mn - 0.1884 \cdot Sr + 0.0519, \quad (9)$$

where:

$Root_i$ – canonical discriminant functions, typological scheme axes of edaphotope in the waste heap impact zone.

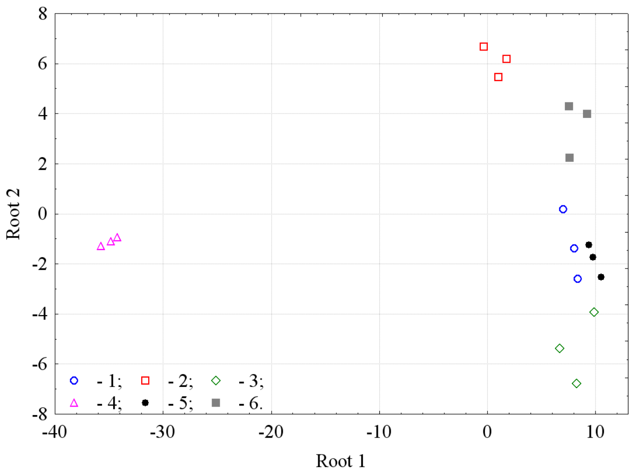


Figure 7. Typological scheme of sites in the waste heap impact zone (sequence numbers of sites are given in Table 2)

The values of the first discriminant $Root_1$ function depend on the concentration of many chemical elements, namely: Cu (correlation coefficient $r = -0.99$), Ni ($r = -0.99$), Sr ($r = -0.98$), Pb ($r = -0.92$), Zn ($r = -0.83$). There is also a close correlation with the concentration of other macro- and microelements that were not directly used in the mathematical model: Al (correlation coefficient $r = -0.99$), Si ($r = 0.99$), Mg ($r = -0.97$), Fe ($r = -0.96$), Fe ($r = -0.96$), Ti ($r = -0.90$), P ($r = 0.72$).

The first typological scheme axis $Root_1$ also reflects a decrease in the level of anthropogenic load. The close relationship between the $Root_1$ function values and the soil pollution index (*PI*) and the total pollution index *Zc* in both cases is characterized by a correlation coefficient $r = -0.99$. Higher P (soil fertility indicator) and Si (lighter mechanical composition) content characterize less disturbed sites No. 1, 3, 5, and 6. At site No. 4, there is a phenomenon of clay deposition due to the washing out of clay fractions from the upper areas of the slope and their accumulation at the foot of the waste heap. The reduction in anthropogenic load reflects the following ecological-geochemical gradient: site No. 4 → site No. 2 → sites No. 1, 3, 5, 6.

The second typological scheme axis $Root_2$ (Fig. 7) additionally explains only 5.1% of the total variance. Low values of the canonical discriminant $Root_2$ function characterize the location of site No. 3 (lake shore), and maximum $Root_2$ values – site No. 2 (Robinia pseudoacacia plantation). *Robinia pseudoacacia L.* is often used for phytomelioration of disturbed lands. This hypothesis is supported by elevated concentrations of many chemical elements, primarily heavy metals. The second discriminant $Root_2$ function values depend on the concentration of Pb (correlation coefficient $r = 0,24$), V ($r = -0.34$), and, in a broader sense, show a correlation with Zr ($r = -0.51$) and P ($r = 0.52$).

The 2D typological scheme (Fig. 7) explains 96.9% of the total variance caused by differences in chemical pollution levels between ecotopes. Schematically, it can be represented as a triangle, with site No. 4 (waste heap foot), site No. 2 (*Robinia pseudoacacia plantation*), and site No. 3 (lake shore) located at its corners. To explain the peculiarities of chemical pollution level between all sites, we determined the Mahalanobis distance D_M – a multidimensional analogue of Euclidean distance, taking into account the correlation between chemical substance concentrations. As a result of calculations, we have determined that the most distant in hyperspace of geochemical parameters are site No. 4 and site No. 5 (birch forest) – the Mahalanobis distance is $D_M^2 = 3022.8$ units. The closest distance to site No. 4 is characteristic of site No. 2 – $D_M^2 = 2013.2$ units. Thus, our typological scheme contains a large "blank spot" that needs to be filled by selecting additional sites from the waste heap and its immediate surroundings. The use of the developed mathematical model will clarify the ecological gradients of the chemical element distribution, primarily heavy metals, in the upper soil layers.

4. Conclusions

The distribution of macro- and microelements in soils of the impact zone of a coalmine waste heap is characterized by significant spatial heterogeneity. The highest concentrations of most of the studied elements were found at the waste heap foot (site No. 4), where increased content of Mg, Al, S, K, Ti, V, Fe, Ni, Cu, Zn, Sr, Y, and Pb was observed, accompanied by reduced Si and P concentrations. Some ecotopes are characterized by specific features of element accumulation, in particular, increased content of P, S, K, Mn, and Pb in Robinia pseudoacacia plantation, as well as Mn and Zr at coastal and forest sites.

The highest exceedance of maximum permissible concentrations was found for Cu, Ni, and Zn, indicating their leading role in the formation of technogenic load on the soil cover. According to the integral soil pollution index, the site at the foot of the waste heap is classified as hazardous, while the site with Robinia pseudoacacia plantation is on the verge of permissible and moderately hazardous levels. Other test sites are characterized by permissible pollution level.

Grouping of chemical elements by concentration coefficients made it possible to distinguish elements with high technogenic accumulation level (Cu, Ni, Zn), elements with moderate and near-background concentration values, as well as elements with minimal accumulation levels, reflecting varying degrees of impact of the waste heap on soil ecotopes.

Analysis of exceeding maximum permissible concentrations showed that the most significant technogenic load levels are characteristic of Cu, Ni, and Zn, for which the multiplicity of exceeding MPC varies within 2.5-22.3, 2.8-20.1, and 0.3-30.0 times, respectively. According to the integral soil pollution index, site No. 4 is classified as hazardous ($Zc = 53.1$-76.5), while site No. 2 is characterized by marginal values of the permissible level with a tendency to transition to a moderately hazardous state ($Zc = 10.8$-15.1). Other test sites comply with the permissible pollution level.

Several groups of chemical elements have been distinguished based on their concentration coefficients. The first group includes Cu, Ni, and Zn, for which the average concentration coefficients are 3.8-6.9. The second group consists of Al, K, Zr, and Si with concentration coefficients of 1.3-1.4. The third group consists of elements with concentrations close to background values (Y, Ti, V), as well as Pb, S, Mg, and Fe with slightly reduced coefficients. The fourth group includes P, Mn, Sr, and Ca, which are characterized by the lowest concentration coefficient values.

For multidimensional ordination of ecotopes in the waste heap impact zone, the concentration of chemical elements is characterized by the presence of an ordered structure. Analysis of the dependence between chemical element concentrations indicates that there is a close relationship between many parameters. The main peculiarity of the ecological state formation at sites lies in the following structure of relationships between chemical elements: with an increase in the concentrations of Sr, Al, Ni, Cu, Fe, Mg, Ti, Pb, Y, S, Zn, K, V in the soil, the concentrations of Si and P decrease.

2D typological scheme of the sites in the waste heap impact zone can be represented as a triangle, with site No. 4 (waste heap foot), site No. 2 (Robinia pseudoacacia plantation), and site No. 3 (lake shore) located at its corners. The first axis of the typological scheme reflects a decrease in the level of anthropogenic load, as evidenced by a negative close relationship with the soil pollution index (*PI*) and the total pollution index *Zc*.

The use of the developed mathematical model will clarify the ecological gradients of the chemical element distribution, primarily heavy metals, in the upper soil layers. Graphical visualization of geochemical information based on typological schemes, where chemical element concentrations or complex environmental gradients serve as axes, can be used to predict the ecological state of objects and monitor the environment.

Author contributions

Conceptualization: VP, VSk, VSe; Data curation: VSk; Formal analysis: VP, VSk, VSe; Investigation: VP, VSe, TB, OK, VK; Methodology: VP, VSk, VSe; Project administration: VP; Resources: VSe, TB, OK, VK; Software: VP, VSk, VSe; Supervision: VP, VSe; Validation: VP, VSk, VSe; Visualization: VP, VSk; Writing – original draft: VP, VSk, VSe, TB, OK, VK; Writing – review & editing: VP, VSk, VSe. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

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

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Геоекологічні аспекти міграції хімічних елементів у ґрунтах зони впливу терикону шахти "Богданка", Люблінський вугільний басейн

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Мета. Метою роботи є дослідження особливостей хімічного забруднення ґрунтів та аналіз закономірностей міграції хімічних елементів у зоні впливу терикону шахти "Богданка" Люблінського вугільного басейну порівняно з контрольною ділянкою. Для досягнення поставленої мети здійснено відбір ґрунтових проб з різних екотопів на глибинах 0-5, 5-10 та 10-15 см, оцінено екологічний стан територій та виконано статистичний аналіз вмісту хімічних елементів.

Методика. Дослідження ґрунтувалися на методах статистичної обробки даних, кореляційного та кластерного аналізу, багатовимірної ординації екотопів із застосуванням аналізу головних компонент (PCA) та канонічного дискримінантного аналізу. Відбір проб здійснювали відповідно до стандарту ISO 10381-8:2006. Аналітичні визначення елементного складу виконано методом рентгенофлуоресцентної спектрометрії на приладі ElvaX Light SDD.

Результати. Встановлено істотну просторову неоднорідність розподілу макро- та мікроелементів у ґрунтах зони впливу терикону. На ділянці підніжжя терикону зафіксовано підвищені концентрації Mg, Al, S, K, Ti, V, Fe, Ni, Cu, Zn, Sr, Y та Pb. Максимальні значення окремих елементів характерні для специфічних екотопів, зокрема Mn і Zr для прибережних та лісових ділянок. Найбільше перевищення граничнодопустимих концентрацій виявлено для Cu, Ni та Zn (до 22.3, 20.1 та 30 разів відповідно).

Наукова новизна. Наукова новизна дослідження полягає у встановленні просторових градієнтів хімічного забруднення ґрунтів у зоні впливу терикону вугільної шахти на основі багатовимірної ординації екотопів. Двовимірна графічна візуалізація геохімічних показників, осями яких є концентрації хімічних елементів або інтегральні градієнти середовища, забезпечує наочне представлення процесів міграції елементів у ґрунтах різних екотопів.

Практична значимість. Практична значущість отриманих результатів полягає у можливості використання встановлених закономірностей розподілу хімічних елементів для оцінки рівня забруднення ґрунтів у зоні впливу породного відвалу. Отримані дані можуть бути використані для прогнозування локальних змін якості ґрунтового покриву та обґрунтування заходів щодо зменшення негативного впливу важких металів на ґрунтове середовище прилеглих територій.

Ключові слова: *породний відвал; терикон шахти; хімічне забруднення; комплексний градієнт середовища; екологічна безпека*

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