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Radioecological analysis of landfill ecosystems in the Western Forest-Steppe (Ukraine)

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Abstract. This study aims to investigate the radiological hazard and possible impact of household waste landfills on adjacent ecosystems (four landfills within the Western Forest-Steppe). Radiation background measurements were made for the first time for the selected landfills, soil samples were taken in the 5-10 cm and 10-20 cm horizons and plant samples were collected, and further examined for radioactivity (^{40}K - natural, ^{137}Cs and ^{90}Sr - artificial radionuclides). The research results revealed a prevailing dynamics of specific mass activity of radionuclides near the waste sites compared to the indicators in the control areas (mainly forest). The situation at the Dunaivtsi landfill is different, since most indicators are lower than background, especially ^{40}K. On the territory adjacent to the Khmelnytskyi landfill, the specific mass activity of ^{137}Cs is higher than the background value, while ^{90}Sr and ^{40}K values fluctuate. The study of plant samples showed a significant excess of ^{137}Cs and ^{90}Sr, but significantly lower values of ^{40}K compared to the control site. The radiation background values are higher than the control value. It has been established that there is no significant radioactive load on ecosystems bordering household waste landfills, but the ionizing capacity and cumulative effect of exposure to ionizing radiation sources, the ability to vertical and horizontal migration, their long-term impact on public health, the existence of living beings, ecosystems and the modifications they can cause should be considered.
Keywords: landfill, municipal waste, radionuclides, radiation background, specific activity of radionuclides, radiation source, environmental safety, environmental hazard

1. Introduction

Waste management is still one of the most important environmental problems both on a global scale and in Ukraine, and requires a systematic approach [1]. Transformation of the waste management system into an environmentally friendly one is one of the priority tasks for Ukraine. As is already known, the prevailing method, both in previous years and in the current period, is waste disposal at landfills. The low level of waste sorting, utilization, and recycling results in landfill overload and non-compliance with the requirements for their operation. As a result, in addition to permanent landfills, there are a large number of unauthorized dumpsites that occupy an increasing area and harm the environment. Along with the growing number of landfills, the number of fires and spontaneous combustions is also increasing, which significantly raises the risks of pollutants spreading and entering the environment.

According to the latest official data, in 2021, more than 51 million m^3 (more than 10 million tons) of household waste was generated, which was placed in 6 thousand landfills and dumpsites with a total area of almost 9 thousand hectares [2].

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Besides, special focus should be placed on the issue of waste generated as a result of hostilities on the territory of Ukraine. Their wide range includes destroyed construction, military, medical, and household waste, damaged machinery, electronic equipment, and more. The accumulation and lack of utilization of this waste may cause environmental crises, public health problems, and epidemics [3, 4, 5]. The use of depleted uranium ammunition during hostilities on the territory of Ukraine is also worth emphasizing [6].

According to Ukrainian legislation, one of the main principles of state policy in the field of nuclear energy use and radiation protection is the priority of protecting people and the environment from ionizing radiation. Therefore, it is important to operate a full-fledged system for collecting and transmitting data on radiation monitoring at facilities, especially those that pose a high risk, in real-time. It is also necessary to ensure continuous monitoring to identify potential sources of ionizing radiation at other facilities [7].

At the present stage of radioecology development, wide systematic radiation monitoring of various areas of management is an important task, which includes assessment of the content of the main dose-forming natural and artificial radionuclides in the main environmental objects: atmosphere, soils, water bodies, agricultural and forest lands, as well as technologically modified and artificially created objects or territories. See the separate guidelines document for further information.

Several foreign and Ukrainian scientists have studied the impact of landfills on ecosystem components, including soil horizons [8], agricultural land [9], air, and water [10].

A significant number of research and publications are also devoted to the impact of landfills on adjacent ecosystems and the population [11, 12]. In particular, a large number of works emphasize the danger of landfills to the health of the population living near these facilities [13, 14]. Many researchers emphasize the sharp rise in the risk of exposure from landfills during spontaneous combustion and fires at waste sites, which is quite common. Partial or incomplete combustion of waste by fires at low temperatures leads to the formation of toxic compounds and poses a serious threat to the health of living beings [15, 16].

Due to violations of the rules for waste sorting, and subsequently non-compliance with incoming control for landfills, which should be carefully carried out at specially equipped checkpoints, waste that may contain ionizing radiation sources and increase the radiation background both on and off the territory of the facility will get to landfills. These may include household items such as fluorescent lamps, TV monitors, worn-out household appliances, clocks, and backlit switches, and industrial items such as medical equipment, construction waste, etc. As you know, depending on the source of ionizing radiation that may be present at a landfill, there are various levels of risk for both the personnel who maintain the landfill and the public who may live nearby.

Some radionuclides are present in trace amounts in the raw materials of electronic devices that are outdated and not properly disposed of. Outdated personal computers become electronic waste and may contain potential environmental contaminants. Moreover, there is an additional threat: the emission of ionizing radiation. Studies have shown the presence of primary radioisotopes in microchips [17].

About 80% of radiation exposure in the world as a whole comes from natural sources, and 99% of the world's population receives a dose of radiation from natural sources [18]. Natural radioactive materials, such as ^{232}Th, ^{238}U, and ^{40}K, are of the greatest concern because they emit ionizing radiation [19].

The main source of gamma radiation for the population is usually exposure from natural radionuclides, especially K^{40}, contained in soil and food (meat, water, bananas, etc.).

Between 1957 and 2011, four major nuclear power plant accidents occurred, such as Windscale, Three Mile Island, Chernobyl, and Fukushima [20, 21]. Given that the long-term effects of large-scale radiation accidents continue to modify the environment with all its components, the importance of radioecological monitoring is becoming increasingly important both in scientific research in Ukraine and globally.

The Chornobyl accident gave a new impetus to the development of the radiation monitoring system in Ukraine. Large areas of numerous countries were contaminated with man-made radionuclides, including ^{137}Cs and ^{90}Sr. The State Hydrometeorological Service, taking into account the experience of radiation observations in previous years, was entrusted with the task of studying the radioactive contamination of the territory of Ukraine. Therefore, up-to-date data is available on official state resources.

Further movement of radionuclides in the ecosystem is associated with water erosion processes, fires [22], secondary transfer due to wind, as well as aging and destruction of radioactive particles, which is very slow. Artificial radionuclides, such as ^{137}Cs, are capable of uneven distribution over the territory due to leaching [23]. Radionuclides are capable of active migration and accumulation in the soil microbial community and soil-plant systems, subsequently entering living organisms through the food chain, as well as through surface contact and respiration.

However, in addition to the operation of nuclear fuel cycle enterprises and the mining and industrial complex, some other aspects of human activity are of concern, among which are landfills.

Landfills are accumulators of various types of waste. And there are often cases of hazardous waste entering landfills as part of household waste. However, not all landfills in Ukraine are operated in accordance with approved standards, as studies have shown the presence of hazardous waste on the territory of landfills (rusty scrap metal, porcelain dishes, fluorescent lamps, TV monitors, worn-out household appliances, etc.)

Very few studies have been devoted to monitoring the radiation impact of landfills because the potential hazard from facilities that are not subject to mandatory radiological monitoring is underestimated [24-27]. This problem is mainly faced by underdeveloped and developing countries, as they do not have a perfect system for managing low-level radioactive waste in household waste and other waste. Therefore, a clear mechanism for radioecological monitoring will allow timely prevention of possible threats and consequences of impact on both adjacent ecosystems and the population.

2. Research Methodology

The research aims to identify possible sources of ionizing radiation at household waste disposal sites by conducting radioecological surveys of soil, plant samples, and air.

Four sites in the Western Forest-Steppe (Ukraine) were selected for the assessment. In particular, these are two landfills in the Khmelnytskyi region—Khmelnytskyi and Dunaivtsi landfills— and two in the Ternopil region—Malashivtsi and Kremenets landfills (Fig. 1).

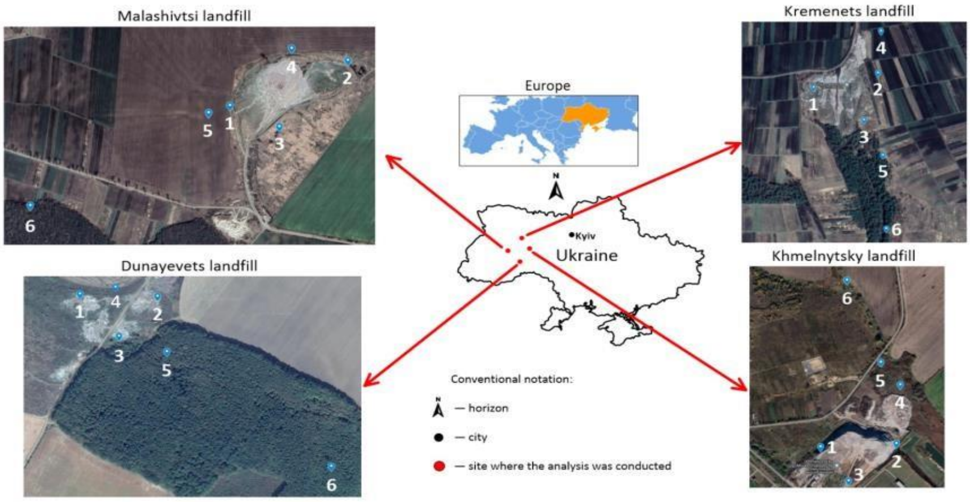

Figure 1. Location scheme of the sites and background measurements, and sampling areas (1 - east, 2 - west, 3 - south, 4 - north, 5 - distance 100 m, 6 - background area) [28]

Within the selected research region, waste landfills were selected that are surrounded by fertile agricultural land with podzolised chernozem soil type. This type of soil has a large sorption capacity, which is why the movement of radioactive substances in them is slow. The sorption properties of chernozem soils are determined by the presence of humus, which contains high molecular weight substances in a colloidal state and is characterised by a good exchangeable absorption capacity. The intensity and completeness of radioactive isotope uptake and the reliability of their fixation in the solid fraction of the soil are significantly affected by the reaction of the medium and its acidity. The acidity of soils has an ambiguous effect on the biological mobility of radionuclides in them. For ^{90}Sr, ^{137}Cs and a large group of nuclides with induced activity, the intensity of radionuclide intake into plants increases with increasing acidity.

The GAMMA-SCOUT dosimeter-radiometer was used to measure the radiation background parameters, a universal dosimeter for comprehensive measurement of all types of radiation: α, β, and γ, and also allows determining the received radiation dose and its power in the real state.

Samples were taken from four sides of each landfill (north, south, west, east) to assess the content of specific activity of radionuclides in the soil, as well as for comparison at a site 100 meters from the facility and in a control background area remote from roads and is considered to be as clean as possible. Sampling horizons: 5-10 cm, 10-20 cm. The envelope method was used for soil sampling. Soil samples were collected, 5 from each horizon in the designated areas (Fig. 1) and mixed samples were made.

Based on the methodology for rapid determination of the activity of the surveyed areas of the selected objects, samples of the test material were selected and prepared (labeled and sealed in vacuum plastic bags); radiation background was measured; and radioactivity measurements of the samples were performed. Laboratory scales, beta and gamma radiation spectrometers were used in a specialized laboratory to measure radionuclide activity in soil and plant samples. The last stage was the statistical processing of the results and the formulating of hypotheses and conclusions.

Plant samples were collected at the same sites as the soil samples. To obtain a combined sample of plants with natural moisture, 8-10 point samples weighing at least 2 kg were taken from the ground part of plants: stems, leaves, and fruits. The aerial part of plants was chosen to study all possible ways of radionuclides entering plants. That is, by studying the aboveground part of plants, we can take into account the complex impact on plants of nearby sources of contamination: aerosol contamination (due to wind, fires), and not only due to contamination from soil or precipitation. Subsequently, combined samples were formed from the plant samples. Sample preparation was carried out in 2 stages: drying and ashing. Gamma spectrometric analysis was also carried out in a specialized laboratory.

The study was conducted in October 2023 (fall season). This period was chosen to repeat the study in the future.

3. Results and Discussion

3.1 Radiation background analysis

According to the Radiation Safety Standards of Ukraine ("RSSU-97"), the standard indicator of natural radiation background is 0.3 μSv/h [30]. Analysis of the obtained indicators shows that all of them do not exceed the established norm (Table 1). However, it is worth considering the fluctuations in the measurements obtained for each site and comparing them with background values in clean areas.

Table 1. Radiation background indicators at waste landfills, μSv/h

	Malashivtsi landfill	Dunaivtsi landfill	Kremenets landfill	Khmelnytsky landfill
West	0,086	0,117	0,100	0,110
East	0,100	0,112	0,090	-
South	0,120	0,090	0,108	-
North	0,133	0,125	0,100	0,127
Distance 100 m	0,122	0,104	0,110	0,120
Background area	0,080	0,088	0,098	0,105
Average value (4 sides)	0,110	0,111	0,100	0,119

Taking into account the results of mathematical calculations, we see that all average values of radiation background at landfills exceed background values, in particular: Malashivtsi landfill- 1.375 times, Dunaivtsi landfill - 1.261 times, Kremenets landfill - 1.020 times, Khmelnytskyi landfill - 1.133 times.

Analyzing the radiation background around the Malashivtsi landfill, we see that the highest radiation background value is on the northern part of the landfill, exceeding the value of the background area by 1.66 times and the average value by 1.21 times. The lowest value is on the western side of the landfill, but it also exceeds the background value by a factor of 1.075, but is lower than the average value by a factor of 1.28.

As for the Dunaivtsi landfill, the highest radiation background value is near the northern part of the landfill, exceeding the background value by 1.42 times and the average value by 1.13 times. The lowest value is on the southern side, but it exceeds the background value by 1.02 times but is lower than the average value by 1.23 times.

The radiation background indicators near the Kremenets landfill are higher compared to the control background area, but only on the eastern side the indicator is 1.09 times lower.

As for the Khmelnytsky landfill, all indicators exceed the values in the background area: on the western side - 1.05 times and on the northern side - 1.21 times, at a distance of 100 m -1.14 times.

3.2 Analysis of radioactivity of soils at the Malashivtsi landfill (Fig. 2)

The content of natural ^{40}K radionuclide and artificial ^{137}Cs and ^{90}Sr radionuclides is below the norms according to radiation safety standards [29, 30].

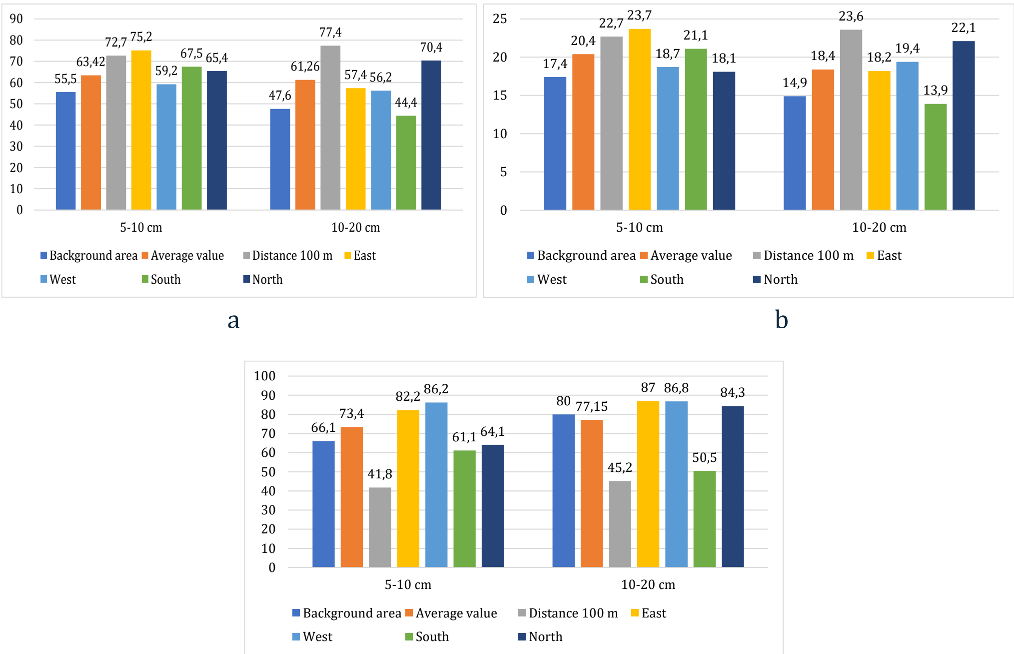

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Figure 2. Diagrams specific mass activity of ^{137}Cs - a, ^{90}Sr- b, ^{40}K - c in soil samples collected at 5- 10 cm and 10-20 cm horizons of the Malashivtsi landfill (Bq/kg).

The specific mass activity of ^{137}Cs in soil samples at a horizon of 5-10 cm from the western side of the landfill exceeds the value in the background area by 1.36 times (35.5%), from the eastern side - 1.07 times (6.7%), from the southern side - 1.22 times (21.6%), from the northern side - 1.18 times (3.1%), and at a distance of 100 m - 1.31 times (31%).

The specific mass activity of ^{137}Cs in soil samples at 10-20 cm horizons from the western side of the landfill exceeds the value in the background area by 1.21 times (by 20.6%), from the eastern side - 1.18 times (by 18.1%), from the northern side - 1.48 times (by 47.9%), at a distance of 100 m - 1.63 times (by 62.6%), but from the southern side it is lower - 1.38 times (by 37.97%).

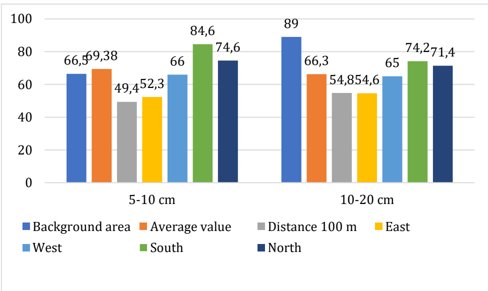
The specific mass activity of ^{90}Sr in soil samples at a horizon of 5-10 cm from the western side of the landfill exceeds the value in the background area by 1.36 times (by 36.21%), from the eastern side - by 1.08 times (by 7.47%), from the northern side - by 1.04 times (by 4.02%), at a distance of 100 m - by 1.31 times (by 30.46%), but from the southern side it is lower - by 1.32 times (by 32.37%).

The specific mass activity of ^{90}Sr in soil samples at a horizon of 10-20 cm from the western side of the landfill exceeds the value in the background area by 1.22 times (by 22.15%), from the eastern side - 1.30 times (by 30.20%), from the southern side - 1.32 times (by 1.32%), from the northern side - 1.48 times (by 48.32%), at a distance of 100 m - 1.58 times (by 58.39%).

The specific mass activity of ^{40}K in soil samples at a horizon of 10-20 cm from the western side of the landfill exceeds the value in the background area by 1.09 times (by 8.75%), from the eastern side - 1.09 times (by 8.5%), from the northern side - 1.05 times (by 5.38%), but is lower: from the southern side - 1.58 times (by 58.42%), at a distance of 100 m - 1.77 times (by 76.99%).

3.3 Analysis of radioactivity of soils at the Dunaivtsi landfill (Fig. 3)

The specific mass activity of ^{137}Cs in soil samples at a horizon of 5-10 cm from the western side of the landfill is 1.27 times lower than the value in the background area (27.15%), from the eastern side - 1.01 times (0.76%), at a distance of 100 m - 1.35 times (34.62%), from the southern side - 1.27 times (27.22%), from the northern side - 1.12 times (12.18%).



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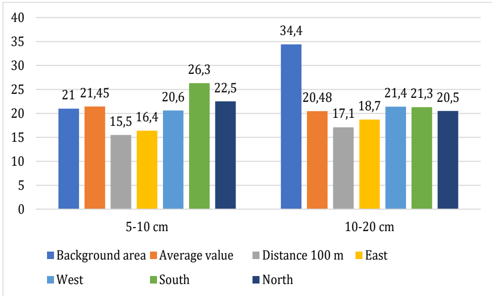

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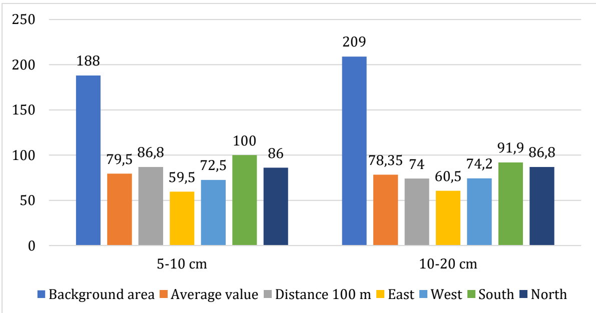

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Figure 3. Diagrams specific mass activity of ^{137}Cs - a, ^{90}Sr- b, ^{40}K - c in soil samples collected at 5- 10 cm and 10-20 cm horizons of the Dunaivtsi landfill (Bq/kg).

The specific mass activity of ^{137}Cs in soil samples at a horizon of 10-20 cm from the western side of the landfill is 1.63 times lower than in the background area (by 63%), 1.37 times lower (36.92%) from the eastern side, 1.25 times lower (24.65%) from the northern side, 1.62 times lower (by 24.65%) at a distance of 100 m, and 1.39 times lower (by 19.95%) from the southern side.

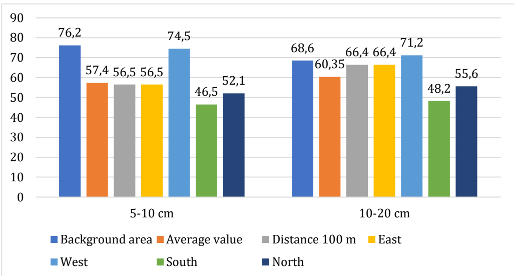
The specific mass activity of ^{90}Sr in soil samples at a horizon of 5-10 cm from the western side of the landfill is 1.28 times lower than in the background area (by 28.05%), 1.02 times lower (by 1.94%) from the eastern side, 1.36 times lower (by 35.48%) at a distance of 100 m, 1.04 times higher (by 7.15%) from the northern side, and 1.26 times higher (by 25.24%) from the southern side.

The specific mass activity of ^{90}Sr in soil samples at a horizon of 10-20 cm from the western side of the landfill is 1.84 times lower than in the background area (by 83.96%), 1.61 times lower (by 60.75%) from the eastern side, 1.62 times lower (by 61.5%) from the southern side, 1.68 times lower (by 67.8%) from the northern side, and 2.01 times lower (by 101.17%) at a distance of 100 m.

The values of specific mass activity of ^{40}K in soil samples collected at 5-10 cm and 10-20 cm horizons from all sides of the Dunaivtsi landfill are significantly lower than the corresponding values in the control background area. All indicators are within the normal range. However, in comparison with the average values, the indicators of the 5-10 cm horizon are higher: from the northern side - by 1.08 (by 8.18%) and from the southern side - by 1.26 times (by 25.77%), and on the 10-20 cm horizon: from the northern side - by 1.11 times (by 10.79%) and from the southern side - by 1.17 times (by 17.29%).

3.4 Analysis of radioactivity of soils at the Kremenets landfill (Fig. 4)

Indicators of specific mass activity of ^{137}Cs in soil samples at the horizon of 5-10 cm and 10-20 cm from all sides of the landfill are lower than the values in the background area, but the indicator at the horizon of 5-10 cm from the eastern side exceeds the average value by 1.3 times (by 29.8%) and at the horizon of 10-20 cm: from the western side - by 1.1 times (by 10.02%) and from the eastern side - by 1.18 times (by 17.98%).



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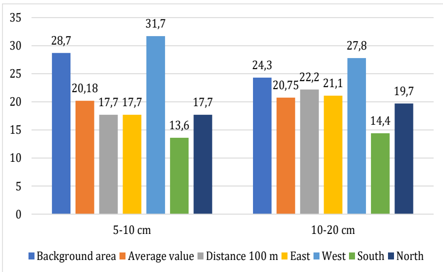

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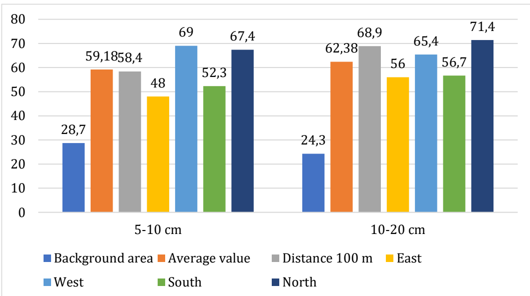

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Figure 4 Diagrams specific mass activity of ^{137}Cs - a, ^{90}Sr- b, ^{40}K - c in soil samples collected at 5- 10 cm and 10-20 cm horizons of the Kremenets landfill (Bq/kg).

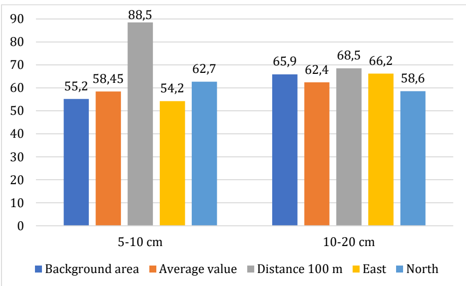
The specific mass activity of ^{90}Sr in soil samples from the eastern side of the landfill at a horizon of 5-10 cm exceeds the value in the background area by 1.11 times (by 10.45%) and at a horizon of 10-20 cm - by 1.14 times (by 14.4%).

The value of specific mass activity of ^{40}K in soil samples at a horizon of 5-10 cm from the western side of the landfill exceeds the value in the background area by 1.67 times (by 67.25%), from the eastern side - by 2.4 times (by 140.42%), from the southern side - by 1.82 times (by 82.23%), from the northern side - by 2.35 times (by 134.84%), at a distance of 100 m - by 2.04 times (by 103.48%).

The specific mass activity of ^{40}K in soil samples at a horizon of 10-20 cm from the western side of the landfill exceeds the value in the background area by 2.31 times (by 130.45%), from the eastern side - by 2.69 times (by 169.14%), from the northern side - by 2.94 times (by 193.83%), from the southern side - by 2.33 times (by 133.33%), at a distance of 100 m - by 2.84 times (by 183.54%).

3.5 Analysis of radioactivity of soils at the Khmelnytskyi landfill (Fig. 5)

The values of specific mass activity of ^{137}Cs in soil samples at the horizon of 5-10 cm are higher than the values in the control background area on the northern side - by 1.14 times (by 13.57 %), at 100 m - by 1.6 times (60.33 %) and at the horizon of 10-20 cm: at 100 m - by 1.04 times (by 3.95 %), on the western side - by 1.01 times (by 0.46 %).



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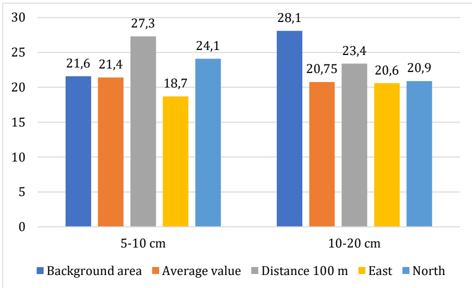

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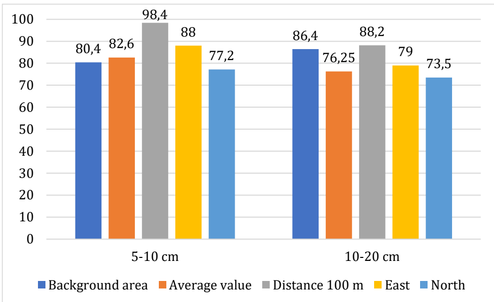

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Figure 5. Diagrams specific mass activity of ^{137}Cs - a, ^{90}Sr- b, ^{40}K - c in soil samples collected at 5- 10 cm and 10-20 cm horizons of the Khmelnytskyi landfill (Bq/kg).

The values of ^{90}Sr specific mass activity in soil samples at a horizon of 5-10 cm are higher than the values in the control background area on the northern side by 1.12 times (by 11.57 %), and at 100 m - by 1.26 times (26.39 %). At the horizon of 10-20 cm, the values are lower than in the control background area, but at 100 m it exceeds the average value by 1.13 times (by 12.77%), and on the northern side - by 1.01 times (by 0.72%).

The values of specific mass activity of ^{40}K in soil samples at a horizon of 5-10 cm are higher than the values in the control background area on the western side - by 1.09 times (by 9.45 %), and at 100 m - by 1.22 times (22.39 %). At the horizon of 10-20 cm, the values are lower than in the reference background area, but at 100 m, the value exceeds the background value by 1.02 times (by 2.08 %) and the average value by 1.16 times (by 15.67 %), and on the western side by 1.04 times (by 3.61 %).

3.6 General analysis of the radioactivity of soils

To make a comparative assessment of the content of radionuclides in soil samples and radiation background indicators, a correlation analysis of the data was performed (Table 2).

Table 2. Determination of correlation coefficients of specific activity of radionuclides in soil samples and radiation background. Results of assessing the significance of correlation coefficients

	Malashivtsi landfill			**Dunaivtsi landfill**			**Kremenets landfill**		
5-10 см									
The correlation coefficient									
	Cs^{137}	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**
Sr^{90}	**0,877**			**0,996**			**0,987**		
K^{40}	-0,076	0,207		**0,994**	**0,990**		0,544	0,659	
Radiation background	-0,365	-0,677	-0,855	-0,573	-0,639	-0,595	**-0,964**	**-0,958**	-0,655
Assessment of the significance of the correlation coefficient (probability 0.05)									
	Cs^{137}	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**
Sr^{90}	**2,580**			**16,315**			**8,623**		
K^{40}	0,107	0,300		**12,474**	**10,075**		0,918	1,238	
Radiation background	0,554	1,300	2,333	0,988	1,175	1,047	**5,127**	**4,728**	1,224
10-20 см									
The correlation coefficient									
	Cs^{137}	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**
Sr^{90}	**0,968**			0,803	1		0,934		
K^{40}	0,753	0,844		**0,995**	0,746	1	0,088	0,374	
Radiation background	0,272	0,163	-0,390	-0,424	-0,475	-0,440	-0,894	**-0,995**	-0,463
Assessment of the significance of the correlation coefficient (probability 0.05)									
	Cs^{137}	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**	**Cs^{137}**	**Sr^{90}**	**K^{40}**
Sr^{90}	**5,436**			1,909			3,702		
K^{40}	1,619	2,230		**14,024**	1,582		0,125	0,570	
Radiation background	0,399	0,234	0,600	0,663	0,763	0,692	2,828	**13,559**	0,740

The significance of the correlation coefficient was assessed using Student's t-test for the selected soil samples at the horizons of 5-10 cm and 10-20 cm according to Formula 1.

$$t = |r_{jk}|\sqrt{n-2} \,/\, \sqrt{1-r_{jk}^2}, \quad (1)$$

where:

j and k - the ranges of the sample data,

r_{jk} - the correlation coefficient,

n -2 - the number of pure degrees of freedom.

The data are arranged in the order of the horizon sides in a clockwise direction: north, east, south, west. MS Excel (CORREL function) was used to automate calculations, in particular, to determine the correlation coefficient of specific activity of radionuclides in soil samples. The actual (observational) value of this criterion is determined by the formula If $t_{fact} > t_{tab}$, the obtained value of the correlation coefficient is recognized as significant and a conclusion is made about the close statistical correlation of the values. The significance level according to the Student's t-test is 4.3.

The results of statistical processing led to the following statements:

for Malashivtsi landfill, a significant correlation coefficient is the relationship between the content of ^{137}Cs and ^{90}Sr on both horizons, it is close to 1 and indicates that with an increase in the content of ^{137}Cs, the content of ^{90}Sr also increases, i.e., there is a man-made load of ionizing radiation sources containing both radionuclides in them;

for the Dunaivtsi landfill, the correlation coefficients of specific mass activity of ^{137}Cs and ^{90}Sr, ^{137}Cs and ^{40}K, ^{90}Sr and ^{40}K at the 5-10 cm horizon are significant, ^{137}Cs and ^{40}K - at the 10-20 cm horizon;

for the Kremenets landfill - at the 5-10 cm horizon, there is a direct correlation between ^{137}Cs and ^{90}Sr, i.e., with an increase or decrease in the content of one, the content of the other increases or decreases accordingly, and an inverse correlation for ^{137}Cs, ^{90}Sr and the radiation background indicator; at the 10-20 cm horizon, a high correlation coefficient between ^{90}Sr and the radiation background indicator is also observed.

These calculations were not performed for Khmelnytskyi landfill due to insufficient sample data.

3.7 Analysis of plant samples

The phytomeliorative effectiveness of vegetation at solid waste landfills shows that low-growing plants dominate on the surface of landfills in the Western Forest-Steppe, and the phytomeliorative coefficient is low [31]. In the process of growth and development, plants consume not only the necessary nutrients but also absorb radioactive and non-essential elements from the environment, and their distribution is uneven in different parts of the plant [32]. Therefore, for the study, pooled samples were formed from herbaceous plants collected at four points of each landfill (to determine the degree of contamination with radioactive substances). Among them are common mugwort *(Artemisia vulgaris L.)*, European wild ginger *(Asarum europaeum L.)*, Giant goldenrod *(Solidago gigantea)*, Sosnowski's hogweed *(Heracleum sosnowskyi)*, Glaucous dog rose *(Rosa dumalis*) and others. The specific mass activity of radionuclides was studied using gamma spectrometry (Fig. 6).

The results reveal that almost all indicators of specific activity of the identified radionuclides exceed the values in the control areas. In particular, the content of ^{137}Cs exceeds the respective background values at all landfills, except for Malashivtsi landfill, in particular, the highest ^{137}Cs value is in plant samples collected at the sites adjacent to Khmelnytsky landfill. The ^{90}Sr values are higher at all landfills except Kremenets, and the ^{40}K values are higher at all landfills except Khmelnytskyi, respectively.

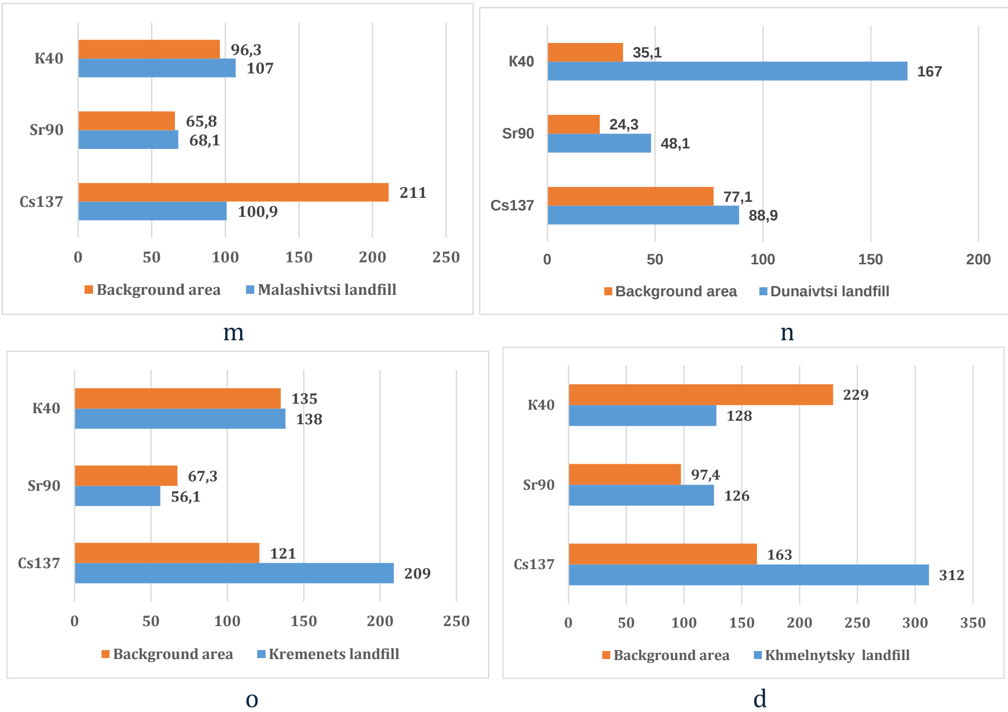

Figure 6. Comparative characteristics of the specific mass activity of radionuclides in plant samples collected from adjacent areas to Malashivtsi landfill - a, Dunaivtsi landfill - b, Kremenets landfill - c, and Khmelnytsky landfill - d (Bq/kg).

4. Conclusion

Considering that landfills are objects of environmental hazard, the radioecological assessment shows no significant radiological threat. Therefore, landfills do not pose a direct radiological risk to people working at landfills and living in their vicinity in real-time.

However, analyzing the obtained research results, it can be concluded that in most cases, the values of both radiation background and radionuclide content in soil and plant samples are within normal limits and exceed the values in the background area (clean area). Therefore, further radioecological monitoring should be carried out to obtain results of possible changes in the dynamics.

The highest background radiation levels are observed at Khmelnytskyi landfill, and the lowest at Malashivtsi landfill.

The study of collected plant samples shows the highest content of ^{137}Cs at Malashivtsi and Khmelnytskyi landfills, ^{90}Sr — at Khmelnytskyi landfill, and ^{40}K — at Khmelnytskyi and Kremenets landfills.

The average values of ^{137}Cs specific activity in soil samples are the highest at the Dunaivtsi landfill, ^{90}Sr is almost the same, and ^{40}K is the highest at the Khmelnytskyi landfill.

The correlation coefficients between the specific activity of radionuclides and the radiation background indicate that there is a connection between these indicators, especially at the Kremenets landfill. There is also a correlation between the content of radionuclides in soil samples, which indicates the origin of contamination from ionizing radiation sources that use both man-made radionuclides in their composition, as well as a similar type of radionuclide migration.

According to the results of the research, the difference in both radiation background and specific activity of radionuclides in soil samples and plant samples is heterogeneous and varies within the normal range. It means that factors cause these fluctuations within the same facility. Thus, radioecological monitoring is a necessary component of monitoring household waste landfills to prevent negative consequences in the future. Processes such as leaching, wind erosion, and many fires at landfills contribute to spreading the existing radionuclides to adjacent territories. Since all landfills border agricultural land, the danger increases many times, accelerating the transfer of hazardous components to nearby areas.

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