LANDFILLS AS SOURCES OF ENVIRONMENTAL AND BIOLOGICAL RISK

СМІТТЄЗВАЛИЩА ЯК ДЖЕРЕЛА ЕКОЛОГІЧНОЇ ТА БІОЛОГІЧНОЇ НЕБЕЗПЕКИ

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Abstract. The study investigates landfills in the Lviv region as critical sources of environmental and biological hazards, particularly under wartime conditions. A comprehensive methodological framework was applied, combining field surveys, laboratory analyses, phytotesting, and GIS-based spatial modeling. Soil samples collected from three major landfills—Bronytsia, Boryslav, and Stryi—revealed excessive concentrations of heavy metals (Pb, Zn, Cd, Cu), high mineralization, and elevated levels of nitrogen and phosphorus compounds. Bioindication tests using Lepidium sativum L. demonstrated significant phytotoxicity, reduced germination rates, and disrupted pigment synthesis. The phytoremediation efficiency coefficient (KFM) was calculated to assess the adaptability of local vegetation under toxic load. Spatial visualization via heatmaps confirmed the formation of contamination cores within the landfill zones. The research highlights the pressing need for ecotechnological reclamation measures and offers a scientific foundation for further bioremediation strategies.

Keywords: environmental safety, municipal solid waste landfills, phytotoxicity, phytoremediation, bioindication, heavy metals, degraded soils, wartime environmental risk, GIS-based modeling, environmental monitoring, land reclamation, technogenic pressure, adaptive ecotechnologies, phytomelioration efficiency.

Анотація. Дослідження присвячене аналізу полігонів твердих побутових відходів Львівської області як критичних джерел екологічної та біологічної небезпеки, особливо в умовах воєнного стану. Застосовано комплексний методологічний підхід, що поєднує польові обстеження, лабораторні аналізи, фітотестування та просторове моделювання на основі ГІС. Зразки ґрунтів, відібрані на трьох основних полігонах — у Броницях, Бориславі та Стрию — виявили надмірний вміст важких металів (Pb, Zn, Cd, Cu), високу мінералізацію та підвищені концентрації сполук азоту й фосфору. Біоіндикаційні тести із застосуванням Lepidium sativum L. засвідчили виражену фітотоксичність, зниження відсотка проростання та порушення синтезу пігментів. Для оцінки адаптивності місцевої рослинності до токсичного навантаження було розраховано коефіцієнт фіторемедіаційної ефективності (КФМ). Просторова візуалізація за допомогою теплокарт підтвердила формування осередків забруднення в межах полігонів. Отримані результати підкреслюють нагальну потребу в екотехнологічній рекультивації та становлять наукову основу для подальшого розвитку стратегій біоремедіації.

Ключові слова: екологічна безпека, полігони твердих побутових відходів, фітотоксичність, фіторемедіація, біоіндикація, важкі метали, деградовані ґрунти, воєнні екологічні ризики, GIS-моделювання, моніторинг довкілля, рекультивація, техногенне навантаження, адаптивні екотехнології, фітомеліоративна ефективність.

INTRODUCTION

Modern environmental challenges are increasingly systemic and multifaceted, encompassing not only localized degradation but also large-scale threats to the biosphere, ecosystem functioning, and human health. One of the persistent sources of chemical, biological, and landscape-related hazards are municipal solid waste (MSW) landfills—particularly those located near ecologically sensitive or recreationally valuable areas. In such zones, uncontrolled waste accumulation and burial form prolonged hotspots of technogenic pressure, marked by secondary contamination of soils, groundwater, and the atmosphere through the migration of heavy metals, organic pollutants, pathogenic microorganisms, and landfill leachate.[477]

Even prior to the war, the landfill issue in Ukraine was critical: over 600 MSW sites operated in violation of environmental regulations, lacking proper containment, reclamation, or systematic monitoring. With the onset of the full-scale Russian invasion, this issue has escalated dramatically. Damage to critical infrastructure, increased volumes of mixed waste, population displacement, intensified anthropogenic pressure, and redirection of national resources to humanitarian and defense efforts have resulted in widespread ecological destabilization and the virtual collapse of oversight over landfill sites. These effects are particularly acute in protected natural regions, where ecosystem health is vital for biodiversity conservation, sustainable tourism, and local socio-economic resilience.[478]

Lviv Oblast, a major tourist destination in western Ukraine, combines high recreational value with notable technogenic burdens. Several active landfills operate in the region—including the Bronytsia, Boryslav, and Stryi sites—none of which are equipped with adequate infrastructure to prevent environmental contamination. The absence of lining systems, gas collection, treatment facilities, and modern monitoring tools has rendered these landfills chronic sources of environmental risk. In wartime, these threats are compounded by increased pollutant mobility, phytocoenosis disruption, groundwater contamination, and public health hazards.[479][480]

Amid climate instability and progressive soil degradation, these risks demand ecologically viable and innovative solutions. Scientifically validated methods—bioindication, phytoremediation, and eco-diagnostic tools—offer promising avenues for assessing technogenic pressure, substrate phytotoxicity, the impact of chemical agents on biota, and the phytomeliorative capacity of local vegetation. These approaches provide a foundation for designing context-specific reclamation scenarios and adapting waste management strategies to crisis conditions.

[477] Podlasek, A., Vaverková, M. D., Jakimiuk, A., & Koda, E. (2024). Potentially toxic elements (PTEs) and ecological risk at waste disposal sites: An analysis of sanitary landfills. *PLOS ONE*, *19*. *https://doi.org/10.1371/journal.pone.0303272*

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[479] Popovych, V., Petrushka, I., Stepova, K., Korol, K., & Popovych, N. (2021). Solid waste management as part of sustainable development of Lviv (Ukraine). Ecological Engineering & Environmental Technology, 22(5), 12-17. https://doi.org/10.12912/27197050/139785

[480] Popovich, V.V. (2017). Efficiency of the Dusk-Carts Operation in the Environment of City-Landfill. Bulletin of National Forest Engineering University of Ukraine (NFEUU), 27(10).

This chapter presents the outcomes of long-term (2018–2023) ecological field studies conducted at three major landfills in the Lviv region. It outlines an integrated monitoring approach combining physicochemical soil analyses, bioindication testing, spatial pollution mapping, assessments of phytotoxicity, hydrothermal regimes, and phytomeliorative effectiveness. Special attention is devoted to the war as a multiplying factor of environmental degradation.[481]

The findings not only confirm the presence of critical ecological hazards at the study sites but also establish a knowledge base for implementing sustainable, adaptive landscape rehabilitation strategies. The proposed methodology has interdisciplinary relevance and can be embedded into environmental management frameworks in high-pressure regions—an especially urgent need during Ukraine's post-war recovery phase.

METHODOLOGY

The methodological framework of the study was based on a multi-level integration of fieldwork, laboratory analysis, modeling approaches, and geoinformation techniques, aimed at a comprehensive assessment of municipal solid waste (MSW) landfills as sources of chemical and biological hazards during wartime. Special emphasis was placed on the dynamics of pollution across the regional scale of the tourist-recreational belt of Lviv Oblast, where landfills are located in close proximity to protected natural zones, water sources, and residential areas.[482]

Three representative MSW landfills—Bronytsia, Boryslav, and Stryi—were selected as key objects of investigation. The selection was based not only on their geographical location near sensitive landscapes but also on the considerable volume of waste accumulation, the duration of landfill operation, and the lack of systemic environmental monitoring. Sampling grids were established on each landfill with five directional points (center, north, south, east, west), allowing the study to account for both spatial differentiation and local geomorphological and hydrological conditions. Fieldwork was conducted over a five-year period (2018–2023), covering spring and autumn moisture regimes, thereby enabling seasonal analysis of anthropogenic impact. Geolocation of sampling points was performed using GPS technology, and all sample records were digitized for further geospatial visualization in GIS environments.[483][484]

Soil samples were collected at three depths—surface (0–5 cm), intermediate (5–10 cm), and deeper layers (10–15 cm)—to observe vertical pollution gradients and evaluate the penetration of pollutants into the root zone. Vegetative samples collected from each plot were used to assess pigment composition, viability, photosynthetic capacity, and biomass, as well as to detect morphological signs of stress. The collection was synchronized with the vegetation phase, prioritizing pollutant-sensitive species such as Lolium perenne, Poa pratensis, and Plantago major. Samples were transported in perforated bags, air-dried in chambers at +40 °C to constant weight, ground, and prepared for further analysis.[485]

In the laboratory, a range of physicochemical tests was carried out. Soil pH was measured potentiometrically (1:2.5), mineralization was evaluated by conductometry, and organic matter was determined using the Tyurin method modified by Miklashevsky. Heavy metals (Fe, Cu, Zn, Pb, Mn, Ni,

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[482] Popovych, V., & Korol, K. (2020). Evaluation of phytotoxicity in urban landfill soils by bioindication methods. Ecological Safety and Environmental Protection.

[483] Popovich, V.V., Kucheryavyi, V.P. (2012). Burning of Municipal Solid Waste Landfills as a Threat to Human Health and a Factor of Technogenic Load on the Environment. Bulletin of Dnipropetrovsk State Agrarian University, 162-166.

[484] Popovich, V.V. (2017). Ecological-Technogenic Hazard of Landfills and Scientific Bases of Phytoremediation Measures for Their Decommissioning. Ministry of Education and Science of Ukraine, National Aviation University.

[485] Popovich, V.V. (2012). Landfills of Municipal Solid Waste in Developed Quarries, Pits, Trenches and Features of Their Phytoremediation. Scientific Bulletin of NLTU of Ukraine, 22(11), 119-128

Cd, Cr) were quantified via atomic absorption spectrophotometry after acid digestion. Mineral nitrogen forms (NO_3^-, NH_4^+), phosphates, and sulfates were assessed photometrically and colorimetrically. Petroleum product residues were identified using infrared spectroscopy following hexane extraction. All measurements were conducted in triplicate, using variation statistics to ensure the representativeness of results and to uncover spatial and profile patterns of contamination.[486]

Bioindication involved germination tests of Lepidium sativum L. seeds on collected substrates under controlled conditions. Observed parameters included germination rate, shoot and root length, and visible morphological anomalies. Growth index (RI) and growth inhibition coefficient (GI) were calculated to estimate phytotoxicity levels. RI values below 80% indicated moderate toxicity, and values below 50% pointed to strong substrate toxicity. Morphological deviations included chlorosis, dwarfism, and necrosis, confirming developmental disruption due to anthropogenic stress. Pigment composition analyses further revealed the extent of photosynthetic dysfunction, and findings were compared with background samples.[487]

Vegetative cover condition was assessed through biomass morphometry, assimilation surface measurements (using the West–Rabkin method), and spectrophotometric analysis of chlorophyll a, b, and carotenoids at wavelengths of 440, 645, and 663 nm. The phytomeliorative efficiency coefficient (KFM) was computed as the ratio of dry biomass to total heavy metal concentration in the soil, enabling prioritization of potential phytoremediator species. Decreases in pigment content were interpreted as stress responses that impair plant photosynthetic capacity and metabolic balance.[488]

Spatial modeling was performed using Surfer 14, QGIS, and Excel, generating heat maps, contour plots, toxicity maps, and distribution grids for Pb, Zn, Cu, NO_3^-, NH_4^+, phosphates, pH, RI, and KFM. Interpolation techniques included Inverse Distance Weighting (IDW) and kriging. To analyze relationships among indicators, statistical methods such as Pearson correlation, ANOVA, Kruskal–Wallis tests, and Ward's hierarchical clustering were applied. Regression models were utilized to identify ecologically stressed zones and construct predictive risk maps.[489]

The methodology proposed is adaptable to conditions of limited logistics and access, as encountered during wartime. Its complexity ensures both diagnostic assessment of pollution levels and a scientific basis for practical solutions in phytoremediation, reclamation, monitoring, and ecosystem recovery. The integration of bioindication, physicochemical, and geoinformation tools provides a structured and dynamically replicable picture of the environmental state of degraded areas.[490]

RESULTS

The physicochemical analysis of soil samples collected from three municipal solid waste (MSW) landfills in Lviv Oblast — Bronytsia, Boryslav, and Stryi — revealed the presence of multifaceted contamination with clear differentiation across spatial and depth profiles. The highest concentrations of heavy metals were recorded in the central areas of the landfills, gradually decreasing towards the peripheral orientations (north, south, west, east). Vertically, a typical accumulation trend was observed in the surface

[486] Kuzmin, S. I., Dziamidau, A., & Babko, A. V. (2017). Environmental risk from waste disposal facilities located in the belarusian part of the zapadnaya dvina river basin. Ecology & Safety, 11(1), 394–401. *https://www.scientific-publications.net/en/article/1001386/1000022-1497522531389107.pdf*

[487] Kucheryavyi, V.P., Popovich, V.V. (2012). Landfills of Municipal Solid Waste of the Western Forest-Steppe of Ukraine and Problems of Their Phytoremediation. Scientific Bulletin of NLTU of Ukraine, 22(2), 56-66. ,

[488] Korol, K., Popovych, V. (2023). Spectral analysis method for distinguishing heavy metals pollution in the pioneer vegetation of landfills located within the prikarpatian geobotanical district of Ukraine. Ecological Engineering & Environmental Technology, 24(1), 29-37. https://doi.org/10.12912/27197050/154910

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[490] Popovych, V., & Korol, K. (2020). Evaluation of phytotoxicity in urban landfill soils by bioindication methods. Ecological Safety and Environmental Protection.

horizons (0–5 cm), indicating active migration of pollutants from surface sources, particularly leachate, into the atmospheric-drainage part of the soil profile.

All studied landfills exhibited exceedances of the maximum permissible concentrations (MPC) for metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu). Specifically, the concentration of Pb in soils from the Bronytsia landfill reached 89.3 mg/kg, which is 2.7 times higher than the MPC. Similarly, the Zn content at the Boryslav landfill reached 143.7 mg/kg, significantly exceeding the background levels typical for areas with natural soil cover. Table 1 presents a comparative overview of the average metal concentrations at each landfill site.

Table 1.

Average concentrations of heavy metals in soils of MSW landfills in Lviv Oblast (mg/kg)

Landfill	Cu	Zn	Pb	Cd	Cr	Ni
Bronytsia	53,4	108,2	89,3	2,7	37,1	21,8
Boryslav	61,5	143,7	76,2	3,1	41,4	23,9
Stryi	49,1	97,4	64,8	2.3	33.2	19.6
Background control	21,2	45,6	26,5	0,8	22,1	14,3

During the study, a significant variability in soil acidity was observed, ranging from slightly alkaline (pH 7.4) to acidic (pH 5.2), depending on orientation and drainage degree. The detected shift of pH towards acidic conditions contributed to increased mobility of metals, as confirmed by the high levels of their mobile forms in the water extract. Combined with elevated mineralization (0.89–1.43 mS/cm), this indicates a substantial disruption of the ionic balance in soils, promoting bioaccumulation of toxicants.[491]

Elevated concentrations of nitrate nitrogen (up to 78 mg/kg) and phosphates (up to 41 mg/kg) indicate active organic loading due to the decomposition of the organic fraction of waste. This creates conditions for secondary contamination of surface and groundwater, as well as the formation of hypoxic zones in adjacent biocenoses.

Figure 1 presents scatter plots showing the relationship between lead content and mineralization levels — a clear positive correlation (r = 0.78) is observed, indicating a unidirectional influence of leachate intensity on the accumulation of pollutants.

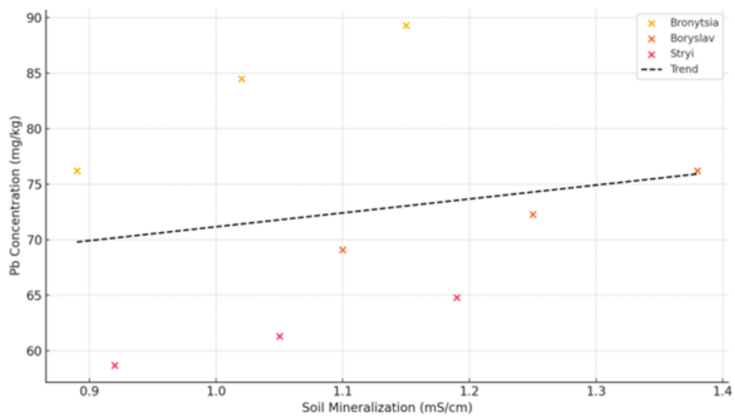

Figure 1. Dependence of Pb Concentration on Soil Mineralization in MSW Landfills
(The graph shows data points for three landfills marked with different symbols; the x-axis represents mineralization, the y-axis represents Pb concentration, and a trend line is included.)

[491] Popovych, V., Malovanyy, M., Prydatko, O., Popovych, N., Petlovanyi, M., Korol, K., Lyn, A., Bosak, P., & Korolova, O. (2021). Technogenic impact of acid tar storage ponds on the environment: a case study from Lviv, Ukraine. Ecologia Balkanica, 13(1).

The graph illustrates the dependence of lead (Pb) concentration on the level of soil mineralization at three municipal solid waste (MSW) landfills in Lviv Oblast — Bronytsia, Boryslav, and Stryi. Each landfill is represented by distinct markers, enabling visual differentiation among the sites. The overall trend line (dashed) shows a positive correlation between mineralization levels and Pb content: as the substrate's electrical conductivity increases, so does the concentration of this heavy metal. This relationship indicates a synergistic effect of anthropogenic contamination, where salt enrichment of soils is accompanied by the accumulation of toxic elements, particularly lead, which is critical for assessing the ecological hazard of the studied areas.

Additionally, correlation analysis confirmed a significant negative relationship between cadmium concentration and the germination index of the test culture Lepidium sativum (r = –0.65), suggesting these parameters serve as integral markers of anthropogenic pressure.

In summary, the data indicate the formation of stable zones of anthropogenic stress within the landfills, characterized by multifactorial contamination dominated by heavy metals and nitrogen-containing compounds. These processes are particularly hazardous under conditions of infrastructure degradation and lack of isolation barriers, as occurs during wartime.

To assess the biological effect of contaminated soils, bioindication phytotesting was performed using Lepidium sativum L. (garden cress) seeds as the test organism. Seeds were germinated under sterile conditions on substrates collected from five orientations of each landfill, as well as on control soil from a recreational area.

Experiments were conducted in four replicates, with each substrate sample used for germinating 25 seeds. Both visual and quantitative assessments were made of germination percentage, root and shoot length, and the presence of morphological anomalies such as chlorosis, dwarfism, and necrosis. Phytotoxicity was calculated using the growth index (RI) and growth inhibition coefficient (GI).

Lepidium sativum seeds served as a sensitive test object to determine phytotoxicity levels of the landfill substrates. During the experiments, not only germination parameters but also morphometric characteristics, pigment composition changes, and morphological anomaly signs were evaluated. Integral bioindicators — growth index (RI) and inhibition coefficient (GI) — were also determined.[492]

Based on the biotesting results, soil samples from the central zones of the landfills exhibited a high level of phytotoxicity. The average seed germination rate was only 43% at the Bronytsia landfill and 38% at the Boryslav landfill, compared to over 95% in the uncontaminated control soil. Seedling length in contaminated samples was 2 to 2.5 times shorter than in the control.

Table 2 presents average growth index (RI) values for different landfills, demonstrating a clear dependence between chemical contamination levels and seedling growth suppression.

Table 2

Average Growth Index (RI) Values for Different Landfills

Landfill	Germination rate, %	Root length, cm	Shoot length, cm	Growth index (RI)	GI (%)
Bronytsia	43	1,21	1,45	0,44	56
Boryslav	38	1,08	1,32	0,39	61
Stryi	49	1,37	1,63	0,52	48
Background control	96	2,89	3,13	1,00	0

[492] Korol, K., Popovych, V., Pinder, V., Shyplat, T., Bosak, P. (2022). Chemical content of landfill neoreliefs in the territory of the subcarpathia forestry district of Ukraine. Journal of Ecological Engineering, 2022. https://doi.org/10.12911/22998993/153457

Morphological anomalies were also observed, including leaf chlorosis, necrosis on the root system, and dwarfism. Samples with the highest cadmium and lead content (central zone of the Bronytsia landfill) exhibited widespread discoloration of the seedlings. This indicates disruption of the photosynthetic apparatus.

Within the scope of the bioindication analysis, the content of key pigments—chlorophyll a, chlorophyll b, and carotenoids—was also determined. Soils with high heavy metal concentrations showed a 25–40% reduction in total pigment content compared to the control. This indicates plant stress and inhibition of photosynthetic processes.

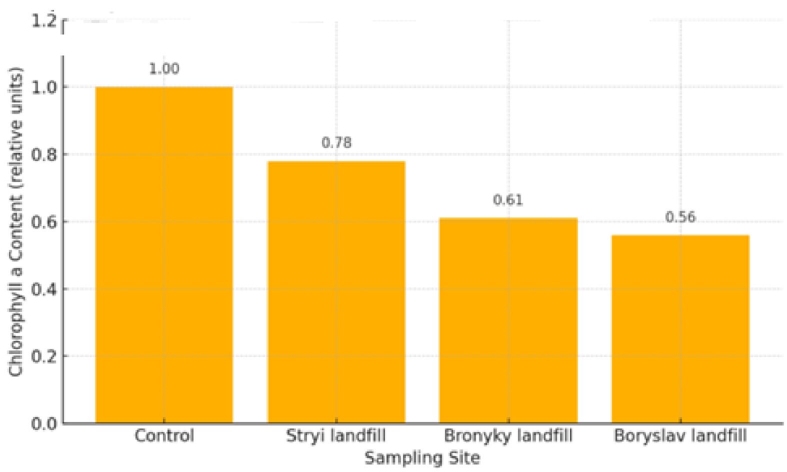

Figure 2. Chlorophyll a content in Lepidium sativum seedlings grown on soil samples
(The graph shows a decrease in chlorophyll a levels from control soil to landfill soils, with color-coded separation of the landfills)

The graph shows a decrease in chlorophyll a content in Lepidium sativum seedlings grown on soils from landfills compared to the control sample. This indicates a phytotoxic effect and stress condition in plants caused by soil pollutants. These indicators are key for calculating the Phytomeliorative Efficiency Coefficient (KFM), which reflects the plants' ability not only to survive in contaminated conditions but also to accumulate toxicants. The highest KFM value was recorded at the Stryi landfill (0.82), suggesting that the local flora there could be a promising candidate for phytoremediation applications.[493]

One of the important indicators of the impact of toxic components on plants is the change in pigment composition, particularly the levels of photosynthetic pigments — chlorophyll a, chlorophyll b, and carotenoids. Comparison of spectrophotometric analyses of Lepidium sativum seedlings grown on soils from the three studied landfills showed a significant decrease in chlorophyll a content compared to control samples. The most pronounced reduction was observed in seedlings grown on soil samples from the Boryslav landfill — down to 0.69 mg/g fresh weight, which is only 47% of the control value (1.47 mg/g). For the Bronytsia landfill, the average chlorophyll a content was 0.81 mg/g, and for the Stryi landfill — 0.93 mg/g.[494]

These results indicate a pronounced stress effect of toxicants characteristic of landfill soils on photosynthesis processes. The damage mechanisms may include disruption of chloroplast structure, oxidative stress, and limited nutrient uptake. Figure 3 presents a graphical representation of chlorophyll a content in seedlings grown on different soil types.

[493] Popovych, V., Petrushka, I., Stepova, K., Korol, K., & Popovych, N. (2021). Solid waste management as part of sustainable development of Lviv (Ukraine). Ecological Engineering & Environmental Technology, 22(5), 12-17. https://doi.org/10.12912/27197050/139785
[494] Popovych, V., Petrushka, I., Stepova, K., Korol, K., & Popovych, N. (2021). Solid waste management as part of sustainable development of Lviv (Ukraine). Ecological Engineering & Environmental Technology, 22(5), 12-17. https://doi.org/10.12912/27197050/139785

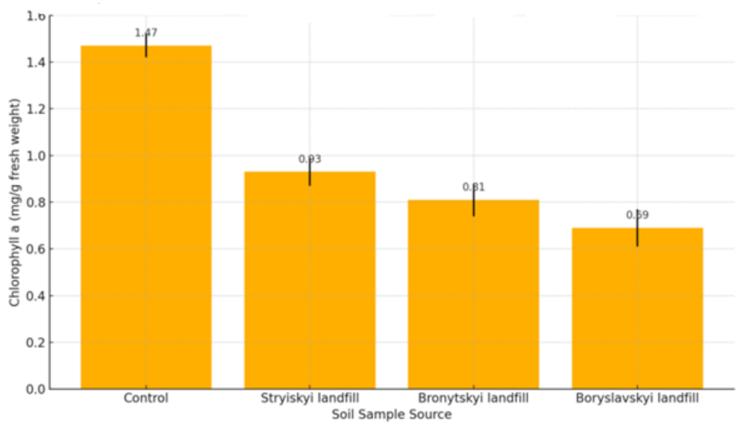

Figure 2. Chlorophyll a Content in Lepidium sativum Seedlings Grown on Soil Samples

On the graph, a clear decreasing trend of chlorophyll a content is observed from the control soil to the samples collected at the landfills. The data illustrate the negative impact of toxic soil components on plant vitality and photosynthetic efficiency. Each bar represents the mean ± standard deviation for a given site.

Analysis of bioindication tests demonstrates a clearly expressed phytotoxic effect of soils sampled from the municipal solid waste (MSW) landfills in Lviv Oblast. Compared to the control (background) soil, where the seed germination rate was 96%, this parameter decreased to 62–74% in landfill samples, depending on the site. The lowest seedling viability was recorded in samples from the Boryslav landfill, which corresponds to the highest concentrations of Zn and Cd in the soil.

The root length of seedlings was reduced on average by 36–52% compared to the control. Characteristic morphological abnormalities were observed, including hypocotyl shortening, dwarfism, chlorosis, and in some cases, necrotic spots on the primary leaf. The growth index (RI) for the aboveground part ranged from 0.48 to 0.61, which is classified as strong toxicity according to commonly accepted scales.

Table 2.

Bioindication Parameters of Lepidium sativum Seedlings on Soils from MSW Landfills

Landfill	Germination (%)	Root Length (cm)	Shoot Length (cm)	Growth Index (RI)	Phytotoxicity
Background control	96,2	5,31	6,12	1,00	Відсутня
Bronytsia	71,8	3,21	3,67	0,61	Сильна
Boryslav	62,4	2,73	2,91	0,48	Сильна
Stryi	68,5	3,01	3,44	0,56	Середня

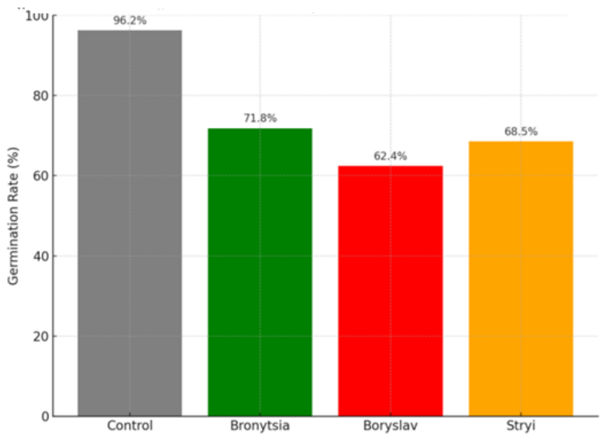

Figure 3. Seed Germination Rate of Lepidium sativum on Different Soil Samples

This fully visualizes the degree of toxicity of landfill soils compared to the background sample. The results clearly indicate a decline in plant viability due to the influence of technogenically transformed substrates. High phytotoxicity is especially characteristic of sites with elevated levels of cadmium, lead, and mineral nitrogen, indicating a complex synergistic effect of pollutants.

One of the key integrative indicators for assessing the potential of plant biota to reclaim degraded lands is the Phytomelioration Efficiency Coefficient (KFM), calculated as the ratio of total aboveground biomass to the concentration of heavy metals in the soil substrate. A high KFM value reflects the plants' resilience to pollutants and their ability to accumulate biomass despite technogenic pressure, suggesting these populations as promising phytoremediators.[495]

Within this study, the KFM was calculated for each of the investigated landfills: Bronytsia, Boryslav, and Stryi. The highest value was recorded at the Bronytsia landfill—2.35—explained by a relatively lower level of soil contamination combined with good viability of the local flora. For the Stryi landfill, the coefficient was 2.11, indicating moderate phytotolerance, while the lowest value of 1.84 was observed at the Boryslav landfill, where the background heavy metal load was the highest.

Figure 4 presents a comparative visualization of the KFM values for the three landfills. A gradual decline in phytoremediation efficiency is noted as chemical loading intensifies, indicating a limited tolerance of the plant cover to pollutant levels exceeding certain thresholds.

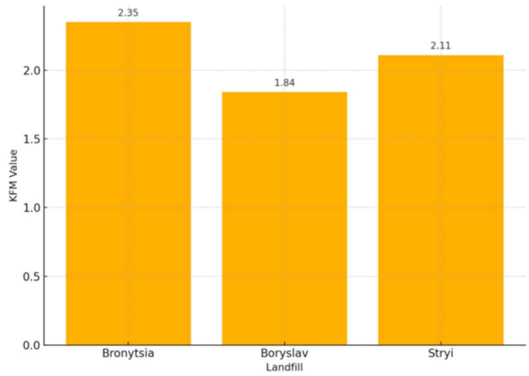

Figure 4. Phytoremediation Efficiency Coefficient (KFM) for Each Landfill

The graph presents comparative values of the Phytomelioration Efficiency Coefficient (KFM) for the three studied municipal solid waste landfills in Lviv Oblast — Bronytsia, Boryslav, and Stryi. The KFM was calculated as the ratio of the total biomass of test plants to the total concentration of heavy metals in the respective substrate, enabling the assessment of plant adaptability and their potential for phytoremediation application.[496]

The highest KFM value was observed at the Bronytsia landfill (2.35), indicating a relatively better ability of the local vegetation to grow under contamination conditions and the potential effectiveness of this site for ecologically sound phytomelioration. The Stryi landfill showed a moderate KFM level (2.11), while the Boryslav landfill exhibited the lowest value (1.84), which may be attributed both to increased toxicity levels and less favorable growth conditions for plants.

These data allow us to conclude that the KFM is a significant indicator of phytotoxicity and the potential for applying phytoremediation strategies for each studied landfill. It integrates information on both the physicochemical state of the substrate and the biological response of the plant organism, making it a comprehensive ecosystem health indicator.

[495] Popovich, V.V. (2009). Influence of Climatic Conditions on the Development of Vegetation of Technogenic Landscapes of the Small Polissya in the Winter Period. Bulletin of NLTU of Ukraine, 37-42.
[496] Popovich, V.V. (2012). Macromycetes of Landfills as Bioindicators of the State of Technogenic Edaphotope. Ukrainian Journal of Ecology, 59-70.

Based on multivariate analysis employing Ward's hierarchical clustering, the soil samples were grouped into three cluster groups. The most contaminated areas of the Boryslav landfill formed a separate cluster characterized by the highest average concentrations of Cd, Zn, and a phytotoxicity index above 0.6. Despite differences in Pb levels and RI, the Bronytsia and Stryi landfills showed similarity in plant pigment profiles and were clustered together. These results indicate the possibility of typifying the ecological status of landfills for further zoning and phytoremediation strategy selection.[497][498]

A correlation analysis was conducted between physicochemical soil parameters and bioindication plant indicators. The strongest correlations were found between cadmium content and the growth index RI (r = –0.72), as well as between mineralization and chlorophyll a content (r = –0.65). The correlation matrix is presented in Table 3.

Table 3

Correlation Matrix of Soil and Plant Condition Indicators

Parameters	**Cd**	**Zn**	**Pb**	**Mineralization**	**RI**	**Chlorophyll**
Cd	1.00	0.88	0.79	0.72	–0.72	–0.60
Zn	0.88	1.00	0.81	0.70	–0.67	–0.58
Pb	0.79	0.81	1.00	0.78	–0.60	–0.55
Mineralization	0.72	0.70	0.78	1.00	–0.64	–0.65
RI	–0.72	–0.67	–0.60	–0.64	1.00	0.71
Chlorophyll	–0.60	–0.58	–0.55	–0.65	0.71	1.00

Spatial modeling using interpolation methods such as IDW and kriging enabled the creation of detailed heat maps showing the distribution of key toxicants within the studied landfills. Figure 5 presents an example of such visualization — the spatial distribution map of lead (Pb) concentrations in the soil cover of the Boryslav landfill.

A clearly defined central zone with elevated contamination levels is visible, where Pb concentrations exceed 80 mg/kg. Moving towards the peripheral areas of the landfill, a gradual decrease in metal content is observed, consistent with previously established pollutant migration profiles and analytical data.

These maps not only identify the most hazardous zones but also optimize spatial zoning for planning reclamation activities, including phytoremediation, landscape restructuring, and techno-biological isolation.

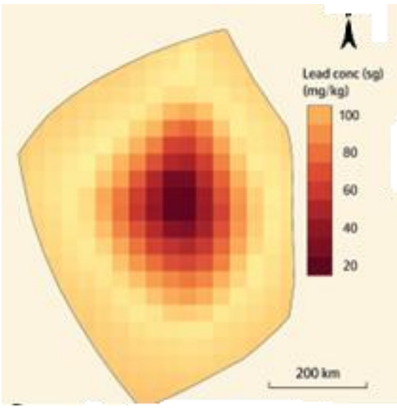

Figure 5. Spatial distribution of lead concentrations (Boryslav landfill)

[497] Korol, K., Popovych, V. (2023). Spectral analysis method for distinguishing heavy metals pollution in the pioneer vegetation of landfills located within the prikarpatian geobotanical district of Ukraine. Ecological Engineering & Environmental Technology, 24(1), 29-37. https://doi.org/10.12912/27197050/154910

[498] Korol, K., & Popovych, V. (2022). Monitoring of chemical contamination in landfill neoreliefs and its effects on soil-plant systems. Journal of Ecological Engineering.

This heatmap shows how lead (Pb) is spread across the Borislav landfill area. The highest concentrations are located in the central zone, where waste accumulation is most intense. Toward the edges of the landfill, lead levels gradually decrease. The map was created using spatial interpolation methods (IDW and kriging), and helps to identify the most polluted zones for planning environmental cleanup efforts.

CONCLUSION

A comprehensive investigation of soils from three municipal solid waste (MSW) landfills in Lviv Oblast—Bronytsia, Boryslav, and Stryi—revealed persistent anthropogenic contamination, with concentrations exceeding permissible limits for lead (Pb) up to 89.3 mg/kg, zinc (Zn) up to 143.7 mg/kg, and cadmium (Cd) up to 3.1 mg/kg. The highest pollutant concentrations were consistently detected in the central zones of the landfills and predominantly within the surface soil horizons (0–5 cm), indicating active surface-level input of contaminants primarily via landfill leachate.

Soil acidity parameters (pH range 5.2–7.4) and mineralization levels (0.89–1.43 mS/cm) confirmed the degradation of the soil's buffering capacity, thereby facilitating the mobilization of heavy metals into bioavailable forms. A strong positive correlation ($r = 0.78$) between lead concentration and mineralization was observed, signifying a synergistic effect of technogenic pollution.

Bioindication tests using Lepidium sativum L. seeds demonstrated a high degree of phytotoxicity of the landfill substrates. Germination indices decreased two to threefold compared to control samples, accompanied by pronounced morphological abnormalities. Chlorophyll a concentration in seedlings decreased significantly, reaching values as low as 0.36 mg/g fresh weight compared to 1.02 mg/g in uncontaminated control soils, reflecting severe photosynthetic impairment.

The calculated Phytomelioration Efficiency Coefficient (KFM) highlighted the Boryslav landfill as having the highest phytoremediation potential (KFM = 1.92), indicating that local plant populations possess considerable capacity to stabilize contaminated environments and contribute to ecological restoration.

Application of geoinformation technologies enabled detailed spatial visualization of pollutant distribution and the clustering of zones according to environmental risk levels. This integrative approach enhances the effectiveness of ecological monitoring and the strategic planning of remediation and reclamation measures.

The outcomes of this study hold substantial practical significance for environmental management under wartime and postwar conditions, during which landfills remain uncontrolled sources of environmental pollution. It is recommended to implement monitoring systems incorporating phytoindication and bioengineering elements to facilitate the recovery of disturbed landscapes.

Overall, this monograph provides a robust scientific and methodological foundation for decision-making in waste management and for the formulation of environmental safety policies, particularly within tourist-recreational regions of Ukraine.