Received: 28.03.2025 Revised: 12.08.2025 Accepted: 23.09.2025

BIOLOGICAL SYSTEMS: Theory and Innovation

Journal homepage: https://bioscience.com.ua/en
Vol. 16, No. 3, 2025, 42-61

UDC 504:5:351.777.6:632.15

DOI: 10.31548/biologiya/3.2025.42

Unauthorised landfills as a source of soil contamination with heavy metals: Phytotoxic aspect

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Abstract. The article examined the issue of soil biotesting as an effective indicator approach to assessing the ecological state of land subjected to anthropogenic pressure from local sources of pollution. The objects of the study were soil samples taken near potentially hazardous man-made sites, namely landfills. Toxicity was assessed using phytotests of oil radish (*Raphanus sativus d.* var. *oleifera* Metzg.), which proved to be a sensitive indicator of the presence of harmful substances in the soil environment. At the same time, an analytical determination of the content of heavy metals (Cd, Pb, Zn, Cu) in the soil was carried out. The results of phytotesting showed a decrease in seed germination compared to control samples, which is evidence of the toxic effect of the soil environment. A decrease in germination energy and suppression of primary biomass growth were also observed. A close correlation was found between high metal content and suppression of growth parameters of oil radish, indicating an interdependence between chemical indicators of pollution and the biological response of organisms. In particular, a decrease in the length of seedlings was observed, indicating the biological activity of heavy metals. In some samples, 30% germination was recorded, indicating a critical level of toxicity. Biotesting combined with chemical analysis made it possible to identify areas with the most critical environmental conditions. The proposed approach can be useful for environmental services, local authorities and land management institutions for operational monitoring of soil condition and identification of pollution hotspots. The methodology can be adapted for monitoring industrial areas, sanitary surveillance areas, and areas near transport routes. The results of the study confirm the feasibility of using integrated approaches to monitoring, including both analytical methods and

Suggested Citation:
Leliushok, S., Naumovska, O., & Moldovan, L. (2025). Unauthorised landfills as a source of soil contamination with heavy metals: Phytotoxic aspect. *Biological Systems: Theory and Innovation*, 16(2), 42-61. doi: 10.31548/biologiya/3.2025.42.

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bioindication tests. This approach provides a more objective assessment of environmental risks and can be used to plan measures for the rehabilitation of contaminated areas, soil fertility conservation, and sustainable land use

Keywords: ecotoxicology; germination index; biomonitoring; agroecosystem risks; test plants; toxicological sensitivity

INTRODUCTION

Unauthorised landfills, especially those located near agricultural land, pose a significant environmental threat due to the release of heavy metals into the soil. Heavy metals are highly persistent, accumulate easily and have a toxic effect on plants, soil microflora and food chains. Phytotoxicity – reduced germination, growth inhibition and reduced plant biomass – is often an early indicator of soil contamination. Analysis of the phytotoxicity of soils contaminated with heavy metals due to unauthorised landfills is crucial for assessing environmental risk and protecting food security.

International studies focus on the analysis of heavy metals in soils near illegal landfills and related phytotoxicity. In their article, authors C. Du & Z. Li (2023) investigated soils near a historic landfill in northern China. As part of the study, 376 soil samples were collected to assess the content of nine heavy metals: As, Hg, Sb, Cu, Pb, Cd, Ni, Zn and Tl. The results showed that in many places, metal concentrations exceed the established limits for agricultural land. In addition, based on the calculation of the health risk index, a high potential for carcinogenic effects on the population living near the specified territory was established.

In the article by M. Sabir *et al.* (2022) investigated the level of heavy metal contamination (As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) in soils near open landfills in Pakistan and assessed the risks to human health and phytotoxicity due to the bioaccumulation of metals in plants. The authors analysed soil and plant samples and found that heavy metal content often exceeded safe limits, especially near landfill boundaries. They also showed that plants growing in these conditions could be a source of toxic elements entering the food chain, highlighting the need for monitoring and remediation of such areas. Research by M. Bozym (2022) indicates that leachates from landfill waste are highly toxic to *Lepidium sativum*, leading to a significant reduction in the germination index (GI $<$ 50%), especially in the case of blast furnace dust waste. This indicates the significant phytotoxic potential of waste that enters the soil near landfills.

Among Ukrainian studies, there was a publication by V. Melnychenko (2024) that examined the phytoremediation of soils contaminated by military and anthropogenic influences, with an emphasis on the accumulation of heavy metals and the possibility of using phytotests to assess phytotoxicity. In a study conducted by O. Datsko *et al*. (2024) from Sumy National Agrarian University, an ecological assessment of the heavy metal content in soils in the Sumy and Chernihiv regions contaminated by explosions and anthropogenic influences was carried out, with an analysis of the consequences for agrocenoses. Another study by L. Kucher *et al*. (2023) revealed soil damage near Donbas coal dumps, where exceedances in the concentrations of Pb, Co, Cr, Cu, and Zn led to changes in the composition of plant cover and a decrease in plant biomass.

Other international studies also emphasise the relevance of using phytotesting for early detection of toxicity. For example, S. Morales-Hernández *et al*. (2022) described the use of various plants for phytoremediation of soils from urban landfills in Mexico, where sensitive plants capable of accumulating Pb, Cd, Zn and other metals were identified and indicated a decrease in the viability of test cultures. A. Acharya *et al*. (2023) also analysed the global status and prospects of phytoremediation of heavy metals in soils, in particular emphasising the need for field studies and the use of indicator plant species for effective toxicity assessment and soil remediation. These studies prove that unauthorised landfills are a stable source of heavy metal accumulation in the soil, and phytotesting based on the growth and development of indicator plants effectively reflects the level of phytotoxicity. Despite this, in the Ukrainian context, there is a lack of localised phytotoxic assessments of soils near illegal landfills using modern methods and test cultures. According to research by S. Albert &

E. Bloem (2023), bioindication methods allow for the assessment not only of the presence of individual chemicals, but also of the actual toxicity of mixtures, including their bioavailability and possible synergistic or antagonistic interactions. This gives an advantage over traditional analytical methods, which often do not reflect the full complex toxic impact of pollutants in natural soil conditions.

Such an assessment is more relevant when studying the impact of local sources of pollution, which are characterised by complex, often unstable combinations of toxicants. In addition, soil acts as an important reservoir of organic carbon, which is a critical element of the global carbon cycle. In their work, P. Borrelli *et al*. (2020) emphasise the importance of soil resources in the context of climate change and land use change, noting that the ability of soil to accumulate carbon not only helps maintain fertility but is also one of the leading natural mechanisms for adapting to climate challenges. At the same time, current trends in the intensive use of soil resources in agricultural production are causing accelerated degradation of the soil cover. As noted by O.H. Tarariko *et al*. (2017), such degradation poses a direct threat not only to global food security but also to the long-term sustainable development of humanity.

The aim of the study was to assess the phytotoxic properties of soils contaminated with heavy metals as a result of unauthorised landfills, using biotesting of indicator plants to determine the level of environmental risk to agroecosystems and the potential for subsequent phytoremediation.

MATERIALS AND METHODS

Soil samples were collected in the third decade of July 2024. The research focused on two unauthorised landfills located in the Chernihiv and Cherkasy regions. The first landfill (Object 1) is located within the Nizhyn district, Bakhmach territorial community of the Chernihiv region (51°09’45‘N, 32°42’14’E), 17 km from the city of Bakhmach. The Object covers an area of 2.25 hectares. The second landfill (Object 2) is located within the Uman district, Kniazha-Krynytska territorial community of the Cherkasy region (49°06’22‘N, 29°44’18’E), 4 km from the village of Kniazha Krynytsia. Its area is 0.2 hectares.

Soil sampling scheme. Soil samples were taken within technologically polluted areas, directly near landfills, at a depth of 5-20 cm. For each of the sites, sampling was carried out in three directions, selected according to the spatial location of the landfill, possible directions of pollutant migration and safe access. At Object 1, samples were taken to the north, northeast and southeast. In each direction, three samples were taken at a distance of 5 metres from the landfill body. At Object 2, sampling was carried out to the west, north and south, also with three samples in each direction at a distance of 5 metres from the landfill body. The control (background) point was established at a distance of about 30 metres from the landfill boundary, in an area that had not been directly affected by human activity. The control point area is characterised by the absence of signs of economic activity, which allows these samples to be used for comparative analysis.

Analytical determination of heavy metal content. Laboratory studies of soil samples were carried out at the State Institution “Derzhgruntohorona”. The content of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}) was determined by atomic absorption spectrophotometry (AAS) using the AAS KVANT-2 AT device, which is highly accurate and widely used in soil chemistry. The samples were prepared by extracting mobile forms of metals with a buffer ammonium acetate solution with a pH of 4.8. After filtration of the extracts, the metal concentrations were determined spectrophotometrically in accordance with the requirements of current national standards:

- DSTU 4770.6:2007 (2007) – copper (Cu);
- DSTU 4770.2:2007 (2007) – zinc (Zn);
- DSTU 4770.3:2007 (2007) – cadmium (Cd);
- DSTU 4770.9:2007 (2007) – lead (Pb).

This approach made it possible to obtain an objective quantitative assessment of the level of soil contamination with potentially toxic elements.

Bioindicative methods: Phytotesting. To assess soil phytotoxicity, *Raphanus sativus d.* var. *oleifera* Metrg (ISO 22030:2005, 2005), a representative of the *Brassicaceae* family, was selected as the biotest object. This species is widely used in biotesting due to its high sensitivity to heavy metals, rapid germination and ease of cultivation in laboratory conditions. Oil radish is recommended by ISO 11269-2:2012 (2012) as a standard test Object for assessing soil phytotoxicity. Other plants were not used in this study because oilseed radish provides sufficient sensitivity and representativeness for primary environmental monitoring. The involvement of additional species is possible at later stages, but is not critically necessary in this study.

Biotesting methodology. Radish seeds were pre-disinfected in a 1% potassium permanganate solution for 15 minutes, followed by rinsing with distilled water. The biotest was carried out in 10 cm diameter Petri dishes with filter paper moistened with water extract from the soil (ratio 1:2). Ten seeds were sown in each dish and incubated in a thermostat at a temperature of 22-24 °C for 7 days. Each sample was analysed in two replicates. After the exposure, the following parameters were evaluated: percentage of germinated seeds, root length, and stem length. The results were interpreted according to the ISO 11269-1:2012 (2012) toxicity scale.

To assess the condition of the soil cover, nine soil samples were taken from each of the studied objects (Object 1 and Object 2). The selection was carried out in three directions, with three samples in each direction, which ensured the spatial representativeness of the sample. The phytotoxicity study was carried out for each sample in two repetitions, which are further referred to in the text as (1) and (2). This scheme was implemented for samples from both objects – Object 1 and Object 2.

Processing of results and analytical approach. To process the obtained data, methods of variational statistics were used with the calculation of mean values, standard deviation and coefficients of variation. Statistical analysis was performed using Microsoft Excel software.

General methodological concept. A comprehensive approach combining analytical (chemical) and bioindication (phytotesting) methods made it possible to reliably assess the ecotoxicological state of the soil cover near unauthorised landfills. The selected methods ensured the sensitivity, representativeness and reproducibility of the results, which is critically important for environmental monitoring and further justification of measures for soil rehabilitation.

A correlation analysis was performed to quantitatively assess the relationship between the content of heavy metals in the soil and the phytotoxic effect on the test Object *Raphanus sativus* var. The calculations used the concentrations of mobile forms of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}) and the corresponding biometric indicators of seedlings (root length, stem length). The calculations were performed in Microsoft Excel. The analysis revealed a statistically significant correlation between the level of soil contamination with lead, cadmium and copper and the germination indicators of oil radish. This confirmed the impact of toxicants on the initial stages of plant ontogenesis, which allowed the results to be used as an indicator of environmental risk in the studied areas. Table 1 below shows the sampling scheme and sample labelling.

Table 1. Procedure for selecting soil samples and their labelling

Name of Objects	Direction	Labelling of samples	Distance from the landfill body, m
Object 1			
	North	I,1	5
		I,2	10
		I,3	15
	North-East	II,1	5
		II,2	10
		II,3	15
	South-East	III,1	5
		III,2	10
		III,3	15
Object 2			
	West	I,1	5
		I,2	10
		I,3	15
	North	II,1	5
		II,2	10
		II,3	15

Table 1. Continued

Name of Objects	Direction	Labelling of samples	Distance from the landfill body, m
	South	III,1	5
		III,2	10
		III,3	15

Source: developed by the authors

Thus, the following studies were conducted: the content of mobile forms of Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, mg/kg was determined in selected soil samples; the level of acute toxicity was established using a biotest object, the experiment was laid for a period of 7 days *Raphanus sativus d.* var. *oleifera* Metrg (ISO 22030:2005, 2005); the morphological composition of the waste was determined. The experimental studies of plants complied with institutional, national and international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

The results obtained indicate a decrease in the germination rate and energy of oil radish on soil samples taken near unauthorised landfills compared to control samples. Despite the fact that the concentrations of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}) did not exceed the established maximum permissible values, a pattern was identified: soil samples with lower germination rates of the phytotest culture showed higher relative concentrations of these elements. This indicates the potentially negative impact of heavy metals, even within acceptable concentrations, on the biological activity of the soil. Therefore, phytotesting results can be a reliable indicator of hidden or cumulative soil toxicity, which emphasises the advisability of a comprehensive approach to assessing the condition of soil cover in areas adjacent to landfills.

Determining the morphological composition of waste

The settlement in Chernihiv region faces a problem in the area of solid waste management, which manifests itself in the growing negative impact of waste on the environment and the health of people and animals, in particular stray dogs living near landfills. It should be noted that plastic waste (21%) and paper waste (23%) predominate in the waste structure.

The work of A. Illiash *et al*. (2023) provides an analysis of the morphological composition of household waste in several regional centres of Ukraine. According to their data, fluctuations in the proportions of plastic (9-29%) and paper (2.5-14%) largely correlate with the socio-economic level of the settlements. The results of this study (plastic – 21%, paper – 23%) coincide with this range, confirming the representativeness and comparability of data on the impact of the private sector and the level of urbanisation. The article by I.V. Satin & O.S. Panchenko (2021) develops an improved methodology for analysing the morphological composition of waste, broken down into specific fractions, including paper, polymers, organic matter, etc. The authors note that in private residential areas, the share of paper was 7-14%, and the share of polymers was 9-22%. The figures obtained in this study (paper – 23%, plastic – 21%) slightly exceed the upper limit of the published values, which may be due to the active growth in the use of plastic packaging. A pattern has also been observed that the larger the rural population and private sector, the slightly higher the percentage of organic and food waste. It should also be noted that in recent years, emissions of plastic packaging products and plastic food packaging, mainly polyethylene, have increased, accounting for 16% at this landfill (Fig. 1).

Figure 1 shows the characteristics of waste in the settlement of Kniazha Krynytsia, Cherkasy region. The landfill is mainly polluted with waste generated by the local residents living nearby. The main components are: plastic waste (28%) – the largest portion of the waste. Plastic is a long-lasting environmental pollutant, as it takes hundreds of years to decompose. It can enter the soil and water, causing ecological problems. Paper and cardboard (27%) – a significant part of the waste consists of paper products, which decompose relatively easily and can be recycled. This indicates a large proportion of packaging materials in the waste. Polyethylene (17%) – one of the most persistent forms of plastic, which pollutes the environment and causes serious ecological issues. Glass (16%) – does not decompose naturally, but is well-suited to recycling. Its considerable share indicates consumption of products in glass containers. Rubber waste (7%) – such as old tyres, which are hazardous to the environment as they decompose very slowly and can release toxic substances. Organic waste (2%) – decomposes the quickest, but may produce unpleasant odours and attract rodents and insects. Iron, textiles, and wood (1% each) – although their share is small, they also require proper disposal or recycling. Below is the morphological composition of waste for Object 2 (Fig. 2).

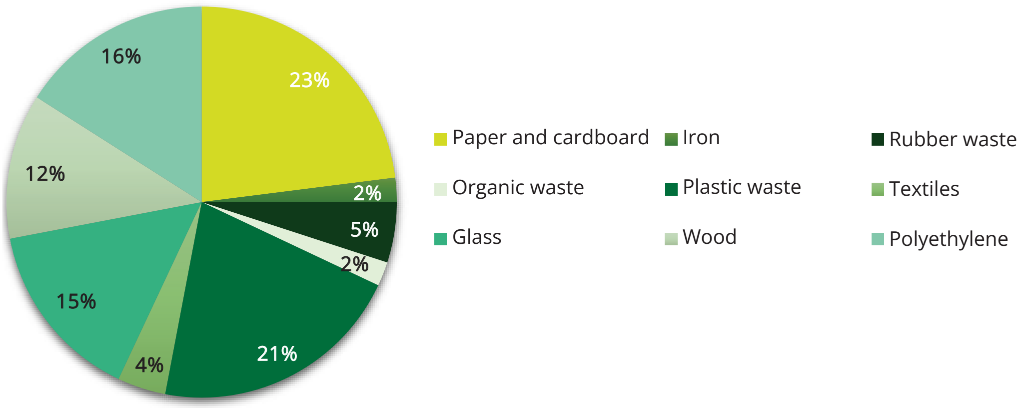

Figure 1. Average morphological composition of selected waste samples Object 1, %
Source: developed by the authors

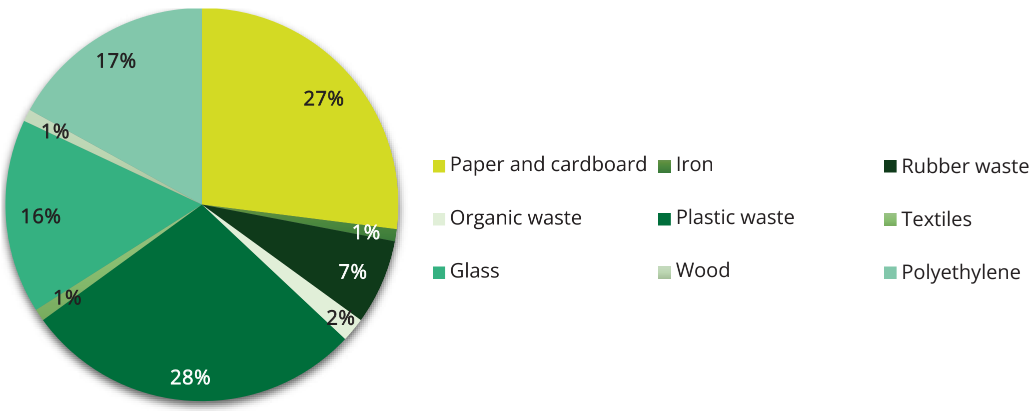

Figure 2. Average morphological composition of selected waste samples Object 2, %
Source: developed by the authors

The morphological analysis of municipal solid waste (MSW) at Object 2 showed that synthetic materials dominate the waste stream (Fig. 2). Plastic waste makes up the largest fraction at 28%, including single-use packaging and containers. This indicates excessive plastic consumption and a poor system for waste separation. Paper and cardboard follow at 27%, representing a valuable recyclable material. Polyethylene accounts for 17%, mainly consisting of bags and films. Glass makes up 16%; it is an inert component that can be recycled to save raw materials and energy. Rubber waste – 7%, which can include worn-out tyres and other technical materials. Smaller fractions include organic waste (2%), which can produce methane and foul odours, and iron, textiles, and wood (1% each).

Metals are recyclable, wood can be biodegraded or used for energy, while textiles are particularly difficult to dispose of due to synthetic additives. The long-term accumulation of these materials at unauthorised landfills can cause toxic compounds to migrate into the soil, altering its chemical and toxicological properties. Therefore, a soil study was conducted around the Object to assess the potential environmental impact. Table 2 provides the results from soil samples at Object 1.

Table 2. Content of mobile forms of heavy metals in soils (mg/kg), Object 1, third decade of July 2024

Sample Code	MPC mg/kg	North			North-East			South-East		
		I,1	I,2	I,3	II,1	II,2	II,3	III,1	III,2	III,3
Cu, mg/kg	3.0	0.675	0.42	0.355	0.559	0.465	0.48	0.208	0.55	0.425
Zn, mg/kg	23	1.854	0.211	0.391	1.925	1.129	0.434	2.262	0.849	4.761
Cd, mg/kg	0.7	0.203	0.248	0.286	0.215	0.225	0.179	0.153	0.25	0.175
Pb, mg/kg	6.0	2.14	1.543	2.245	0.8	0.764	1.59	1.25	1.805	1.472

Note: MPC – maximum permissible concentration
Source: developed by the authors

Contamination by heavy metals is one of the main environmental problems affecting soil quality, water resources, and ecosystem health. Heavy metals can accumulate in the biosphere and influence microorganisms, plants, and higher trophic levels, including humans. Table 2 shows that in all samples the concentration of Cu (copper) does not exceed the maximum permissible concentration (MPC) of 3.0 mg/kg. Copper is known to be an essential micronutrient for plants; however, its excess may lead to toxic effects such as disruption of growth and development of root systems. At all sampling points, Zn (zinc) is below the MPC of 23.0 mg/kg, indicating no significant technogenic pollution. Zinc is necessary for enzyme function in plants and microorganisms, although high concentrations may cause phytotoxicity. All measured values of Cd (cadmium) are below the MPC of 0.7 mg/kg, which suggests a natural origin of the metal. Cadmium is a highly toxic element, and its accumulation in soils can disrupt plant metabolism and adversely affect organisms. The concentration of Pb (lead) in all samples is lower than the MPC of 6.0 mg/kg, indicating no large-scale anthropogenic contamination. Lead is hazardous to the environment and human health as it can accumulate in plants, enter food chains, and cause neurotoxic effects.

According to V. Laptiev *et al*. (2024), the concentration of Cu and Zn in the plant biomass of *Erigeron canadensis* in Dnipro significantly exceeded background values, even though the total content of these metals in the soil had not yet exceeded regulatory limits. This corresponds with the findings of the present study: it was observed that the concentrations of Cu and Zn in the soils did not exceed the MPC but were higher in the samples with lower germination rates of radish. The research demonstrates that even permissible levels of heavy metals affect bioavailability and accumulation in plants.

Similar conclusions were drawn in the work of N. Chernykh *et al.* (2021). Their study of soils near the Sharra landfill (Tirana, Albania) revealed that, despite Cd and Pb levels being clearly within norms, accumulation of heavy metals in *Trifolium repens* was already recorded, which reduced germination. Unlike the present study, where the main focus was on phytotoxic effects through reduced germination, the aforementioned work emphasised the translocation of metals into plant tissues. Thus, the results of this study support the observations of other authors regarding the risks of hidden toxic effects of heavy metals even within regulatory limits.

Differences in the content of heavy metals are observed across the three sampling directions, although none of the recorded levels exceed the maximum permissible concentrations. In Direction I, the highest maximum concentrations of Pb (2.245 mg/kg) and Zn (1.854 mg/kg) were recorded, which may indicate either the local natural origin of these metals or a minor influence of anthropogenic factors. In Direction II, the values of heavy metals remain relatively stable, without sharp fluctuations, which may suggest the absence of pronounced sources of contamination. At the same time, in Direction III, the highest values of Zn (4.761 mg/kg) and Pb (1.805 mg/kg) were observed compared to other directions. This is likely due both to the natural properties of the soil and the influence of local sources of pollution, in particular transport infrastructure or industrial facilities.

From Table 2, a preliminary conclusion can be drawn about the experiment at Object 1. All measured concentrations of heavy metals in soil samples do not exceed the maximum permissible concentrations, which indicates the environmental safety of the studied area and the absence of significant anthropogenic load. The highest values of zinc and lead were recorded in Direction III, which may point to local peculiarities of the geochemical composition of the soil or the presence of potential minor sources of contamination, although all indicators remain within permissible limits. Overall, all sampling points demonstrate similar results without significant deviations, which further confirms the absence of considerable technogenic impact. At the same time, given the ability of heavy metals to accumulate in the soil environment, it is advisable to continue monitoring studies and environmental risk assessments, particularly in the context of their potential entry into food chains. In general, the results of the study indicate a stable ecological condition of the area and no signs of critical soil contamination by heavy metals. Table 3 presents the results of soil samples from Object 2.

Table 3. Content of mobile forms of heavy metals in soils (mg/kg), Object 2, third decade of July 2024

Sample Code	MPC mg/kg	Western			Northern			Southern		
		I,1	I,2	I,3	II,1	II,2	II,3	III,1	III,2	III,3
Cu, mg/kg	3.0	0.429	0.405	0.62	0.635	0.412	0.49	0.18	0.115	0.67
Zn, mg/kg	23	1.234	0.723	0.873	8.097	3.788	1.467	0.425	0.135	0.128
Cd, mg/kg	0.7	0.37	0.324	0.253	0.135	0.18	0.265	0.108	0.188	0.205
Pb, mg/kg	6.0	0.903	1.041	0.832	2.125	2.395	1.575	0.668	0.705	0.68

Note: MPC – maximum permissible concentration
Source: developed by the authors

Soil contamination by heavy metals is one of the key environmental issues affecting ecosystem functioning, biodiversity, and the state of the agroecological environment. The conducted studies (Table 3) showed that the concentrations of the analysed metals (Cu, Zn, Pb, Cd) in the soils of the studied area do not exceed the maximum permissible concentrations (MPC), which indicates the overall environmental safety of the territory. The highest level of Zn (8.097 mg/kg) was recorded in Direction II, Pb (2.395 mg/kg) also in Direction II, Cd (0.37 mg/kg) in Direction I, while Cu (3.0 mg/kg) remained within the norm across all directions. The spatial distribution of metals suggests the influence of local natural factors (such as soil type, pH, organic matter content) or a weakly expressed anthropogenic impact (transport emissions, small-scale waste burning or accumulation). Although the concentrations of metals do not exceed MPC, even minor accumulation may lead to long-term changes in the structure of the microbiocenosis, a reduction in phytobiomass, and toxic effects on root systems, particularly under conditions of increased bioavailability (e.g., in acidic soils). This could threaten the decline of agronomic fertility and increase the risk of heavy metals entering food chains.

The obtained results may serve as a basis for environmental risk assessment, taking into account the spatial characteristics of contamination, as well as for the development of effective reclamation measures – in particular, the selection of phytoremediation methods according to the level of metal bioavailability. In addition, the findings may be applied in planning the locations of sorting stations or other waste management facilities: areas with the lowest concentrations of toxicants may be prioritised for further development with minimal environmental burden, whereas directions with localised increases in concentrations require additional monitoring. The concentrations of heavy metals in soil do not exceed MPC, which confirms the ecological safety of the studied areas. The highest levels of Zn and Pb were observed in Direction II, likely linked to natural or anthropogenic factors. All sampling points demonstrate stable indicators without critical deviations.

Since heavy metal concentrations do not exceed permissible levels, their presence in soils is primarily attributed to natural processes, such as mineral weathering. However, possible anthropogenic factors include transport emissions, industrial sources, and the use of agrochemicals. Although soil concentrations remain below MPC, their levels in the biosphere may change under the influence of natural and human-induced processes. The accumulation of cadmium and lead in soils may lead to their entry into food chains, negatively affecting human and animal health. It is also important to consider the bioavailability of metals, as even low concentrations may be toxic to microorganisms and plants.

The results indicate that concentrations of heavy metals (Cd, Cu, Pb, Zn) in the studied soils do not exceed the established maximum permissible concentrations (MPC), pointing to the relative ecological safety of the study area. The spatial distribution of metals demonstrated certain local fluctuations, which may be attributed to both natural factors (geochemical features, soil properties) and anthropogenic influences (transport, local unauthorised landfills, use of agrochemicals). Nevertheless, even at concentrations below MPC, heavy metals can accumulate in biota, creating risks for agroecosystems, biodiversity, and human health through their transfer into food chains. In this regard, emphasis should be placed not only on total concentrations but also on bioavailability, which determines the actual impact on living organisms. To reduce risks and plan further environmental protection measures, it is recommended to:

1. Regular monitoring of soils for heavy metal content over time, particularly in areas where higher concentrations of Pb and Zn were detected. Such an approach will enable timely identification of changes in the chemical composition and assessment of pollution trends.

2. Study of metal bioavailability using modern biotests and chemical fractionation analyses. This will make it possible to determine which fraction of the elements is potentially hazardous to plants and microorganisms, even at low overall concentrations.

3. Assessment of soil parameters such as pH, organic matter content, granulometric composition, and cation exchange capacity, which directly influence the mobility of metals. For instance, soil acidification may significantly increase the toxicity of heavy metals.

4. Establishment of sorting stations and control over unauthorised waste disposal. The results may be used to identify priority areas for land reclamation or reconnaissance when planning the development of environmental infrastructure.

5. Conducting environmental risk assessments with the use of models of contaminant migration in the soil – plant system. This will allow prediction of the long-term impact on the agroecosystem and ensure scientifically sound planning of agricultural land use.

6. Involvement of local communities in environmental monitoring and awareness campaigns on household waste management, since local pollution is most often caused by indirect impacts of domestic activities.

Thus, the results of the study are not merely descriptive but may serve as a basis for decision-making in the fields of environmental monitoring, land reclamation, and the organisation of waste management infrastructure. The practical application of the obtained data will help to reduce environmental pressures and preserve soil resources for sustainable use. The concentrations of heavy metals recorded in both data sets do not exceed the maximum permissible concentrations, which indicates a relatively stable environmental condition of the soil cover in the study area. At the same time, the detected increase in zinc (Zn) content in direction II (Table 3) may indicate the presence of a local anthropogenic source of pollution, which requires further observation and clarification of its spatial distribution. A slight increase in lead (Pb) concentrations in the same direction may also be an indicator of the influence of anthropogenic factors, in particular transport or industrial activity. Additional monitoring studies will allow assessing the spatial and temporal dynamics of heavy metal distribution in the soil, as well as identifying potential pathways for their migration in the environment. In general, the soil is characterised by a satisfactory ecological state, but the detected local anomalies in Zn and Pb content in direction II justify the need for further monitoring.

Study of acute toxicity levels using oil radish as a biotest Object conducted at Object 1

Northern direction. In each of the three directions, ten seeds were sown in two replicates. The table below presents the number of germinated seeds relative to the total number of seeds sown. Number of germinated seeds: I,1(1) – 3 out of 10, I,1(2) – 8 out of 10, I,2(1) – 7 out of 10, I,2(2) – 6 out of 10, I,3(1) – 3 out of 10, I,3(2) – 8 out of 10. The highest germination rate was recorded in directions I,1(2) and I,3(2) (8 germinated seeds each), which may indicate a lower level of toxicants in the soil compared to other directions. In contrast, the lowest germination rates were recorded in directions I,1(1) and I,3(1) – only 3 seeds each.

In the work of K. Phoungthong *et al.* (2016), the effect of leachates from inert materials obtained by leaching ash waste from waste incineration plants on the germination of wheat seeds (*Triticum aestivum* L.) was investigated. It was found that at extreme pH values, as well as at elevated heavy metal content in leachates, a decrease in seed viability and inhibition of root growth were observed. These findings show that even moderate levels and dependence on the environment can affect seed viability. This is similar to the results of the study: in areas with lower germination rates (I,1(1); I,3(1)), seed development was also inhibited despite normal heavy metal content.

The study by S. Hazratqulov *et al.* (2024) examined how the treatment of organic waste reduces the availability of heavy metals, which stimulates plant growth, particularly root growth. The authors argue that even in the presence of metals in the soil, bioavailability determines the effect on germination. The data obtained in the study support this view: at points with better germination (I,1(2); I,3(2)), the bioavailability of toxicants is likely to be lower, although the total metal content was within normal limits. Below is an analysis of the phytotoxicity of oil radish in direction I of Object 1 (Fig. 3).

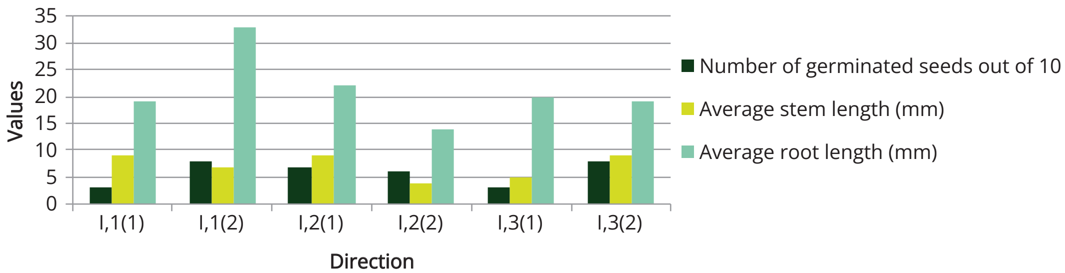

Figure 3. Bioindication of soil contamination with seed germination

Source: developed by the authors

Within the framework of biotesting of oil radish in different directions of Object 1, variability in germination and morphometric indicators of plants was revealed (Fig. 3). The lowest values of stem and root length, as well as a reduced number of germinated seeds, were recorded in direction I,3(1), indicating an increased level of soil phytotoxicity at this point. In contrast, better growth indicators were observed in direction I,1(2), which may indicate a lower level of contamination. A decrease in germination was observed in directions I,1(1) and I,3(1), indicating an increase in heavy metal content at these points. These are areas close to the source of pollution, as these samples also had an accumulation of debris before it was removed to the general waste. A significant reduction in root and stem length indicates plant stress at the cellular level. The situation is particularly critical in direction I,1(1), which has the lowest average morphometric values.

North-Eastern direction. Within the study, the phytotoxicity of soils was assessed using bioindication approaches, in particular, the reaction of seed germination and morphometric parameters of seedlings. Ten seeds were sown in each experimental direction (II,1(1); II,1(2); II,2(1); II,2(2); II,3 (1); II,3(2)). Variability in seed germination and growth indicators was established, indicating different toxicological quality of soils in the study area.

The maximum germination values (70%) were recorded in areas II,1(1) and II,1(2), indicating a relatively low level of phytotoxicity in these areas.

The lowest germination rates (30%) were found in direction II,2(2), indicating significant growth inhibition under the influence of existing pollutants. At the same time, the maximum morphometric parameters of stems (27.2 mm) and roots (8.2 mm) were found in direction II,3(2), indicating optimal growth conditions. The worst indicators of root system development (3.2 mm) were also recorded in direction II,2(2), which, combined with low germination rates, indicates the presence of biologically active toxic substances even in the absence of significant exceedances of the maximum permissible concentrations of heavy metals. Such approaches are relevant in the context of increasing anthropogenic transformation of landscapes and the need to restore degraded areas. Below is an analysis of the phytotoxicity of oil radish in direction II of Object 1 (Fig. 4).

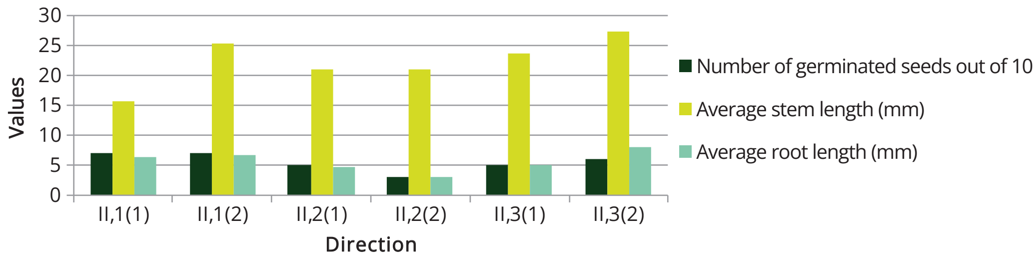

Figure 4. Morphometric parameters and germination
Source: developed by the authors

In direction II (Fig. 4), the overall seed germination rate was relatively stable; however, root length remained shorter than stem length, indicating a slowdown in root system development. This morphological response may suggest the chronic action of pollutants that do not critically affect germination but inhibit normal plant growth. Bioindication has proven to be an effective method for assessing spatial variation in soil contamination. Based on a combination of indicators – seed germination, root length and stem length – it can be concluded that: the most contaminated area is II,2(2); the least contaminated, in terms of phytotoxicity, are II,1(2) and II,3(2); the direct correlation between root length and contamination confirms the sensitivity of the root system to toxicants, especially heavy metals that suppress meristematic tissue growth.

South-Eastern direction. Number of germinated seeds: III,1(1) – 7 out of 10; III,1(2) – 6 out of 10; III,2(1) – 10 out of 10; III,2(2) – 10 out of 10; III,3(1) – 8 out of 10; III,3(2) – 9 out of 10. The lowest germination rates were observed in samples III,1(1) and III,1(2), which may indicate increased anthropogenic pressure, despite only minor levels of heavy metals in these samples. In contrast, samples III,2(1) and III,2(2) showed 100% germination, suggesting relatively better soil quality or lower levels of contamination.

Average stem length (K): III,1(1) – 18.1 mm, III,1(2) – 11.0 mm, III,2(1) – 34.0 mm, III,2(2) – 36.3 mm. Average root length (C): III,1(1) – 6.4 mm, III,1(2) – 3.7 mm, III,2(1) – 24.5 mm, III,2(2) – 18.4 mm. The low values of germination and morphometry in directions III,1(1) and III,1(2) may indicate a deterioration in the ecological state of soils. Improved values in III,2(1) and III,2(2) suggest potentially lower contamination. Longer stems and roots in these samples are a sign of better metabolic activity and the absence of phytotoxic substances. From an ecotoxicological perspective, the most contaminated samples are III,1(1) and III,1(2), as confirmed by low germination percentages and morphometric parameters. Conversely, samples III,2(1) and III,2(2) demonstrate high levels of germination and growth, indicating relatively clean soil conditions in these directions.

The results of the bioindication study confirm the relevance of including phytotesting in systems of ecological monitoring and soil assessment. The obtained indicators may be used to substantiate ecological risk assessment, to plan reclamation measures, or to organise waste sorting facilities with due consideration of toxicant bioavailability and their impact on biodiversity. The findings also highlight that chemical analysis of element content alone does not provide a complete picture of ecological threats. Phytotesting makes it possible to determine the bioavailability of toxicants and their effects on living organisms, which is particularly important for assessing real ecological risks. The practical significance of the study lies in the possibility of zoning the territory according to degrees of phytotoxicity. The spatial variations observed in seed germination and morphometric characteristics of plant development may serve as a basis for ecological mapping of the area and for identifying zones with increased toxic pressure.

The obtained results allow for the formulation of recommendations regarding the further use of such areas. Specifically, plots with low germination and significant suppression of growth processes (e.g., site II,2(2)) should be temporarily excluded from intensive agricultural use or subjected to restricted use under special agrotechnical regimes. To reduce ecotoxic pressure, phytomelioration measures should be applied, including the cultivation of plant species tolerant to contamination, the introduction of organic ameliorants, and the implementation of biological remediation. Particular attention should be given to reclamation planning. Plots that exhibit high levels of phytotoxicity should be identified as priorities for reclamation, since even relatively low pollutant concentrations in the soil are associated with suppression of plant viability. The study results are also relevant for assessing the suitability of these territories for infrastructure development, particularly for waste-sorting stations. The presence of phytotoxic manifestations indicates potential risks linked to the long-term use of such areas for waste management facilities.

Study of acute toxicity levels using a biotest Object conducted at Object 2

Western direction. The highest germination rate is observed in samples I,1(1) and I,1(2), with 9 and 8 out of 10 seeds, respectively. The lowest level is in samples I,2(2) and I,3(2), with only 5 germinated seeds each, indicating potential soil contamination. Below is an analysis of oil radish germination in direction I of Facility 2 (Fig. 5).

The percentages shown in Figure 5 do not reflect the absolute percentage of germination for each sample (out of 10 seeds), but rather the relative share of each sample in the total number of germinated seeds in the western direction. For example, for sample I,2(2), 5 seeds out of 39 total seeds in this direction germinated, which is 13% – this is the percentage shown in Figure 5.

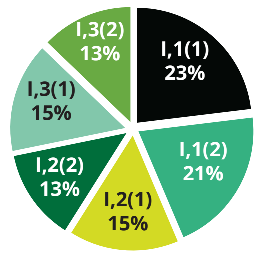

Figure 5. Percentage of germinated seeds in the Western direction
Source: developed by the authors

The biotest conducted confirmed the variability of oil radish seed germination shown in Figure 5 and indicates different levels of phytotoxicity of the samples studied. The highest biological activity of the soil was observed in the first sample I,1(1), where the highest percentage of germinated seeds was recorded. On the other hand, some samples showed inhibition of germination, which may be due to the presence of pollutants. In general, the results indicate an uneven distribution of toxicity within one direction, which indicates localised soil contamination. The average values of stem and root lengths indicate a negative impact of contamination in directions I,2(1), I,2(2) and I,3(2), where the lengths are significantly lower compared to control samples I,1(1) and I,1(2). Below is an analysis of the phytotoxicity of oil radish in direction I of Object 2 (Fig. 6).

Samples I,1(1) and I,1(2) can be considered reference samples or the least contaminated, as they show high germination and morphometric characteristics (Fig. 6). The decrease in germination rates in samples I,2(2) and I,3(2) indicates probable increased soil contamination, especially with heavy metals or residual agrochemicals. The results confirm the advisability of further analysis of the chemical composition to confirm the ecotoxicological status of these samples.

Southern direction. According to the data obtained, the number of germinated seeds was: III,1(1) – 4 out of 10, III,1(2) – 7 out of 10, III,2(1) – 5 out of 10, III,2(2) – 10 out of 10, III,3(1) – 3 out of 10, III,3 (2) – 5 out of 10. There is variability in germination, which indicates the heterogeneity of the impact of pollution factors at different sampling points. Morphometric indicators of plants: stem length (K) varies from 18 to 142 mm. The maximum stem length values (over 100 mm) were observed in samples III,2(2) and III,3(1), which may indicate local areas with relatively better conditions for seedling development; root length (C): varies from 2 to 36 mm. Shorter root lengths (<10 mm) are recorded in most samples, which is an indicator of the presence of toxic substances in the soil that inhibit the development of the root system.

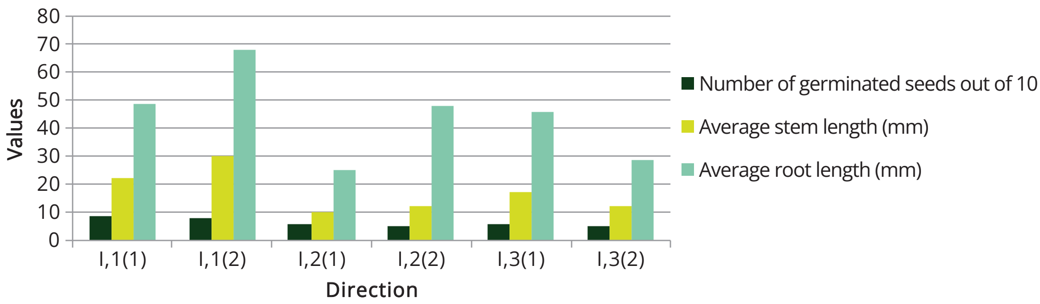

Figure 6. Bioindication of soil contamination based on seed germination
Source: developed by the authors

In general, shorter roots compared to stem length indicate an increased toxicant load, as the root system is more sensitive to pollutants. A high percentage of seeds that did not germinate also confirms the presence of toxic stress. he situation is particularly critical in samples III,3(1) and III,3(2), where the number of germinated seeds was the lowest (3-5 out of 10), which may indicate the level of soil contamination. Below is an analysis of the phytotoxicity of oil radish in direction III of Object 2 (Fig. 7).

The results of biotesting indicate differences in the phytotoxicity of soil samples in direction III in Figure 7. There is a general trend towards reduced seed germination and suppression of growth parameters (stem and root length) at certain points, which may indicate the presence of toxicants in the soil. At the same time, some samples show better growth indicators, which indicates local heterogeneity of contamination. Data analysis shows significant heterogeneity of soil contamination in the southern direction. The main indicators of contamination are a decrease in root length, a decrease in the number of germinated seeds, and a disruption in the ratio between stem and root development. The signs of stress indicate the need for soil remediation measures in this area.

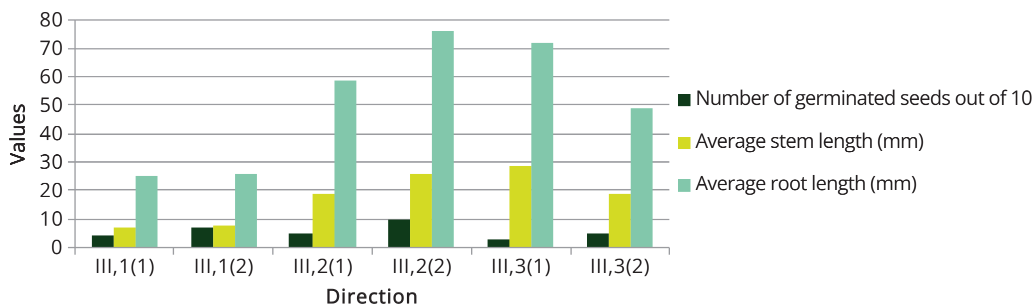

Figure 7. Bioindication of soil contamination based on seed germination
Source: developed by the authors

Northern direction. In each variant of the experiment, 10 seeds were sown, but since the experiment was conducted in two replicates, the total number of seeds was 20. Therefore, the analysis of germination took into account the total indicators of both replicates. Seed germination: II,1 – 11 out of 20 germinated seeds (5 + 6) = 55% germination, II,2 – 6 out of 20 seeds germinated (2 + 4) = 30% germination, II,3 – 8 out of 20 seeds germinated (3 + 5) = 40% germination. Thus, the best germination was observed at points II,1, indicating a relatively lower level of soil contamination. The worst germination rates (only 30%) were recorded at points II,2. Analysis of the average values of stem length (K) and root length (C) for each point: I,1 (average values): Stem (K): ~33 mm Root (C): ~25 mm, II,2 (average values): Stem (K): ~6 mm, Root (C): ~5 mm, II,3 (average values): Stem (K): ~26 mm, Root (C): ~25 mm (Fig. 8).

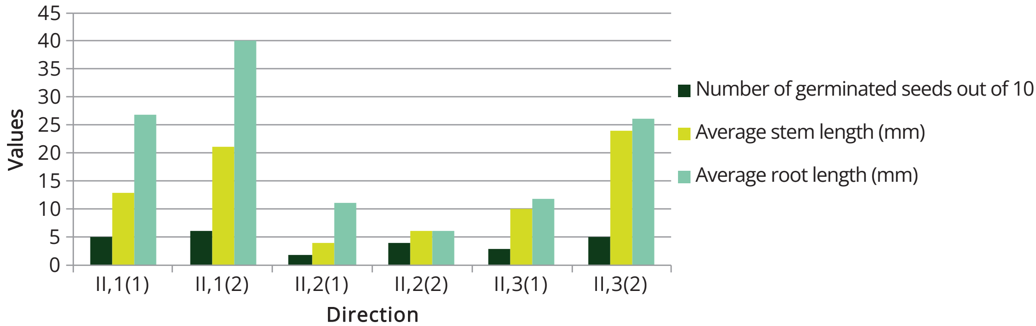

Figure 8. Bioindication of soil contamination based on seed germination
Source: developed by the authors

The morphometric indicators of seedlings at points II,2 are significantly lower, which indicates a strong inhibition of growth processes shown in Figure 8, most likely due to the presence of toxic substances in the soil. The length of the root and stem is on average reduced by 4-5 times compared to II,1. Low seed germination energy and suppressed seedling development at points II,2 may indicate the presence of significant concentrations of toxicants or pesticide residues in the soil. The reduction in stem length indicates a general suppression of photosynthetic activity in seedlings. In turn, the indicators in II,3 are intermediate: although germination is insignificant, morphometric characteristics indicate the adaptation of some plants to the present contaminants. This may indicate a less toxic but still disturbed chemical composition of the soil.

Similar results were observed in a study by J. Bae *et al*. (2016), who studied the effect of heavy metals (Zn, Pb, Ni, Cu, Cd) on the germination of *Ambrosia artemisiifolia* and legume seeds. The authors noted that even moderate concentrations of these metals significantly reduced germination energy and inhibited seedling development, with the root being particularly sensitive. This is consistent with the results of this study, where root length is one of the most affected indicators in contaminated sites. In a study by I. Sanjosé *et al*. (2021) using *Salsola vermiculata* as an example, it was found that an increase in the concentration of Cd, Cu, Pb and Zn in the soil led to a delay in germination and a decrease in seedling biomass. In particular, the authors point out that the most contaminated samples showed a decrease in stem length, which, in their opinion, is a consequence of a general decrease in photosynthetic activity. These results are similar to the observations at points II,2 of this study, where stem growth inhibition was also found, which can be interpreted as a decrease in photosynthetic efficiency due to toxic load. Thus, the results of both analysed studies confirm the hypothesis of the negative impact of heavy metals on seed germination and morphometric characteristics of seedlings, which is consistent with the conclusions of the present study. The only difference is the type of test objects used in the studies (in I. Sanjosé *et al.* – a steppe plant, in J. Bae *et al*. – weeds and legumes), but the general trends remain similar.

Thus, the generalisation of the data presented indicates a clear trend of inhibition of seed germination and initial plant growth under the influence of heavy metals. Common features are a decrease in germination energy and a reduction in root and stem length, reflecting the overall toxicity of the soil and a decrease in photosynthetic activity. The results obtained confirm the relevance of data from other authors and reinforce the argument in favour of using phytotesting to assess soil contamination.

Correlation analysis of *Raphanus sativus d.* var. *oleifera* Metrg germination under conditions of soil contamination with heavy metals
The study found a statistically significant correlation between the level of soil contamination with heavy metals (lead, cadmium, copper) and the germination rates of oil radish. Details are given in the table below for Object 1 (Table 4).

Based on the results of the analysis, the following conclusions can be drawn: high concentrations of Cu^{2+} do not cause a sharp decrease in seed germination, but may slightly reduce the number of germinated seeds. Higher concentrations of Zn^{2+}) theoretically may promote better root and stem growth, but the number of germinated seeds does not increase significantly. Excess Zn^{2+} can be toxic, but in this experiment, growth is observed. Even in small concentrations, Cd^{2+} negatively affects germination and growth, reducing the number of germinated seeds and the length of the root and stem. Pb^{2+}, like Cd^{2+}, inhibits seed germination and plant growth. Higher concentrations lead to a decrease in the number of germinated seeds.

Table 4. Correlation analysis of *Raphanus sativus d.* var. *oleifera* Metrg germination by Object 1

Copper (Cu^{2+})				
Sample Mark	**Concentration Cu (mg/kg)**	**Root Germination (R). mm**	**Stem Germination (S). mm**	**Number of Germinated Seeds. pcs**
I,1	0.675 (highest)	I – repeat – 19 II – repeat – 33	I – repeat – 9 II – repeat – 7	I – repeat – 3 II – repeat – 8
III,1	0.208 (lowest)	I – repeat – 19 II – repeat – 31	I – repeat – 7 II – repeat – 17	I – repeat – 7 II – repeat – 6
Zinc (Zn^{2+})				
Sample Mark	**Concentration Zn (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds. pcs**
III,3	4.761 (highest)	I – repeat – 20 II – repeat – 31	I – repeat – 10 II – repeat – 9	I – repeat – 4 II – repeat – 9
I,2	0.211 (lowest)	I – repeat – 22 II – repeat – 7	I – repeat – 7 II – repeat – 9	I – repeat – 7 II – repeat – 6
Cadmium (Cd^{2+})				
Sample Mark	**Concentration Cd (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds. pcs**
I,3	0.286 (highest)	I – repeat – 20 II – repeat – 19	I – repeat – 5 II – repeat – 9	I – repeat – 3 II – repeat – 8
III,1	0.153 (lowest)	I – repeat – 19 II – repeat – 31	I – repeat – 7 II – repeat – 17	I – repeat – 7 II – repeat – 6
Lead (Pb^{2+})				
Sample Mark	**Concentration Pb (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds. pcs**
I,3	2.245 (highest)	I – repeat – 20 II – repeat – 19	I – repeat – 5 II – repeat – 9	I – repeat – 3 II – repeat – 8
II,2	0.764 (lowest)	I – repeat – 29 II – repeat – 11	I – repeat – 3 II – repeat – 3	I – repeat – 5 II – repeat – 3

Source: developed by the authors

It has been determined that heavy metals (especially Cd^{2+} and Pb^{2+}) have a toxic effect on seed germination, reducing both the number of germinated seeds and the length of the root and stem. Cu^{2+} and Zn^{2+} in moderate concentrations can slightly stimulate growth, but their excess also inhibits germination. The presence of heavy metals in the soil is a serious environmental problem, as they reduce plant viability, which can lead to reduced yields and ecosystem disruption. When determining the level of acute toxicity, it was found that the lowest germination rates of the biotest Object were recorded at a distance of 5 metres from the landfill body at the northern point, namely 30% seed germination, where the Zn^{2+} level was 1.854 mg/kg. The highest germination energy level was observed in the sample at a distance of 15 metres from the landfill body at the south-eastern point, namely 100% seed germination, which is 92% higher than the germination of plant roots and 76% higher than the germination of plant stems from the control experiment.

According to M.O. Alotaibi (2024), studies of the effect of cadmium (Cd) and lead (Pb) on the germination of *Cymbopogon comosum* seeds showed a marked inhibition of germination, as well as a change in the protein profile of seedlings, confirming the toxic effect of these metals at concentrations above a certain threshold. This conclusion is consistent with the results of the present study – a low germination rate (30%) was recorded at the point with elevated Zn^{2+} content along with Cd^{2+} and Pb^{2+}, indicating the inhibitory effect of heavy metals even at relatively low concentrations.

Author M. Sharifi-Rad (2017) investigated the effect of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn) on the germination and development of *Hyssopus officinalis* in laboratory conditions at concentrations of 50, 100 and 150 µM. The results showed that all metal stressors significantly inhibited germination, reducing the germination rate, root and stem length, and biomass, with the order of inhibition strength being Cr > Cd > Cu > Ni > Zn. This partly coincides with the observations: moderate levels of Zn could stimulate the development of individual indicators (for example, at the southern point there was 100% germination), but at Zn values ~1.85 mg/kg, growth inhibition was noted. The table below shows the correlation analysis for Object 2 (Table 5).

Table 5. Correlation analysis of *Raphanus sativus d*. var. *oleifera* Metrg germination by Object 2

Copper (Cu^{2+})				
Sample Mark	**Concentration Cu (mg/kg)**	**Root Germination (R), mm**	**Stem Germination (S), mm**	**Number of Germinated Seeds, pcs**
III,3	0.67 (highest)	I – repeat – 72 II – repeat – 49	I – repeat – 29 II – repeat – 19	I – repeat – 3 II – repeat – 5
III,2	0.115 (lowest)	I – repeat – 59 II – repeat – 76	I – repeat – 19 II – repeat – 26	I – repeat – 5 II – repeat – 10
Zinc (Zn^{2+})				
Sample Mark	**Concentration Zn (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds, pcs**
II,1	8.097 (highest)	I – repeat – 27 II – repeat – 40	I – repeat – 13 II – repeat – 21	I – repeat – 5 II – repeat – 6
III,3	0.128 (lowest)	I – repeat – 72 II – repeat – 49	I – repeat – 29 II – repeat – 19	I – repeat – 3 II – repeat – 5
Cadmium (Cd^{2+})				
Sample Mark	**Concentration Cd (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds, pcs**
I,1	0.37 (highest)	I – repeat – 49 II – repeat – 68	I – repeat – 22 II – repeat – 30	I – repeat – 9 II – repeat – 8
III,1	0.108 (lowest)	I – repeat – 25 II – repeat – 26	I – repeat – 7 II – repeat – 8	I – repeat – 4 II – repeat – 7
Lead (Pb^{2+})				
Sample Mark	**Concentration Pb (mg/kg)**	**Root Germination (R)**	**Stem Germination (S)**	**Number of Germinated Seeds, pcs**
II,2	2.395 (highest)	I – repeat – 11 II – repeat – 6	I – repeat – 4 II – repeat – 6	I – repeat – 2 II – repeat – 4
III,1	0.668 (lowest)	I – repeat – 25 II – repeat – 26	I – repeat – 7 II – repeat – 8	I – repeat – 4 II – repeat – 7

Source: developed by the authors

The results of the studies showed that an increase in the content of Cu^{2+}, Zn^{2+} and Pb^{2+} in the soil negatively affects the germination of oil radish (*Raphanus sativus* var.), which indicates the phytotoxic effect of these metals even at concentrations that do not exceed the MPC. The lowest germination rate (30%) was recorded in the northern area near the landfill, where the concentration of Pb^{2+} was 1.575 mg/kg. In the control sample, 100% germination was observed.

This pattern is confirmed by the studies of K. Phoungthong *et al*. (2016), who also found inhibition of wheat (*Triticum aestivum* L.) germination under the influence of soluble forms of heavy metals, especially copper and lead, in waste leachates. The authors found that even without exceeding the regulated limits for metal content in ash residue extracts, there was a significant decrease in the energy of germination and growth of primary roots, which is consistent with the results obtained in this study. In addition, a similar approach to studying phytotoxicity was applied by S. Hazratqulov *et al*. (2024), who assessed the impact of heavy metals in soils stabilised with organic waste. According to their data, the greatest growth inhibition occurred at high bioavailability of lead and zinc, and the use of bioamendments significantly reduced phytotoxicity. Unlike their work, no soil remediation was carried out in this study, but the results obtained regarding the sensitivity of germination to Pb^{2+} and Zn^{2+} confirm that even under natural conditions there is a high risk of phytotoxic effects of these elements near unauthorised landfills. Thus, a summary of the available literature data and the results of this study indicates a stable negative reaction of plant biotests to elevated concentrations of heavy metals, in particular Pb^{2+}, Cu^{2+} and Zn^{2+}, even at relatively low levels of contamination, which is characteristic of areas with long-term exposure to landfill waste.

The results of the study, which demonstrate the impact of heavy metals (in particular Cu^{2+}, Zn^{2+}, Pb^{2+}) on the phytotoxicity of soils in the area of unauthorised landfills, can serve as an important basis for planning measures for recultivation and the organisation of sorting stations. Firstly, identifying the points with the most negative impact of heavy metals on plant development allows for the targeted identification of priority areas for reclamation. The use of biotests, as in this study, helps to assess the real biological effect of pollution, which is critical for the selection of adequate restoration technologies (e.g., phytoextraction, amendment application, use of biological preparations). This information contributes to the optimisation of resources and the improvement of the effectiveness of measures. Secondly, data on specific toxic metals that dominate the pollution indicate the need to sort waste according to its composition to prevent the further spread of toxicants. The organisation of sorting stations with a focus on the removal of metal and hazardous components from waste can significantly reduce the level of heavy metals in waste, reducing the risk of soil contamination. Thus, the results obtained are a valuable scientific basis for the development of a comprehensive waste management system that combines preventive measures with technical solutions to minimise phytotoxic effects and improve the ecological condition of areas near landfills.

CONCLUSIONS

The study showed that the soil samples taken near the landfill did not contain heavy metal concentrations exceeding the maximum permissible concentrations (MPC). Despite the absence of toxicologically hazardous levels of contamination, the results of phytotoxic testing showed a decrease in seed germination, indicating an inhibitory effect on growth processes. Thus, for Object 1, the lowest seed germination rate (3 out of 10 in each repetition) was recorded at points with the highest concentrations of cadmium (0.286 mg/kg) and lead (2.245 mg/kg), indicating their impact on phytotoxicity. A similar trend was observed for Object 2: at the highest content of Zn (8.097 mg/kg) and Pb (2.395 mg/kg), the number of germinated seeds decreased to 5-6 out of 10, while with a decrease in these concentrations, germination increased to 8-10 seeds. In addition, the reduction in the length of roots and stems of seedlings at elevated concentrations of heavy metals confirms the presence of a negative effect even within acceptable levels. For example, at the lowest Zn content (0.128 mg/kg), the root length reached 72-73 mm, while at the highest content, it was only 27-40 mm.

The results obtained confirm the feasibility of combining chemical analysis with bioindication methods in assessing soil condition, particularly in terms of ecotoxicology. It is planned to continue regular monitoring of soils in areas adjacent to solid waste landfills, using phytotesting as a sensitive tool for early diagnosis of potential environmental threats. The results of the study are of great practical and scientific importance for further improvement of approaches to environmental monitoring of soil condition in areas affected by landfills. The proposed phytotesting methodology can be integrated into the system for evaluating the ecotoxicity of soil cover as a sensitive indicator of early changes in the soil environment that are not always detected by standard chemical analysis. The use of a bioindication approach allows the detection of hidden forms of pollution caused by the complex influence of factors that do not exceed regulatory indicators but still have a negative impact on living organisms. Prospects for further research include expanding the number of research sites, conducting seasonal monitoring, and studying the synergistic effects of several pollutants simultaneously in order to comprehensively assess the phytotoxic potential of soils in areas affected by solid waste landfills.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Несанкціоновані сміттєзвалища як джерело забруднення ґрунтів важкими металами: фітотоксичний аспект

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Анотація. У статті розглянуто питання біотестування ґрунту як ефективного індикаторного підходу до оцінки екологічного стану земель, що зазнають антропогенного навантаження з боку локальних джерел забруднення. Об'єктами дослідження були зразки ґрунту, відібрані поблизу потенційно небезпечних техногенних ділянок, а саме з територій сміттєзвалищ. Проведено оцінку токсичності за допомогою фітотестів культури редьки олійної (*Raphanus sativus d.* var. *oleifera* Metzg.), що виявилася чутливим індикатором наявності шкідливих речовин у ґрунтовому середовищі. Паралельно здійснено аналітичне визначення вмісту важких металів (Cd, Pb, Zn, Cu) у ґрунтах. Результати фітотестування засвідчили зниження схожості насіння порівняно з контрольними зразками, що є свідченням токсичної дії ґрунтового середовища. Також спостерігалося зменшення енергії проростання та пригнічення росту первинної біомаси. Виявлено тісний кореляційний зв'язок між високим вмістом металів і пригніченням ростових параметрів культури редьки олійної, що вказує на взаємозалежність між хімічними показниками забруднення та біологічною відповіддю організмів. Зокрема, спостерігалося зменшення довжини проростків, що свідчить про біологічну активність важких металів. У деяких зразках було зафіксовано 30 % проростання, що свідчить про критичний рівень токсичності. Біотестування в поєднанні з хімічним аналізом дозволило виявити ділянки з найбільш критичним екологічним станом. Запропонований підхід може бути корисним для екологічних служб, органів місцевого самоврядування та установ, що займаються землеустроєм, для оперативного моніторингу стану ґрунтів та виявлення «гарячих точок» забруднення. Методика може бути адаптована для моніторингу промислових зон, зон санітарного нагляду, а також територій поблизу транспортних магістралей. Результати дослідження підтверджують доцільність використання інтегрованих підходів до моніторингу, що включають як аналітичні методи, так і біоіндикаційні тести. Такий підхід забезпечує більш об'єктивну оцінку ризиків для довкілля та може бути використаний для планування заходів з реабілітації забруднених територій, збереження родючості ґрунтів і сталого землекористування

Ключові слова: екотоксикологія; індекс проростання; біомоніторинг; ризики для агроекосистем; тест-рослини; токсикологічна чутливість