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ECOLOGICAL ASSESSMENT OF HEAVY METAL CONTAMINATION OF SOILS AND PLANTS IN THE IMPACT ZONE OF LANDFILLS

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Abstract. The article presents the results of a comprehensive environmental study of the impact of municipal waste landfills on s oil and vegetation in the Ternopil and Khmelnytskyi regions of Ukraine. The objects of the study involved four landfills located near the villages of Malashivtsi, Dunayivtsi, Kremenets, and Khmelnytskyi. X-ray fluorescence analysis of soil and plant samples was conducted to a ssess the level of contamination. Concentration coefficients, integral pollution indic es (Zc), and bioaccumulation coefficients of heavy metals in the soil-plant system were calculated. Higher concentrations of Fe, Cu, Zn, Pb, Sr, and Mn were detected in the soils, exceeding both background values and MPCs, indicating a significant man-made impact of landfills. The highest pollution coefficients were recorded at Khmelnytskyi and Dunayivtsi landfills. The high capacity of plants for biological accumulation of Cu, Mn, Zn and Sr was revealed, which poses a potential danger of toxicant transfer to the biosphere. The active dynamics of vertical migration of elements in the soil profile was established. The obtained results emphasize the need for systematic environmental monitoring, improvement of waste management technologies and implementation of landfill reclamation measures to reduce the anthropogenic impact on the environment.

Keywords: waste, environmental safety, dump, municipal solid waste, landfill, contamination.

1. Introduction

The world community today is facing environmental problems and crises with increasing frequency. Polluted air, unsatisfactory quality of drinking water, and sometimes its shortage or lack, soil degradation and erosion, droughts, and declining biodiversity affect the quality of life of the population (Pukish et al., 2024; Pukish et al., 2023).

The main cause of environmental problems is a significant anthropogenic impact, including the intensive development of industry and agriculture, unsustainable use of natural resources, and the generation of large volumes of waste. Each industry is accompanied by the generation of by-products that cannot always be reused or properly recycled. But as part of the development of zero waste technologies and production, and the circular economy, the issue of effective waste management is becoming increasingly important. Household waste management is an important area in every country.

In Ukraine, there is a critical situation related to the generation, accumulation, storage, treatment, recovery and disposal of waste, characterized by the further development of environmental threats (Verkhovna Rada of Ukraine, 2024). According to officially published data

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for 2023, more than 83 % of the more than 9 million tons of collected solid waste was landfilled (Ministry of Infrastructure of Ukraine, 2024).

A significant share of the total amount of household waste in the world is organic (Abdel-Shafy & Mansour, 2018). In Ukraine, it is 20.3 % (Ministry of Environmental Protection and Natural Resources of Ukraine, 2024).

The predominant way to manage household waste is to remove it and store it in landfills and dumpsites with a total area of more than 12 thousand hectares. Dumps and landfills are sources of pollution and environmental hazards. Given the non-compliance with the rules and regulations in the design and operation of landfills, and their overtime operation, this leads to serious environmental and social consequences, including groundwater and surface water pollution, the spread of toxic substances hazardous to human health, methane accumulation with the risk of explosions and fires, landscape degradation, and a decrease in the quality of life of nearby residents.

Scientific research on the hazards of landfills and their negative impact on the environment and public health demonstrates the importance of environmental monitoring both within the facilities themselves, on the territory of the sanitary protection zone, and beyond (Popovych et al., 2020; Malovanyy et al., 2021, Naeem et al., 2024). In particular, there is a significant impact of leachate from landfills, soil and water pollution, and changes in air quality due to fires at household waste landfills. These factors also lead to an increase in radiation levels (Skyba & Popovych, 2025).

Russia's large-scale armed aggression against Ukraine has resulted in a sharp increase in waste, including damaged and abandoned vehicles and equipment, shell fragments, demolition waste, household and other waste. Some of the waste is hazardous, especially shell fragments, medical waste, and demolition waste containing asbestos and heavy metals. According to official data, as of the end of 2023, the total amount of waste from the destruction caused by the armed aggression of the Russian Federation in Ukraine amounted to more than 607 thousand tons (Ministry of Infrastructure of Ukraine, 2024). This has threatened the state of the environment, as military actions have a direct impact on the natural resources quality (Huminilovych et al., 2023; Polukarov et al., 2024; Petrushka & Petrushka, 2025).

Studying the factors that cause environmental pollution with heavy metals is an important component of environmental monitoring (Kabata-Pendias & Szteke, 2015; Petrushka et al., 2023). This is because these elements are highly toxic, persist in the environment and are capable of bioaccumulation. The most common methods for removing heavy metals from all components of the environment are adsorption methods (Pstrowska et al., 2024, Saraydın et al., 2022, Kochubei et al., 2020, Soloviy et al., 2020). Research into the content of heavy metals in the soil and plants of landfill sites allows us to id entify the scale of man-made pollution and assess the risks to ecosystems and public health. Studies on the impact of landfills on surrounding ecosystems can be found in the works of foreign scientists (Beinabaj et al., 2023; Vongdala et al., 2018).

2. Materials and Methods

Four household waste landfills within the Western Forest-Steppe were selected for the study (Fig. 1).

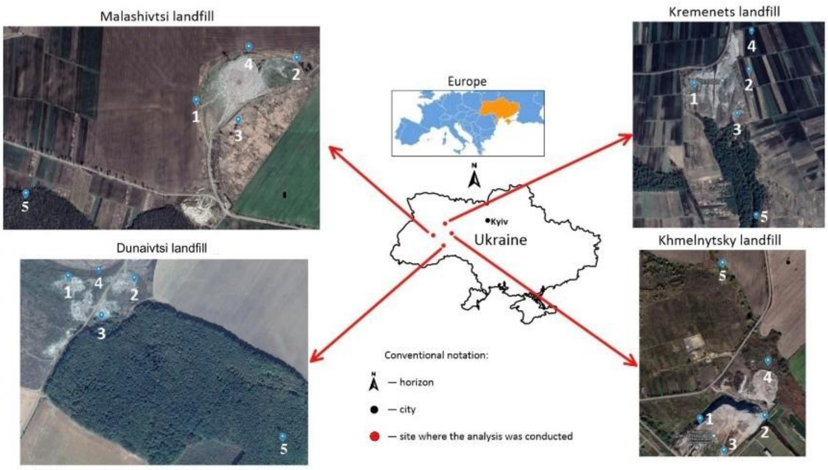

Fig. 1. Landfill localization: 1, 2, 3, 4, 5 – sampling sites (Google Earth)

Soil and plant samples were collected from four sides of each landfill, from which samples for research were formed. The gross content of chemical elements in soil and plant ash samples was analyzed using X-ray fluorescence analysis. This method is effective and simple for determining and assessing soil and plant contamination (Huminilovych et al., 2024). X-ray fluorescence (XRF) analysis is a powerful and widely used tool for determining the elemental composition and concentration of chemical species in materials (An, 2020).

Subsequently, to determine the environmental hazard and degree of contamination from the impact of household waste landfills, contamination coefficients, a total contamination index, and the coefficient of adsorption of chemical elements from the soil by plants were calculated.

The most common species of herbaceous plants adapted to growing in landfill conditions were selected. Plant samples were collected from four sides of each landfill site and combined into composite samples. These included *Artemisia vulgaris L.*, *Asarum europaeum L.*, *Solidago gigantea*, *Heracleum sosnowskyi*, *Rosa dumalis*. The study of flora that naturally grows on landfill sites is a valuable scientific field for determining the conditions of plant growth (humidity, temperature, lighting) and bioindication of soil contamination (Skrobala et al., 2024).

2.1. Methods of soil and plant sampling

Soil samples were collected in accordance with the rules set out in (DSTU 4287:2004, 2005). Soil samples for analysis were collected using a shovel. The combined sample should weigh approximately one kilogram. The first step was to remove the top layer of soil (1–5 cm), and samples were taken from depths of 5–10 cm and 10–20 cm by the envelope method, preventing the samples from mixing. One composite sample consisted of 5 point samples, which were taken on a 1 m x 1 m site at the four corners of an imaginary envelope and in the middle of it. Visible vegetation remains, soil fauna elements, and foreign impurities (stones) were carefully removed from the selected sample. Then, these 5 point samples were mixed by quartering on a sheet of thick paper and poured into plastic bags with stickers, and appropriately labeled (DSTU 4287:2004, 2005; Kochmar & Levynska, 2024).

2.2. Methodology of the component composition determination of soils

To measure the content of studied elements, soil samples were prepared in accordance with (DSTU ISO 11464:2007, 2012). The measurement of the content of studied elements in soil was carried out using an ElvaX Light SDD X-rayfluorescence analyzer. The device can detect chemical elements in the range from ^{11}Na to ^{92}U with high accuracy (0.01 %). The data collection time was 2 × 180 s for all samples. The absolute measurement error limits were ±0.05–0.2 % (measurement time 180 s). Each sample was measured in triplicate. The concentration of the studied elements in the soil samples was determined in mg/kg. For soil analysis, samples (~2 g) were placed on a transparent (for X-rays) ultra-thin (4 μm) polypropylene film (included in the device delivery set) and carefully transferred to the device for measurements. The methodology is described in more detail in (Pidlisnyuk et al., 2022).

2.3. Assessment of the ecological state of soils

Since there is no up-to-date data on determining the actual state of soils in the regions of Ukraine, it was decided to compare the determined values with the values in the background area, which is located at a distance of at least 1 km from the landfills and away from highways. The environmental assessment was carried out by comparing the actual concentration values of the tested samples with the background concentrations. The soil contamination level was assessed using the concentration coefficient (K_c), since soils are often contaminated with several elements, the total contamination index (Z_c) is calculated using a methodology that is widely used by scientists (Chaika et al., 2018; Madzhd et al., 2016; Sonko et al., 2020).

The concentration coefficient K_C is defined as the ratio of the actual content of a chemical element in the soil to the background content of the same element according to Formula 1:

$$K_C = \frac{C_i}{C_b}, \quad (1)$$

where C_i is the content of the chemical element in a particular object, mg/kg; C_b is a background content of the chemical element in soil, mg/kg.

The total pollution index, which reflects the complex effect of the impact of the group of analyzed elements and is calculated by Formula 2:

$$Z_c = (\sum_{i=1}^{n} K_{C_i}) - (n-1), \quad (2)$$

where Z_c is the total soil contamination index; K_{C_i} is the concentration coefficient of i-th chemical element in soil sample; n is the number of chemical elements included in the calculation.

The assessment of the soil contamination hazard by a complex of chemical elements according to the Z_c indicator is based on an assessment scale, the gradation of which is based on a review of the health status of the population inhabiting areas with different levels of soil contamination (Table 1).

Table 1

Approximate assessment scale of soil contamination hazard based on the total indicator Z_c (Chaika et al., 2018; Madzhd et al., 2016)

Soil contamination category	Z_c	Change in health indicators of residents in areas of soil contamination
Acceptable	<16	Lowest level of childhood morbidity and minimum functional abnormalities in the adult population
Moderately hazardous	16–32	Increase in overall morbidity
Hazardous	32–128	Increase in overall morbidity, number of children who are frequently ill, children with chronic diseases, cardiovascular disorders
Extremely hazardous	>128	Increase in the incidence of disease among children, reproductive disorders in women (increase in cases of toxicosis during pregnancy, premature births, stillbirths, infant hypotrophy)

2.4. Assessment of biological uptake of heavy metals by plants

In order to identify the behavior of heavy metals in the soil-plant system, biological accumulation coefficients (K_b) were calculated according to the Formula 3:

$$K_b = C_p / C_s, \quad (3)$$

where C_p is the concentration of a chemical element in plant ash, mg/kg; C_s is the concentration of a chemical element in soil, mg/kg. This method is actively used in scientific research for studying the ecological hazard of absorption and accumulation of harmful substances from soil by plants (Konovalenko et al., 2019; Samchuk et al., 2015).

3. Results and Discussion

Investigating the concentration of heavy metals in soils and plants at municipal waste landfills enables the assessment of the level of contamination and impact both within the landfills and beyond their sanitary protection zones. Large landfills are usually located near agricultural land, populated areas, recreational areas, and forest areas. Therefore, studying the possible impact of landfills will help prevent consequences for both the environment and human health.

Particular attention should be paid to examining the concentration of harmful chemicals, which are classified according to their effect on the body as follows:

– carcinogenic (blastogenic) compounds (benzo(a)pyrene, arsenic (As), mercury (Hg), lead (Pb), zinc (Zn), molybdenum (Mo), nickel (Ni));

– sensitizing chemicals or allergens (nickel (Ni));

– mutagenic substances (lead (Pb), manganese (Mn));

– substances exhibiting reproductive toxicity (mercury (Hg), lead (Pb), manganese (Mn)) (Ministry of Health of Ukraine, 2020).

3.1. Results of soil and plant contamination assessment at the Malashivtsi landfill

The chemical element content in the soil at the Malashivtsi landfill is shown in Table 2, and in plants in Table 3.

Table 2

Metal content in the soils of a landfill site near the village of Malashivtsi (Ternopil region), mg/kg

Element	Sampling site									
	North		South		West		East		Background	
	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm
Ti	7766.03 ± 507.21	6702.47 ± 485.73	6907.53 ± 493.33	6962.62 ± 507.16	6609.31 ± 508.87	6756.55 ± 479.53	6173.01 ± 465.01	6139.24 ± 444.56	5720.07 ± 528.69	4810.67 ± 544.74
Mn	928.68 ± 96.64	771.74 ± 94.18	635.70 ± 91.96	702.05 ± 94.47	842.19 ± 95.61	795.18 ± 96.32	765.93 ± 93.57	667.75 ± 87.51	551.53 ± 100.73	622.91 ± 102.07
Fe	28863.82 ± 298.42	28105.72 ± 297.68	28840.39 ± 299.99	30588.75 ± 315.88	30944.49 ± 316.72	31207.64 ± 317.47	27554.91 ± 289.33	28787.78 ± 290.99	15085.90 ± 244.10	17254.95 ± 271.17
Ni	49.59 ± 21.96	31.49 ± 23.36	34.22 ± 23.62	41.93 ± 24.72	41.45 ± 23.92	37.15 ± 23.63	42.18 ± 20.88	22.65 ± 22.73	20.23 ± 24.45	37.37 ± 25.08
Cu	25.14 ± 16.06	30.57 ± 15.04	25.98 ± 15.50	28.67 ± 15.88	25.19 ± 15.94	39.73 ± 16.30	30.00 ± 15.17	32.50 ± 15.17	18.58 ± 17.19	< 18.59*
Zn	79.35 ± 13.10	65.74 ± 12.46	70.00 ± 12.42	83.91 ± 12.49	61.24 ± 13.34	66.11 ± 12.22	< 14.64*	61.43 ± 11.17	492.89 ± 23.42	394.82 ± 22.66
Rb	123.85 ± 5.05	118.98 ± 4.96	122.78 ± 5.04	129.19 ± 5.34	121.43 ± 5.15	120.20 ± 5.08	113.99 ± 4.77	110.44 ± 4.55	56.09 ± 4.38	57.71 ± 4.69
Sr	124.97 ± 4.72	127.43 ± 4.69	127.15 ± 4.77	133.88 ± 4.97	132.16 ± 4.97	128.62 ± 4.74	125.01 ± 4.60	123.77 ± 4.47	263.49 ± 7.10	303.61 ± 7.74
Y	43.10 ± 4.56	39.80 ± 4.40	40.52 ± 4.43	46.59 ± 4.75	44.93 ± 4.72	43.55 ± 4.54	39.72 ± 4.36	42.22 ± 4.10	18.02 ± 4.40	29.40 ± 4.75
Zr	739.41 ± 10.32	720.81 ± 10.17	756.32 ± 10.40	795.15 ± 11.09	743.80 ± 10.63	704.80 ± 10.13	762.87 ± 10.27	655.71 ± 9.40	508.58 ± 10.11	441.85 ± 9.98
Pb	55.02 ± 8.77	34.61 ± 7.71	34.72 ± 7.74	30.60 ± 8.22	39.98 ± 8.35	28.08 ± 7.84	30.11 ± 7.59	24.03 ± 7.09	76.22 ± 10.16	58.69 ± 9.95

Note: * – concentration below the detection limit or error prevails over the value (disregarded).

Table 3

Heavy metal content in plants at the Malashivtsi landfill, mg/kg

Element	North	South	West	East	Background
Ti	558.7380 ± 161.0047	544.2243 ± 158.9505	826.6244 ± 143.0802	436.0970 ± 144.4194	1299.7835 ± 130.5901
Mn	553.1877 ± 30.6582	1596.3669 ± 40.9394	2552.4572 ± 46.5884	452.9799 ± 27.1107	1465.1004 ± 35.2781
Fe	4084.5131 ± 46.4309	4275.4351 ± 51.6810	6559.7684 ± 61.1303	3545.5514 ± 40.8151	7879.8888 ± 61.0422
Cu	129.9642 ± 7.6579	177.5801 ± 8.4398	256.1237 ± 8.8399	91.8472 ± 6.6715	271.1702 ± 8.3233
Zn	351.2745 ± 7.6141	392.2409 ± 8.4707	372.1321 ± 7.9396	478.5243 ± 7.8976	2447.9741 ± 17.0669
Br	76.1647 ± 4.8829	355.8088 ± 6.2611	271.5502 ± 5.2480	–	164.9632 ± 4.6331
Sr	1042.6921 ± 8.4622	591.1558 ± 7.9735	637.4424 ± 7.4740	948.3030 ± 7.6049	1003.9173 ± 7.8056
Y	–	–	49.9826 ± 6.7148	6.8329 ± 6.0317	28.3769 ± 6.0396
Zr	–	60.7410 ± 8.2198	99.6361 ± 7.5770	–	190.4415 ± 7.4617
Pb	< 5.7828	< 6.0974	< 5.6759	< 5.2225	< 5.4521

Note: – not detected; * – concentration below the detection limit or error prevails over the value (disregarded).

It can be seen that the concentrations of heavy metals in soil samples from the Malashivtsi landfill exceed background values (Table 4). Analysis of the spatial distribution of heavy metals shows that on the north side, the highest concentrations of Ti, Mn, Ni, Rb, and Pb are found; on the west side, there are high levels of Fe and Y and moderate contamination with Ni; on the east side, there is a relatively uniform accumulation, particularly of Cu and Zr, although Zn is below the detection limit; on the southern side, there are generally average levels of contamination, with high concentrations of Rb and Y (Table 5).

According to the calculated concentration coefficients of pollutants (Table 4), namely heavy metals, in soil samples from the Malashivtsi landfill, most indicators are higher than 1. The exceptions are Zn, Sr, and Pb. However, if we accept the background values according to Vinogradov (Zn–52 mg/kg, Sr-119 mg/kg), then the Zn indicators exceed the background values by 1.181–1.614 times (with the exception of the east 5–10 cm), Sr is 1.040–1.125 times higher, and Pb is 2.185–5.002 times higher, respectively (Fatjejev & Paščenko, 2003). Considering the concentration of heavy metals in soils and plants, a correlation analysis shows a strong correlation between the concentration of chemical elements in soils and plant samples, indicating that the soil is an accumulator of pollutants coming from the landfill with leachate and as a result of waste decomposition.

The total soil pollution index $Z_c<16$, i.e., these soils belong to the acceptable pollution category, which is characterized by the lowest incidence of children's diseases and a minimum of functional deviations in the adult population.

The highest values of the coefficient of variation are for Zn, Pb, Cu, and Mn, but the maximum value is over 25 % for Zn (Table 5). The rest of the values are below 5 %. The low heterogeneity of heavy metal distribution indicates uniform contamination from the landfill body (transfer with filtrate or airborne dispersion).

Table 4

Concentration coefficient of the investigated elements in the soils of the Malashivtsi landfill

Horizon side	North		South		West		East	
Sampling depth (cm)	5–10	10–20	5–10	10–20	5–10	10–20	5–10	10–20
Ti	1.358	1.393	1.208	1.447	1.155	1.404	1.079	1.276
Mn	1.684	1.239	1.153	1.127	1.527	1.277	1.389	1.072
Fe	1.913	1.629	1.912	1.773	2.051	1.809	1.827	1.668
Ni	2.451	0.843	1.692	1.122	2.049	0.994	2.085	0.606
Cu	1.353	1.644	1.398	1.542	1.356	2.137	1.615	1.748
Zn	0.161	0.167	0.142	0.213	0.124	0.167	0.030	0.156
Rb	2.208	2.062	2.189	2.239	2.165	2.083	2.032	1.914
Sr	0.474	0.420	0.483	0.441	0.502	0.424	0.474	0.408
Y	2.392	1.354	2.249	1.585	2.493	1.481	2.204	1.436
Zr	1.454	1.631	1.487	1.800	1.463	1.595	1.500	1.484
Pb	0.722	0.590	0.456	0.521	0.525	0.478	0.395	0.409
Z_c	6.170	2.971	4.367	3.809	5.409	3.850	4.630	2.177

Table 5

Coefficient of variation of heavy metals in the investigated soils of the Malashivtsi landfill

Element	Mean	Standard deviation	Coefficient of variation, %
Sr	128.48	2.29	1.78
Ni	39.4	1.02	2.6
Rb	121.33	3.65	3
Zr	741	23.49	3.17
Y	42.72	1.39	3.25
Fe	29664.17	1075.02	3.62
Ti	6829.26	331.4	4.85
Mn	779.58	79.11	10.15
Cu	30.63	3.65	11.91
Pb	35.15	6.77	19.26
Zn	63.39	16.31	25.72

3.2. Results of soil and plant contamination assessment at the Khmelnitskyi landfill

Concentrations of heavy metals in the soil of the Khmelnytskyi landfill exceed background levels. In particular, the highest levels are detected: on the north side: Cr, Mn, Fe, Zn, Cu, Sr, Pb; on the south side: Ti, Rb; on the west side: Zr; on the east side: Ni (Table 6). The content of heavy metals in plants is shown in Table 7.

Table 6

Metal content in soils at the Khmelnytskyi municipal waste landfill, mg/kg

Element	Sampling site									
	North		South		West		East		Background	
	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm
Ti	5484.14 ± 494.38	6187.34 ± 475.96	6220.36 ± 411.86	6311.66 ± 411.31	6167.57 ± 445.68	5811.34 ± 416.76	5835.95 ± 478.83	5462.92 ± 506.33	5933.59 ± 429.61	6162.33 ± 414.85
Cr	680.58 ± 131.33	1252.62 ± 139.09	155.69 ± 94.72	–	–	122.28 ± 97.58	–	–	–	187.75 ± 94.06
Mn	1138.12 ± 109.29	1068.08 ± 107.45	822.66 ± 80.68	651.84 ± 79.74	760.57 ± 86.65	647.15 ± 78.10	902.23 ± 94.39	837.08 ± 99.81	708.87 ± 80.28	744.25 ± 82.29
Fe	31136.85 ± 330.75	31882.51 ± 325.92	25612.94 ± 261.61	24191.65 ± 246.90	26488.79 ± 277.74	24425.32 ± 250.71	30313.40 ± 318.13	25763.52 ± 308.94	25973.15 ± 264.96	27568.00 ± 270.22
Ni	28.71 ± 23.82	24.35 ± 25.11	35.39 ± 19.52	–	–	29.14 ± 18.67	41.18 ± 24.72	33.24 ± 24.36	30.54 ± 19.93	22.59 ± 20.43
Cu	101.08 ± 17.16	71.37 ± 16.47	< 17.05*	19.80 ± 12.98	34.48 ± 14.54	23.61 ± 13.09	46.06 ± 15.22	43.70 ± 17.41	17.75 ± 13.26	29.77 ± 12.83
Zn	478.90 ± 21.74	469.14 ± 20.77	77.91 ± 11.30	62.70 ± 10.34	79.03 ± 11.41	63.42 ± 10.67	157.47 ± 14.12	268.17 ± 18.31	51.03 ± 10.71	60.55 ± 10.64
Rb	97.41 ± 4.77	99.49 ± 4.68	113.20 ± 4.29	107.05 ± 4.22	111.44 ± 4.62	104.27 ± 4.16	109.11 ± 4.85	89.58 ± 4.92	111.40 ± 4.35	110.72 ± 4.42
Sr	285.28 ± 6.83	244.55 ± 6.14	112.28 ± 3.93	106.17 ± 3.79	118.45 ± 4.30	111.52 ± 3.93	174.65 ± 5.36	271.82 ± 6.93	113.04 ± 4.08	113.79 ± 4.04
Y	29.94 ± 4.36	33.37 ± 4.19	37.73 ± 3.76	37.89 ± 3.69	39.91 ± 4.01	34.75 ± 3.70	38.73 ± 4.28	27.77 ± 4.47	37.10 ± 3.86	39.92 ± 3.87
Zr	571.19 ± 9.94	477.44 ± 8.84	596.68 ± 8.32	554.91 ± 7.89	652.91 ± 9.22	619.70 ± 8.44	561.51 ± 9.37	436.92 ± 9.17	637.88 ± 8.81	604.06 ± 8.54
Pb	57.57 ± 8.98	52.84 ± 8.29	32.60 ± 6.58	37.28 ± 6.76	38.27 ± 7.50	32.22 ± 6.30	32.00 ± 8.35	37.62 ± 8.78	28.99 ± 6.72	29.13 ± 6.64

Note: – not detected; * – concentration below the detection limit or error prevails over the value (disregarded).

Table 7

Heavy metal content in plants at the Khmelnitskyi landfill, mg/kg

Element	North	South	West	East	Background
1	2	3	4	5	6
Ti	948.1998 ± 154.0662	592.0510 ± 146.4338	633.5781 ± 133.0775	704.0075 ± 138.5843	695.4523 ± 153.9208
Mn	606.6879 ± 31.9388	642.8020 ± 32.2302	1583.6450 ± 37.7148	< 39.5314*	803.5019 ± 31.8143
Fe	6312.6051 ± 60.5855	3450.0587 ± 45.8046	4369.1836 ± 48.8586	796.0194 ± 32.8395	5283.8638 ± 51.9781
Cu	89.0758 ± 7.4441	112.9237 ± 7.4388	386.9693 ± 9.6399	5985.4612 ± 57.3866	92.1664 ± 7.1189
Zn	1201.1651 ± 13.2248	705.9494 ± 10.3305	911.6500 ± 10.9391	71.0105 ± 6.7374	303.5705 ± 7.1111

Continuation of Table 7

1	2	3	4	5	6
Br	< 5.5728*	6150.4607 ± 23.3841	119.9869 ± 4.8285	608.1508 ± 9.5009	240.7895 ± 5.3613
Sr	801.8696 ± 8.4759	549.9723 ± 7.3033	652.4355 ± 7.2016	157.0060 ± 5.1682	829.4102 ± 7.9942
Y	< 7.5014*	< 6.6855*	–	652.5023 ± 7.7251	117.7514 ± 7.8230
Zr	89.5946 ± 8.4767	< 7.5854	25.9055 ± 7.0606	110.5141 ± 7.9161	65.0867 ± 5.9337
Pb	< 6.3634	50.6636 ± 5.7823	64.4902 ± 5.7349	15.1762 ± 5.6912	–

Note: – not detected; * – concentration below the detection limit or error prevails over the value (disregarded).

According to the calculated total soil contamination index on the northern side at depths of 5–10 cm and 10–20 cm, the soil at the Khmelnytskyi landfill is moderately hazardous on the northern side, since $Z_c > 16$, which may lead to an increase in the overall morbidity rate of the population (Table 8). The concentration coefficients of Cu, Zn, Sr, and Pb are also high on the northern side, Ti, Zn, and Pb on the southern side, all heavy msetals on the western side at a depth of 10–20 cm, and Mn, Fe, Ni, Cu, Zn, Sr, Y, and Pb on the eastern side. The coefficients of variation of heavy metals in the soil are listed in the table in ascending order (Table 9). The highest fluctuations are demonstrated by Sr, Cu, Zn, and Cr. The average values are for Ni, Mn, and Pb. The lowest values of the coefficients of variation are for Ti, Rb, Y, Zr, and Fe.

Table 8

Concentration coefficient of the investigated elements in the soils of the Khmelnytskyi landfill

Horizon side	North		South		West		East	
Sampling depth (cm)	5–10	10–20	5–10	10–20	5–10	10–20	5–10	10–20
Ti	0.924	1.004	1.048	1.024	1.039	0.943	0.984	0.887
Cr	–	6.672	–	–	–	0.651	–	0.000
Mn	1.606	1.435	1.161	0.876	1.073	0.870	1.273	1.125
Fe	1.199	1.157	0.986	0.878	1.020	0.886	1.167	0.935
Ni	0.940	1.078	1.159	–	–	1.290	1.348	1.471
Cu	5.695	2.397	–	0.665	1.943	0.793	2.595	1.468
Zn	9.385	7.748	1.527	1.036	1.549	1.047	3.086	4.429
Rb	0.874	0.899	1.016	0.967	1.000	0.942	0.979	0.809
Sr	2.524	2.149	0.993	0.933	1.048	0.980	1.545	2.389
Y	0.807	0.836	1.017	0.949	1.076	0.870	1.044	0.696
Zr	0.895	0.790	0.935	0.919	1.024	1.026	0.880	0.723
Pb	1.986	1.814	1.125	1.280	1.320	1.106	1.104	1.291
Z_c	16.834	16.979	1.967	0.526	3.091	0.405	6.005	5.222

Table 9

Coefficient of variation of heavy metals in the investigated soils of the Khmelnytskyi landfill

Element	Mean	Standard deviation	Coefficient of variation, %
Ti	5935.16	260.73	4.39
Rb	103.94	5.91	5.69
Y	35.01	3.03	8.66
Zr	558.91	60.65	10.85
Fe	27476.87	3015.90	10.98
Ni	32.07	5.06	15.77
Mn	853.47	181.17	21.23
Pb	40.05	10.10	25.23
Sr	178.09	78.11	43.86
Cu	44.99	29.38	65.30
Zn	207.09	190.13	91.81
Cr	414.86	478.12	115.25

3.3. Results of soil and plant contamination assessment at the Dunaivtsi landfill

The concentration of heavy metals is higher than background levels on the western side for Fe, Cu, Zn, Sr, and Pb, on the eastern side for Rb, on the northern side for Ni, and on the southern side for Y and Zr (Tables 10, 11). This may indicate the main direction of pollution spread from the landfill or the presence of the largest sources of pollution here. There is an uneven accumulation of waste across the landfill, with the highest concentration on the western side. Particular attention should be paid to lead, as it belongs to the first hazard group. According to the approved standards, the MPC for lead in soil is 32 mg/kg. This means that the indicators on all sides of the Dunaivtsi landfill exceed the MPC, in particular on the western side by 2.43 times and on the southern side by 1.6 times. These are significant indicators that testify to the significant impact of pollution.

Table 10

Heavy metal content in soils at the Dunaivtsi landfill, mg/kg

Element	Sampling site									
	North		South		West		East		Background	
	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm
Ti	6233.63 ± 431.24	6740.36 ± 447.02	7002.59 ± 485.13	6623.10 ± 468.06	5759.32 ± 486.21	5663.55 ± 482.13	7032.43 ± 440.07	7056.24 ± 452.62	6758.81 ± 424.64	7156.55 ± 440.77
Mn	688.10 ± 80.76	807.04 ± 86.14	919.16 ± 91.37	934.08 ± 91.32	943.89 ± 103.93	983.53 ± 100.62	803.42 ± 84.24	910.73 ± 89.70	763.95 ± 79.04	691.29 ± 80.87
Fe	29753.79 ± 284.91	29100.00 ± 291.70	30794.15 ± 304.04	31237.04 ± 304.11	40624.44 ± 384.79	37731.36 ± 369.17	27365.49 ± 273.68	29492.81 ± 289.07	22209.39 ± 239.76	21745.14 ± 240.32
Ni	33.44 ± 19.19	25.85 ± 20.52	29.07 ± 22.72	26.74 ± 22.34	56.58 ± 25.41	28.59 ± 25.74	20.29 ± 19.91	31.73 ± 20.54	27.19 ± 18.52	16.61 ± 18.81*
Cu	41.52 ± 12.72	27.89 ± 13.74	< 21.64*	< 19.36*	58.63 ± 18.44	77.39 ± 17.01	26.02 ± 12.99	23.84 ± 13.39	11.14 ± 11.92*	< 12.32*
Zn	121.54 ± 12.02	95.68 ± 12.34	97.00 ± 13.27	94.98 ± 12.64	209.17 ± 17.14	245.54 ± 17.97	77.18 ± 10.89	77.05 ± 11.30	54.88 ± 10.28	56.06 ± 9.89
Rb	106.88 ± 4.33	113.08 ± 4.61	120.45 ± 4.98	123.48 ± 4.94	120.00 ± 5.32	94.51 ± 4.96	125.41 ± 4.57	126.18 ± 4.76	108.07 ± 4.19	109.78 ± 4.28
Sr	135.48 ± 4.32	154.71 ± 4.82	121.14 ± 4.49	122.78 ± 4.47	308.93 ± 7.16	337.95 ± 7.48	114.51 ± 4.08	114.24 ± 4.15	100.51 ± 3.75	104.54 ± 3.86
Y	32.73 ± 3.70	35.31 ± 3.99	42.11 ± 4.29	41.89 ± 4.32	31.59 ± 4.44	31.01 ± 4.24	34.77 ± 3.86	38.00 ± 3.95	38.00 ± 3.72	38.05 ± 3.74
Zr	464.67 ± 7.68	510.47 ± 8.32	700.52 ± 9.82	682.72 ± 9.59	357.43 ± 8.37	366.88 ± 8.47	508.07 ± 7.93	527.93 ± 8.22	603.89 ± 8.31	616.87 ± 8.51
Pb	40.29 ± 7.48	37.36 ± 7.26	51.08 ± 8.14	45.35 ± 7.98	77.62 ± 10.07	68.29 ± 9.91	31.90 ± 6.87	36.85 ± 7.14	31.46 ± 6.52	25.52 ± 6.28

Note: * – concentration below the detection limit or error prevails over the value (disregarded).

Table 11

Heavy metal content in plants at the Dunaivtsi landfill, mg/kg

Element	North	South	West	East	Background
1	2	3	4	5	6
Ti	1295.1996 ± 155.6429	2943.9329 ± 150.9164	1354.6819 ± 149.1772	2971.8147 ± 158.1853	1707.1387 ± 150.0701
Mn	1083.3476 ± 37.2393	1137.7407 ± 34.2601	771.3374 ± 32.2259	2957.3264 ± 51.6034	1601.1985 ± 39.9381
Fe	8703.2796 ± 71.2235	16188.1301 ± 89.4293	8749.1874 ± 69.6360	15839.1423 ± 102.6866	10379.3601 ± 75.8976
Ni	–	50.1348 ± 10.5361	–	–	

Continuation of Table 11

1	2	3	4	5	6
Cu	159.9640 ± 8.5235	195.5994 ± 8.3319	153.6914 ± 7.9306	129.2309 ± 8.3212	224.7910 ± 8.8994
Zn	981.9039 ± 12.2659	629.6850 ± 9.3448	926.2861 ± 11.5695	699.9602 ± 10.6853	2036.9499 ± 16.8481
Br	< 5.7383	151.6368 ± 4.7575	90.5361 ± 4.9417	257.9822 ± 5.7060	165.9288 ± 5.1955
Sr	838.2177 ± 8.6532	581.8912 ± 7.0431	1114.2215 ± 9.0026	435.1392 ± 7.4732	951.4983 ± 8.5277
Y	25.2868 ± 7.3749	< 6.5790	29.5313 ± 6.8815	59.4532 ± 7.2857	44.7829 ± 6.9862
Zr	102.6988 ± 8.6198	220.9404 ± 7.5409	166.5563 ± 8.3948	597.8368 ± 9.1159	487.3136 ± 8.9285
Pb	33.5025 ± 6.4928	56.0479 ± 5.8742	< 6.2024*	33.1259 ± 6.3001	36.4546 ± 6.1048

Note: – not detected; * – concentration below the detection limit or error prevails over the value (disregarded).

The concentration coefficients of heavy metals Ti, Zr, and Y are lower than 1. High pollution levels are detected for Zn, Cu, Pb, Sr, Fe, Ni, and Mn (especially on the western side) (Table 12). The highest values of the coefficients of variation of heavy metals in the soil of the Dunaivtsi landfill are for Zn, Sr, and Cu, exceeding 50 %; Y, Fe, Ni, Zr, and Pb are in the range of 10–35 %, while the uniformity of distribution of Rb and Ti is less than 10 % (Table 13).

Table 12

Concentration coefficient of the investigated metals in the soils of the Dunaivtsi landfill

Horizon side	North		South		West		East	
Sampling depth (cm)	5–10	10–20	5–10	10–20	5–10	10–20	5–10	10–20
Ti	0.922	0.942	1.036	0.925	0.852	0.791	1.040	0.986
Mn	0.901	1.167	1.203	1.351	1.236	1.423	1.052	1.317
Fe	1.340	1.338	1.387	1.437	1.829	1.735	1.232	1.356
Ni	1.230	1.556	1.069	1.610	2.081	1.721	0.746	1.910
Cu	3.727	2.264	1.943	1.571	5.263	6.282	2.336	1.935
Zn	2.215	1.707	1.767	1.694	3.811	4.380	1.406	1.374
Rb	0.989	1.030	1.115	1.125	1.110	0.861	1.160	1.149
Sr	1.348	1.480	1.205	1.174	3.074	3.233	1.139	1.093
Y	0.861	0.928	1.108	1.101	0.831	0.815	0.915	0.999
Zr	0.769	0.828	1.160	1.107	0.592	0.595	0.841	0.856
Pb	1.281	1.464	1.624	1.777	2.467	2.676	1.014	1.444
Z_c	5.583	4.704	4.617	4.873	13.147	14.511	2.883	4.420

Table 13

Coefficient of variation of heavy metals in the investigated soils of the Dunaivtsi landfill

Element	Mean	Standard deviation	Coefficient of variation, %
Rb	116.25	9.02	7.76
Ti	6513.90	581.78	8.93
Mn	873.74	95.02	10.88
Y	35.93	4.55	12.67
Fe	32012.39	4894.30	15.29
Ni	31.54	7.51	23.83
Zr	514.84	135.79	26.38
Pb	48.59	17.24	35.47
Zn	127.27	67.97	53.41
Sr	176.22	99.01	56.19
Cu	37.04	21.49	58.01

3.4. Results of the assessment of soil and plant contamination at the Kremenets landfill site

Heavy metal content in the soil of the Kremenets landfill is highest in the following areas: Ti Ni Y, Zr, Pb in the north; Mn, Cu, Zn, Sr in the west; Fe, Rb in the south; and Pb in the east (Tables 14, 15). The concentration of lead exceeds the MPC on the western (1.65 times) and eastern (2.44 times) sides of the horizon. The concentration of zinc on all sides of the horizon exceeds the MPC (23 mg/kg), in particular on the western side – by 13.8 times. The concentration of nickel also significantly exceeds the MPC (4 mg/kg).

Table 14

Metal content in soils at the Kremenets municipal waste landfill, mg/kg

Element	Sampling site									
	North		South		West		East		Background	
	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm	5–10 cm	10–20 cm
Ti	6143.65 ± 489.28	6151.96 ± 491.63	6097.49 ± 435.92	5613.89 ± 437.52	6214.10 ± 512.71	4685.75 ± 501.06	5563.30 ± 453.95	4761.37 ± 461.35	5684.84 ± 429.97	5725.41 ± 452.09
Mn	706.92 ± 87.96	609.19 ± 89.25	509.03 ± 80.55	577.77 ± 81.37	485.99 ± 90.50	610.91 ± 96.89	625.82 ± 89.46	614.90 ± 90.07	502.44 ± 81.75	536.18 ± 83.30
Fe	22249.57 ± 262.22	21808.44 ± 258.63	23491.81 ± 258.98	22831.03 ± 253.80	18716.54 ± 257.89	22642.04 ± 287.68	22329.00 ± 253.37	18271.91 ± 252.94	20212.50 ± 230.88	22203.33 ± 253.31
Ni	43.91 ± 21.98	< 22.80*	40.22 ± 19.86	21.86 ± 21.03	45.12 ± 20.74	14.78 ± 24.73*	26.15 ± 21.19	36.56 ± 22.33	22.31 ± 19.37	23.06 ± 21.76
Cu	24.32 ± 15.28	20.19 ± 15.35	16.95 ± 13.04	22.83 ± 14.06	35.09 ± 15.87	58.73 ± 17.93	21.16 ± 14.61	34.21 ± 15.74	10.94 ± 13.20	20.37 ± 13.95
Zn	67.29 ± 11.00	46.95 ± 11.64	56.04 ± 10.97	53.70 ± 10.84	108.00 ± 14.09	316.45 ± 19.79	46.27 ± 11.29	96.80 ± 13.72	45.31 ± 10.32	52.48 ± 11.23
Rb	98.15 ± 4.67	99.82 ± 4.64	99.19 ± 4.38	97.30 ± 4.34	71.05 ± 4.43	62.44 ± 4.33	99.81 ± 4.49	73.66 ± 4.56	87.12 ± 4.08	93.92 ± 4.42
Sr	130.47 ± 4.78	129.20 ± 4.77	102.30 ± 4.18	110.37 ± 4.21	206.31 ± 6.11	241.68 ± 6.52	127.42 ± 4.61	222.16 ± 6.20	105.69 ± 4.02	114.90 ± 4.35
Y	38.15 ± 4.38	38.19 ± 4.44	34.75 ± 4.05	32.70 ± 3.97	23.24 ± 4.23	23.34 ± 4.26	36.45 ± 4.15	33.48 ± 4.38	34.82 ± 3.85	35.51 ± 4.10
Zr	806.52 ± 10.72	847.06 ± 10.98	730.38 ± 9.74	772.93 ± 9.93	565.83 ± 9.88	469.47 ± 9.31	798.97 ± 10.26	728.00 ± 10.87	717.37 ± 9.27	735.50 ± 9.90
Pb	25.78 ± 7.59	25.06 ± 7.34	25.26 ± 6.79	23.62 ± 6.70	34.33 ± 7.63	52.74 ± 8.87	27.43 ± 6.88	78.18 ± 9.10	22.34 ± 6.46	25.01 ± 6.95

Table 15

Heavy metal content in plants at the Kremenets landfill, mg/kg

Element	North	South	West	East	Background
Ti	907.7037 ± 143.5786	405.5285 ± 151.9224	582.3381 ± 142.7149	334.4222 ± 135.5152	808.0512 ± 138.0623
Mn	1051.4369 ± 33.6707	828.0747 ± 32.0677	501.5594 ± 29.2366	1124.3112 ± 34.6072	985.2961 ± 33.3176
Fe	6506.2065 ± 57.9354	3215.1191 ± 41.7667	4220.5069 ± 48.9170	3270.6708 ± 44.0157	5838.5824 ± 55.7018
Cu	117.8076 ± 7.0261	81.8960 ± 6.8523	410.3288 ± 10.3705	234.8313 ± 8.3635	219.8194 ± 8.2264
Zn	360.9297 ± 7.4696	251.2172 ± 6.5910	3553.1262 ± 22.2360	640.6354 ± 9.6482	754.4890 ± 10.2493
Br	190.7091 ± 5.1381	51.2577 ± 4.6926	184.6765 ± 5.2683	58.5239 ± 4.6270	467.8310 ± 6.2121
Sr	1032.3073 ± 8.2787	1072.4430 ± 8.3656	1360.3748 ± 9.5483	829.3521 ± 7.8947	589.0351 ± 7.3125
Y	22.1652 ± 6.4309	12.7657 ± 6.4011	–	–	–
Zr	72.6586 ± 7.6269	–	78.6272 ± 8.5562	–	–
Pb	< 5.5938*	< 5.5712*	< 6.0324*	< 5.4664*	< 5.6730*

Note: – not detected; * – concentration below the detection limit or error prevails over the value (disregarded).

All heavy metal concentration coefficients across the landfill, with a few exceptions, are higher than 1 (Table 16). The total soil contamination index of the Kremenets landfill ranges from 1.091 to 8.704. Therefore, it falls within the acceptable category of soil contamination.

However, the values vary depending on the depth and side of the horizon. In particular, the highest values on the western side of the landfill are Cu, Zn, Sr, Pb, and Ni. Values higher than 1 are found on the northern and eastern sides at a depth of 5–10 cm.

Table 16

Concentration coefficient of the heavy metals in the soils of the Kremenets landfill

Horizon side	North		South		West		East	
Sampling depth (cm)	5–10	10–20	5–10	10–20	5–10	10–20	5–10	10–20
Ti	1.081	1.075	1.073	0.981	1.093	0.818	0.979	0.832
Mn	1.407	1.136	1.013	1.078	0.967	1.139	1.246	1.147
Fe	1.101	0.982	1.162	1.028	0.926	1.020	1.105	0.823
Ni	1.968	0.989	1.803	0.948	2.022	0.641	1.172	1.585
Cu	2.223	0.991	1.549	1.121	3.207	2.883	1.934	1.679
Zn	1.485	0.895	1.237	1.023	2.384	6.030	1.021	1.845
Rb	1.127	1.063	1.139	1.036	0.816	0.665	1.146	0.784
Sr	1.234	1.124	0.968	0.961	1.952	2.103	1.206	1.934
Y	1.096	1.075	0.998	0.921	0.667	0.657	1.047	0.943
Zr	1.124	1.152	1.018	1.051	0.789	0.638	1.114	0.990
Pb	1.154	1.002	1.131	0.944	1.537	2.109	1.228	3.126
Z_c	5.000	1.484	3.090	1.091	6.360	8.704	3.196	5.687

The coefficient of variation is distinguished by high values for the variability of Zn, Cu, Pb, and Sr concentrations.

The distribution of Rb, Zr, and Y is more uniform. The coefficients of variation for Ni, Fe, Ti, and Mn are less than 10 % (Table 17).

Table 17

Coefficient of variation of heavy metals in the investigated soils of the Kremenets landfill

Element	Mean	Standard deviation	Coefficient of variation, %
Ni	31.43	1.42	4.52
Fe	21542.54	1309.63	6.08
Ti	5653.94	435.09	7.70
Mn	592.57	56.05	9.46
Rb	87.68	15.04	17.15
Zr	714.90	135.57	18.96
Y	32.54	6.44	19.80
Sr	158.74	51.95	32.73
Pb	36.55	13.95	38.16
Cu	29.19	12.26	42.00
Zn	98.94	75.89	76.70

3.5. Biological accumulation coefficients in the soil-plant system at municipal waste landfills

The biotic absorption coefficient is directly proportional to the intensity of biotic absorption of elements. Once they enter the biogeochemical cycle, metals are fixed by vegetation and, after a certain period of time, end up in precipitation. After decomposition of the precipitation, chemical elements are converted into water-soluble forms, re-entering the biotic cycle or being removed from the soil profile and ecosystem. Together with precipitation, heavy metals can migrate in a fixed state with wind and water flows and accumulate in collection areas or be carried out of the ecosystem. In this regard, the bioaccumulation coefficient reflects the self-cleaning ability of soils (Denchylia-Sakal et al., 2012; Kornelyuk, 2019; Ryženko, 2018).

Studying the efficiency of heavy metal absorption by plants allows for a qualitative and quantitative assessment of the prospects for phytomeliorative measures to restore technologically disturbed landscapes (slag heaps, landfills, etc.) (Fig. 2).

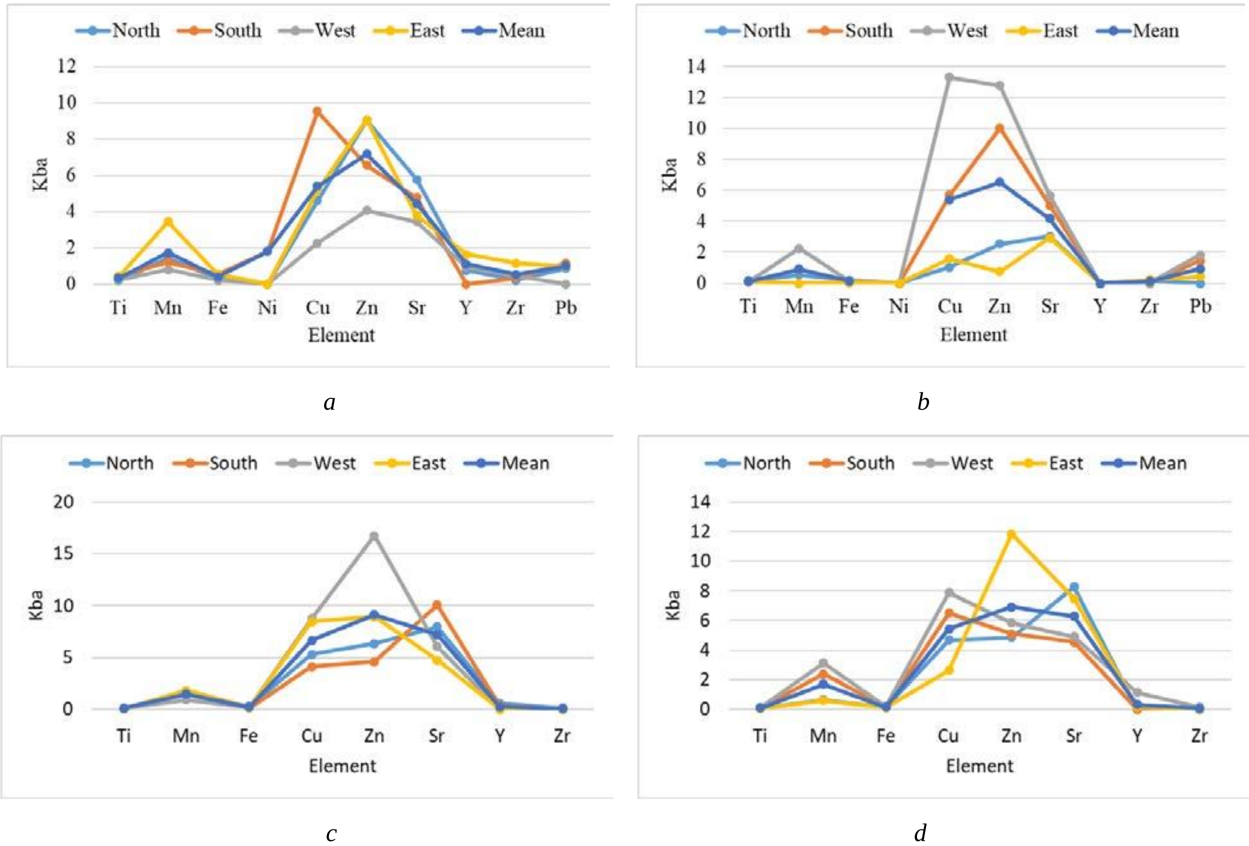

Fig. 2. Bioaccumulation coefficient (Kba) in the soil-plant system at landfills:
a – Dunaivtsi; *b* – Khmelnitskyi; *c* – Kremenets; *d* – Malashivtsi

At the Dunaivtsi landfill, the accumulation coefficients of heavy metals in plants are in ascending order

Ti<Fe<Zr<Pb<Y<Mn<Ni<Sr<Cu<Zn,

at the Khmelnitskyi landfill

Ti<Fe<Zr<Mn<Pb<Sr<Zn<Y<Cu,

at the Kremenets landfill

Zr<Ti<Fe<Y<Mn<Zn<Ni<Sr<Cu,

the Malashivtsi landfill

Zr<Ti<Fe<Y<Mn<Cu<Sr<Zn.

The highest accumulation rates are observed for strontium, copper, and zinc at all sites.

The mean values of Cu bioaccumulation coefficients are: at the Khmelnytskyi landfill – 38.36 and at the Kremenets landfill – 31.933. The biological absorption coefficient of Cu is high, as this metal has the ability to form strong complexes with organic matter (Tsytsyura et al., 2022).

The bioaccumulation coefficient values for Zn are high at municipal waste landfills: Dunaivtsi – 7.188, Malashivtsi – 6.909, Khmelnytskyi – 6.427.

4. Conclusions

The concentrations of heavy metals in the soils of municipal waste landfills exceed background values and maximum permissible concentrations.

Correlation analysis of the chemical element content on each side of the horizon of each object of study in selected samples of soil layers 5–10 cm and 10–20 cm shows a strong relationship, i.e., with an increase in concentration in the upper layer, the concentration in the lower layer also increases. This indicates the surface influx and active migration of chemical elements, which occurs in the favorable conditions of the black soil environment. In other words, there is a constant influence of leachate from the landfill on environmental components, which enters the upper horizon and seeps into deeper soil layers.

The highest values of the total soil contamination index were recorded at the Khmelnytskyi and Dunaivtsi landfills, which may indicate the intensive spread of pollutants from the landfill bodies into the environment.

Vertical migration of heavy metals in the soil profile is observed, confirming the presence of mobile forms of heavy metals and a high probability of penetration into surface and groundwater.

Plants showed a high capacity for bioaccumulation of heavy metals, in particular Mn, Zn, Sr, and Cu, which poses a risk of toxicants entering the food chain.

The highest exceedances of maximum permissible concentrations were observed for Pb, Zn, Cu, and Ni – elements that have carcinogenic, mutagenic, or toxic properties.

The results of the studies indicate the need to introduce regular environmental monitoring in areas affected by household waste landfills, improve waste management technologies, and implement reclamation measures to minimize anthropogenic pressure.

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