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Evaluation of the ecological state and phytomeliorative efficiency of vegetation at landfills

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ABSTRACT

Phytomeliorative efficiency of vegetation species composition on devastated landscapes, including landfills, is a key factor in improving the ecological state at both local and regional levels. This article presents results of assessing heavy metal content and phytomelioration potential of vegetation cover on devastated areas, particularly at the Bronytsia landfill (Lviv region, Ukraine). Depending on the edaphic and climatic conditions, the surface of the devastated territories may have significant phytomeliorative potential, which is an important component of the reclamation process. Urban green spaces play a multifunctional role in improving the environment by providing oxygen production, microclimate regulation, filtration, noise absorption, and decorative and aesthetic functions. The key indicator for assessing the level of phytomelioration in devastated areas is the phytomelioration efficiency coefficient (K_{FM}). During the research at the landfill, various categories of plant communities were identified, such as frutocenoses, sylvacenoses, ruderalenoses, pratocenoses, and agrocenoses. The K_{FM} estimation for each landfill site showed the following results: Site 1 (western side): $K_{FM} = 4.5$; Site 2 (northern side): $K_{FM} = 4.0$; Site 3 (eastern side): $K_{FM} = 5.0$; Site 4 (southern side): $K_{FM} = 5.5$; Site No. 5 (central part): $K_{FM} = 2.1$; Site 6 (control): $K_{FM} = 6.55$. The results obtained indicate the suitability of the study area for reclamation activities for minimizing the negative impact on the environment.

Keywords: landfill, phytomelioration, vegetation cover, reclamation, environmental safety, heavy metals.

INTRODUCTION

Landfills in Ukraine pose a significant environmental threat to both natural components of the environment and public health. Due to the underdeveloped system of waste collection and disposal, particularly those containing toxic substances, the risk of environmental pollution by hazardous components is rising. Today, landfilling remains the most common method of waste treatment in Ukraine, although this approach is accompanied by numerous environmental risks (Shyshkin et al., 2024).

Urban green spaces play a key role in revitalization processes, performing important functions such as oxygen production, microclimate regulation, pollutant filtration, noise absorption, and aesthetic appeal. Landfills, as technologically hazardous objects, require special attention due to their constant negative impact on the environment. Recent studies confirm that soil, groundwater and air pollution caused by landfills is a serious environmental problem. The lack of effective protective systems, such as barriers and mechanisms for leachate collection and disposal, only exacerbates this situation (Frazer-Williams et al., 2024).

Phytoremediation, or using plants to restore contaminated areas, is a promising approach to improving ecosystems that have been affected by human activity. Plants are able to remove pollutants from the soil, improve microclimatic conditions, and help restore biodiversity.

Landfills, including those located in Ukraine, are becoming an increasingly serious source of environmental threats. The lack of effective systems for separate waste collection and disposal significantly increases the risk of environmental pollution with toxic substances. Recent studies indicate that landfilling remains the primary method of waste disposal in Ukraine, presenting significant threats to the environmental safety of the regions. (Novarlić et al., 2024)

A review of scientific literature reveals that landfills frequently have adverse effects on various environmental components, including both groundwater and surface water. As noted, many landfills do not have an adequate groundwater protection system, which leads to contamination of aquifers. These problems are also confirmed by studies that indicate the lack of project documentation and necessary protection systems at many landfills in Lviv region (Canal et al., 2023, Gautam et al., 2019)

In terms of phytoremediation research, recent publications have emphasized the potential of vegetation to restore ecosystems in contaminated areas. It is known that vegetation has the potential to play a key role in phytoremediation by improving soil quality, purifying water, and reducing air pollution. Studies of the phytoremediation potential of different types of plant communities, such as sylvatic, pratocenoses, frutocenoses, and others, are important for developing effective strategies for reclamation and ecosystem restoration (Jan et al., 2023).

Phytoremediation, using pollutant-resistant plants, is a popular ecological method for remediating contaminated sites by storing, degrading, or transforming contaminants, increasing ecosystem stability and productivity (Oziegbe et al., 2021). A study (Ayd et al., 2023) highlights local plants such as Bassia indica and Chenopodium album as potential phytoremediators on contaminated soils, demonstrating their ability to accumulate and transport pollutants, helping in ecosystem restoration.

In the context of landfills, phytoremediation offers prospects for improving the ecological state of the areas through the introduction of specially selected plants that can absorb pollutants, improve soil structure and promote natural recovery. Recent studies emphasize the need for an integrated approach to landfill remediation, which includes assessing the phytoremediation potential of vegetation and implementing practices that promote environmental rehabilitation (Skrobala et al., 2014).

Research indicates that implementing sustainable waste management practices can greatly mitigate the environmental impact of landfills, ultimately enhancing biodiversity and improving ecosystem health over time. By adopting innovative recycling methods and promoting waste reduction strategies, communities can effectively mitigate the negative environmental impact of landfills. This approach allows not only to preserve natural resources, but also to create a more sustainable future for the next generations (Vaverková et al., 2018)

Modern scientific studies emphasize the significance of phytomelioration as an effective approach for remediating areas contaminated with heavy metals. This method is particularly relevant for promoting sustainable development and enhancing the ecological condition of regions burdened by problematic landfills, due to the transformative role plants play in such environments.

MATERIALS AND METHOD

The research aims to examine the concentration of chemical elements in vegetation surrounding recreational areas and evaluate the effectiveness of plants in restoring landfill ecosystems.

The research focuses on the Bronytsia landfill, a technogenically contaminated site marked by waste accumulation and insufficient environmental protection measures. Specifically, the study analyzed the concentration of heavy metals in the root systems of trees growing in this area.

The study examines the impact of heavy metals on the roots of trees at the Bronytsia landfill and explores the phytomeliorative potential of vegetation. Particular attention is given to various plant communities, their capacity to purify soil and water from pollutants, and their role in improving microclimatic conditions and restoring biodiversity in the area.

The research was carried out with consideration of methodological approaches proposed by Sneha Bandyopadhyay, Pierre Lucisin, Guillaume Echevarria, Thibaut Sterckeman, Jessica Vallance, Patrice Rey, Emile Benizri. Figure 1 presents the territory of the Bronytsia landfill with indicated sites for analysis. Each of the sites has its own coordinates and pollution level:

- Site 1 (49.430637, 23.437195): Located in the southwestern part of the landfill. This site is characterized by an average level of contamination.
- Site 2 (49.429726, 23.439048): Located in the northwest of the landfill. The level of contamination is known to be above average.
- Site 3 (49.429192, 23.436457): The middle part of the landfill, which has a moderate level of contamination compared to the neighboring areas.
- Site 4 (49.430156, 23.435165): Located on the southeastern edge of the landfill. This site may show varying levels of contamination depending on local conditions.
- Site 5 (49.429876, 23.436945): Located on the western part of the landfill, indicating an average level of contamination.
- Site 6 (49.428648, 23.431781): The southern edge of the landfill, where the level of contamination may be higher due to the proximity to old dumpsites.

In June 2022, a total of 10 samples were collected to assess the concentration of heavy metals in the root systems of trees at the Bronytsia landfill. The samples were taken from four different sides of the landfill, as well as from its central area. After collection, the samples were dried, chopped, and labeled for further analysis. The methodology for sampling and preparing the root specimens is described in detail in the study. Figure 2 presents the external appearance of the research sites. The tree root samples were analyzed for toxic elements from the first hazard class (Pb, Zn, Cd) and the second hazard class (Co, Cu). The study included samples from various sections of the landfill and involved the following tree species: *S. cinerea* L., *C. betulus* L., *P. spinosa* L., *M. sylvestris* Mill., *A. negundo* L., *P. nigra* L., *F. sylvatica* L., and *S. alba* L. These species were selected for their ability to absorb and accumulate heavy metals from the soil.

The investigation of copper (Cu) levels in tree roots from the northern area of the Bronytsia landfill showed that *M. sylvestris* Mill. Cu concentration was 0.1 ± 0.01 mg/kg, and *P. spinosa* L. had 0.2 ± 0.01 mg/kg. These values are below the maximum allowable concentration (MPC) of 5 ± 0.01 mg/kg as per the regulations. On the southern side of the landfill, zinc (Zn) concentrations were 0.25 ± 0.01 mg/kg for *M. sylvestris* Mill. and 0.29 ± 0.01 mg/kg for *P. spinosa* L., both under the 10 ± 0.01 mg/kg permissible limit. Conversely, lead (Pb) concentrations were notably higher, with 1.29 ± 0.01 mg/kg in *M. sylvestris* Mill. and 1.58 mg/kg in *P. spinosa* L., exceeding the MPC of 0.5 ± 0.01 mg/kg by more than three times. Cadmium (Cd) levels were 0.03 mg/kg in *M. sylvestris* Mill. and 0.07 ± 0.01 mg/kg in *P. spinosa* L., which is double the permissible limit. Cobalt (Co) concentrations were 0.05 ± 0.01 mg/kg in *M. sylvestris* Mill. and 0.16 ± 0.01 mg/kg in *P. spinosa* L., with the latter slightly surpassing the allowable concentration of 1 ± 0.01 mg/kg as outlined by the standards. (Figure 3).

The concentrations of heavy metals in the roots of *S. cinerea* L. and *C. betulus* L. from the

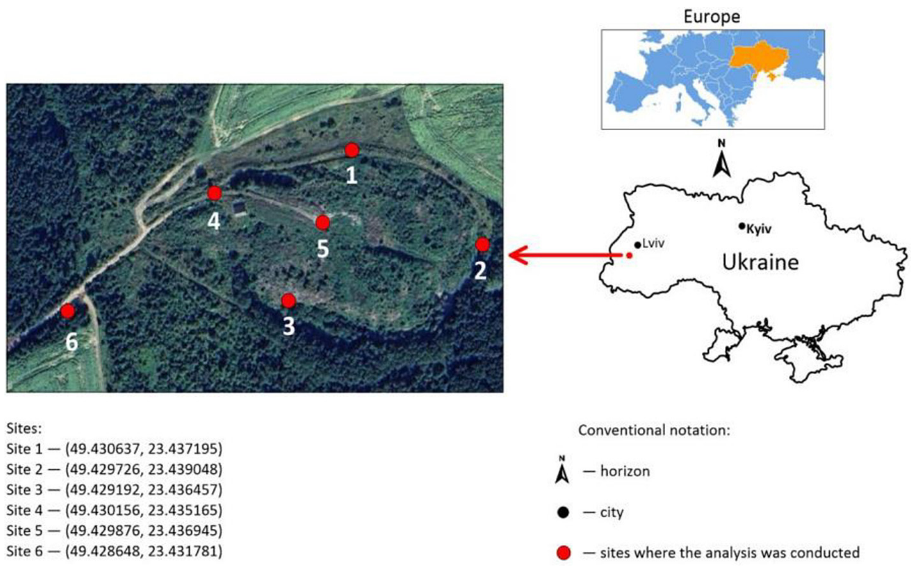

Figure 1. Location map of the investigated landfill

Site 1 (western side)

Site 2 (northern site)

Site 3 (eastern side)

Site 4 (southern side)

Site 5 (central part)

Site 6 (control site)

Figure 2. General view of the research sites

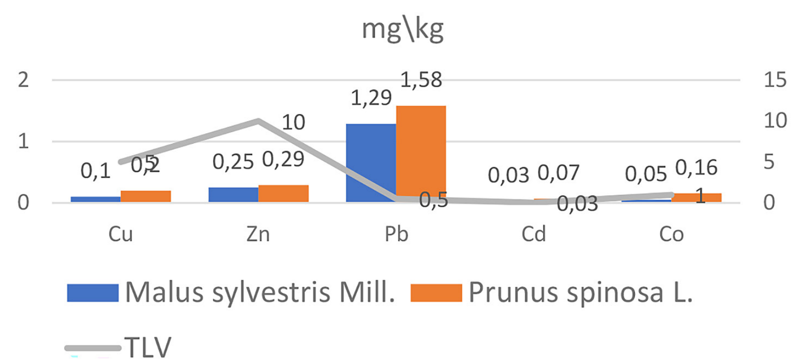

Figure 3. Heavy metal content in the roots of *M. sylvestris* Mill. and *P. spinosa* L. on the northern side of the Bronytsia landfill

western region of the Bronytsia landfill were evaluated individually for each element. In the case of copper (Cu), the levels measured were 0.39 ± 0.01 mg/kg in *S. cinerea* L., which falls within acceptable limits, and 5.57 ± 0.01 mg/kg in *C. betulus* L., a concentration that exceeds the established threshold for Cu, as per the regulatory guidelines. Zinc (Zn) content was found to be 0.17 ± 0.01 mg/kg in *S. cinerea L.* and 8.15 ± 0.01 mg/kg in *C. betulus* L., both within the permissible concentration range. However, lead (Pb) levels surpassed the allowed limits, with concentrations of 1.27 ± 0.01 mg/kg in *S. cinerea* L. and 2.95 ± 0.01 mg/kg in *C. betulus* L., indicating significant contamination. Cadmium (Cd) was present at 0.02 ± 0.01 mg/kg in *S. cinerea* L., which is within the normal range, but in *C. betulus* L., the cadmium content reached 0.33 ± 0.01 mg/kg — ten times higher than the allowable concentration. This indicates a severe cadmium accumulation in the latter species. Cobalt (Co) concentrations were also notable, with 1 mg/kg in *S. cinerea* L. (within normal limits) and 1.7 ± 0.01 mg/kg in *C. betulus* L., exceeding the standard. These findings demonstrate varying degrees of metal accumulation, with C. betulus L. showing higher susceptibility to heavy metal uptake compared to *S. cinerea* L. (Figure 4).

The analysis of heavy metals in the roots of *P. nigra* L. and *S. alba* L. from the central part of the landfill yielded various findings. Copper (Cu) concentrations were found to be 0.09 ± 0.01 mg/kg in *P. nigra* L. and 0.22 ± 0.01 mg/kg in *S. alba* L., both of which fall within the acceptable limits set by the regulations. Zinc (Zn) levels were recorded at 0.6 ± 0.01 mg/kg in *P. nigra* L. and 0.23 ± 0.01 mg/kg in *S. alba* L., also adhering to permissible standards. However, lead (Pb) concentrations were significantly higher, with measurements of 0.84 ± 0.01 mg/kg in *P. nigra* L. and 1.03 ± 0.01 mg/kg in *S. alba* L., surpassing the allowable thresholds. Cadmium (Cd) levels were 0.02 ± 0.01 mg/kg in *P. nigra* L., which is within the normal range, while *S. alba* L. exhibited a higher concentration of 0.23 ± 0.01 mg/kg, exceeding the standard limits. Cobalt (Co) levels were consistent across both species, with a measurement of 0.05 ± 0.01 mg/kg, which remains within the allowable range. This detailed analysis reveals differing levels of heavy metal accumulation in the roots of trees, emphasizing areas where the concentrations of lead and cadmium exceed the established safety thresholds. (Figure 5).

The assessment of heavy metal concentrations in the roots of *F. sylvatica* L. and *M. sylvestris* Mill. from the southern section of the Bronytsia landfill yielded several key findings. Copper (Cu) levels were measured at 0.04 ± 0.01 mg/kg in *F. sylvatica* L. and 0.59 ± 0.01 mg/kg in *M. sylvestris* Mill., both of which are within the acceptable limits. Zinc (Zn) concentrations were 0.08 ± 0.01 mg/kg in *F. sylvatica* L. and 0.74 ± 0.01 mg/kg in *M. sylvestris* Mill., also staying within permissible ranges. In contrast, lead (Pb) levels were higher,

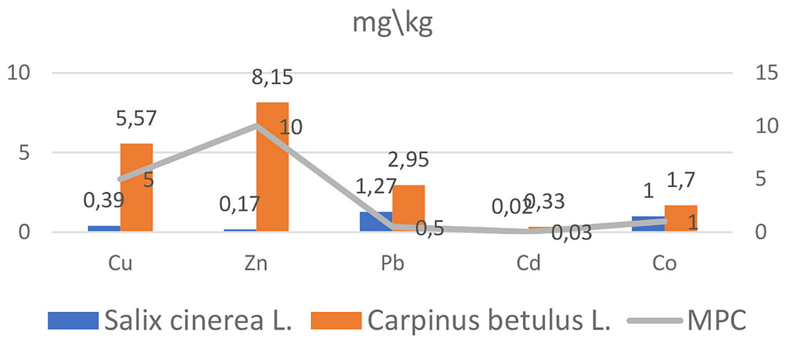

Figure 4. Heavy metal content in the roots of *S. cinerea* L. and *C. betulus* L. on the western side of the landfill

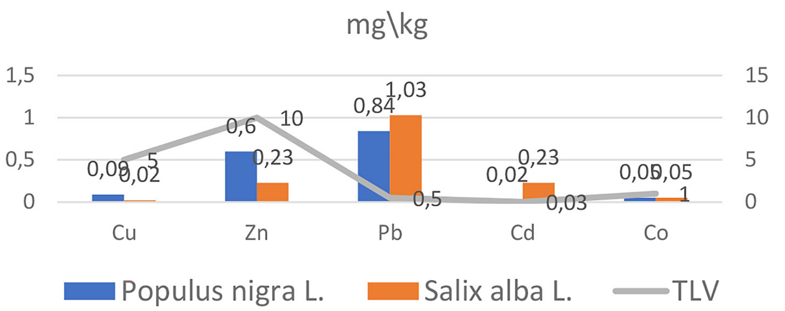

Figure 5. Heavy metal content in the roots of *P. nigra* L. and *S. alba* L. on the central part of the landfill

recorded at 0.61 ± 0.01 mg/kg in *F. sylvatica* L. and 3.55 ± 0.01 mg/kg in *M. sylvestris* Mill., both surpassing the allowable maximum concentration. Cadmium (Cd) was found at 0.02 ± 0.01 mg/kg in *F. sylvatica* L., meeting the standard, while *M. sylvestris* Mill. showed a level of 0.34 ± 0.01 mg/kg, exceeding the acceptable limit. Cobalt (Co) concentrations were 0.05 ± 0.01 mg/kg in *F. sylvatica* L., which is within normal parameters, whereas *M. sylvestris* Mill. had a value of 2 ± 0.01 mg/kg, exceeding the allowable limit. (Figure 6).

The evaluation of heavy metal concentrations in the roots of *A. negundo* L. and *P. nigra* L., from the eastern region of the Bronytsia landfill, produced several notable findings. Copper (Cu) levels were measured at 0.13 ± 0.01 mg/kg for *A. negundo* L. and 0.33 ± 0.01 mg/kg for *P. nigra* L., both of which are within the acceptable range according to regulatory standards. Zinc (Zn) concentrations were found to be 0.86 ± 0.01 mg/kg in A. negundo L. and 0.48 ± 0.01 mg/kg in *P. nigra* L., also remaining within the permissible limits. Lead (Pb) levels, however, were markedly elevated, with measurements of 2.05 ± 0.01 mg/kg in *A. negundo* L. and 3.12 ± 0.01 mg/kg in *P. nigra* L., significantly exceeding the allowable thresholds for Pb. Cadmium (Cd) concentrations were 0.11 ± 0.01 mg/kg in *A. negundo* L. and 0.25±0.01 mg/kg in *P. nigra* L., both surpassing the standard limits. Cobalt (Co) levels were 0.27 ± 0.01 mg/kg in *A. negundo* L., which falls within the acceptable range, while *P. nigra* L. showed a higher concentration of 1.99 ± 0.01 mg/kg, exceeding the permissible limit. Overall, the analysis highlights a significant exceedance of Pb concentrations across all sampled tree species from the landfill, indicating elevated levels of contamination in this area. (Figure 7).

The data reveal considerable contamination of the Bronytsia landfill area, especially with heavy metals including Pb, Cd, and Co. This indicates the importance of implementing measures to improve the environmental situation, such as phytomelioration and other engineering measures to reduce pollution. The research confirms that plants on the landfill site are able to absorb these heavy metals, which helps clean the substrate. It is a commonly known fact that heavy metals migrate in the environment and enter the human body causing irreversible changes that ultimately lead to serious illnesses (Nersesyan et al., 2021, Serhiyenko et al., 2022). As a result of heavy metal exposure, humans can develop diseases such as cancer, diabetes, eczema,

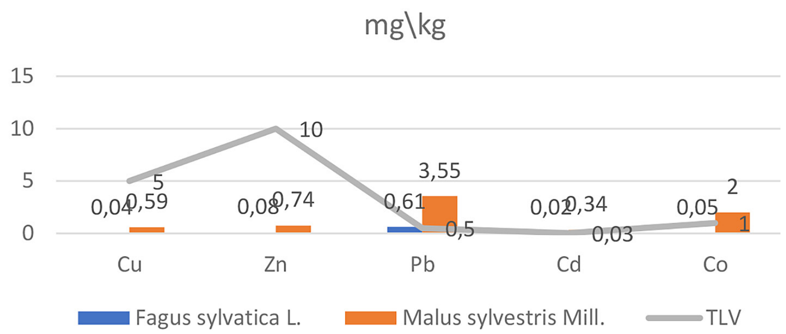

Figure 6. Heavy metal content in the roots of *F. sylvatica* L. and *M. sylvestris* Mill. on the southern side of the landfill

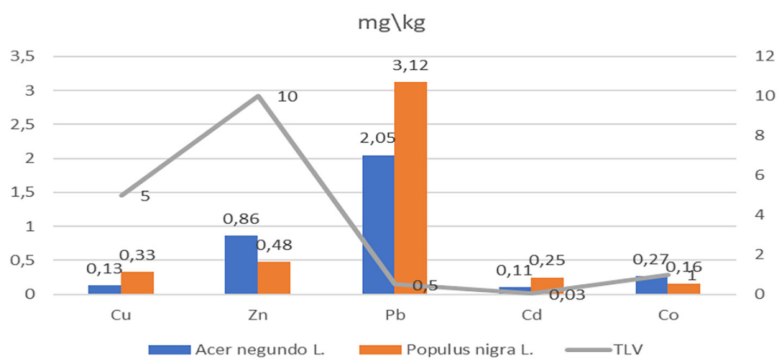

Figure 7. Heavy metal content in the roots of *A. negundo* L. and *P. nigra* L. on the eastern side of the landfill

and liver cirrhosis (Serhiyenko et al., 2021, Serhiyenko et al., 2022). The analysis of phytomeliorative potential at the Bronytsia landfill was assessed using special methods allowing to explore the effectiveness of vegetation cover in improving the ecological state. An integral indicator for assessing the effectiveness of phytomelioration processes in devastated areas is the coefficient of phytomelioration efficiency (K_{FM}). This indicator is determined using special assessment methods that measure the impact of vegetation on improving soil, water and air quality, as well as on restoring biodiversity. For its determination, the following mathematical dependence is used (according to Kucheryavyi, 2003):

$$K_{FM} = \frac{S_p \cdot b + S_a \cdot b + S_{pm} \cdot b + S_f \cdot b + S_v \cdot b + s_{sv3} \cdot b + S_{sv1} \cdot b + S_{st} \cdot b + S_r \cdot b}{S} \quad (1)$$

Table 1. Species composition of vegetation across investigated landfill sites

No.	Species	Site					
		1	2	3	4	5	6
1	*Ledum palustre* L.	+			+		+
2	*Robinia pseudoacacia* L.		+	+		+	
3	*Plantago lanceolata* L.	+			+		+
4	*Triticum aestivum* L.	+	+				+
5	*Equisetum sylvaticum* L.				+		+
6	*Juncus effusus* L.		+		+	+	+
7	*Artemisia absinthium* L.		+		+		+
8	*Tripleurospermum aritimum* (L.) W.D.J. Koch.	+		+		+	
9	*Apera spica – venti* (L.) P. Beauv		+		+	+	
10	*Echium vulgare* L.	+		+	+		
11	*Melica nutans* L.			+	+	+	
12	*Chelidonium majus* L.	+	+			+	
13	*Tussilago farfara* L.	+		+	+		
14	*Taraxacum officinale* L.		+		+	+	
15	*Typha latifolia* L.		+	+			
16	*Trifolium pratense* L.	+	+		+		+
17	*Chenopodium glaucum* L.		+		+		
18	*Juncus effuses* L.	+	+			+	
19	*Rosa canina* L.	+		+		+	
20	*Crataegus monogyna* Jacq.				+	+	+
21	*Populus tremula* L.				+		+
22	*Quercus robur* L.		+				
23	*Carpinus betulus* L.	+		+	+		+
24	*Malus sylvestris* Mill.						
25	*Salix caprea* L.	+		+			
26	*Pinus sylvestris* L.						+
27	*Corylus avellana* L.				+		+
28	*Betula pendula* L.			+			
29	*Prunus spinosa* L.		+				+
30	*Malus sylvestris* Mill.		+		+		+
31	*Acer negundo* L.			+			
32	*Populus nigra* L.			+		+	+
33	*Fagus sylvatica* L.				+		
34	*Salix alba* L.			+		+	+
35	*Salix cinerea* L	+		+		+	+

where: Sx is the occupied area: p – pratocenosis; a – agrocenosis; pm – pomolocenosis; f – frutocenosis; v – vitocenosis; sv_3 – three–tier silvacenosis; sv_1 – single–tier silvacenosis; st – striocenosis; r – ruderalenosis; b – score of the cenosis; S – total area.

The mathematical dependence takes into account the differentiation in functions, features and development possibilities in specific conditions of the territory of each of the listed groups of plantations: pratocenoses – meadow communities, agrocenoses – agricultural plantations, pomolocenoses – orchards or their remains, frutocenoses – shrub plantations, vitocenoses – vineyards, silvacenoses – forest communities, strepocenoses – strips of various functional adaptations, and ruderalenoses – weed communities.

The phytomelioration efficiency coefficient was determined by evaluating various areas of the Bronytsia landfill. To carry out this assessment, a series of test plots measuring 10 × 10 meters were established at different locations: the northern and southern sides, the western and eastern sides, the central part of the landfill, and a control plot located 100 meters from the landfill boundaries.

RESULTS

The following functional categories of plantations were identified at the landfill: frutocenoses, silvacenoses, ruderalenoses, pratocenoses, and agrocenoses. The assessment of phytomelioration efficiency coefficients in all the studied areas is presented below: Site 1 (western side) – single–tier silvicenoses (10%), frutocenoses (5%), ruderalenoses (40%); Site 2 (northern side) – single–tier silvicenoses (5%), ruderalenoses (10%), agrocenoses (10%); Site 3 (eastern side) – single–tier silvicenoses (35%), frutocenoses (10%), ruderalenoses (30%); Site 4 (southern side) – single–tier silvicenoses (30%), frutocenoses (25%), ruderalenoses (40%); Site 5 (central part) – single–tier silvicenoses (2%), frutocenoses (1%), ruderalenoses (40%); Site 6 (control) – single-tier silvaceous plants (15%), fruticaceous plants (10%), ruderal plants (20%), pratocenoses (30%).

At the investigated landfill, 35 vegetation species from 14 families and 6 genera were recorded. (Table 1). The Bronytsia landfill exemplifies a severely contaminated site in urgent need of remediation. Characterized by substantial waste accumulation and the absence of an effective environmental protection system, the landfill presents a critical case for studying the phytomeliorative potential of vegetation. Various plant communities have been identified at the site, including silvaceous, fruticaceous, ruderal, and others. Each of these communities offers distinct phytomeliorative benefits, contributing to environmental improvement at the landfill. Specifically, silvaceous communities enhance the microclimate, mitigate erosion, and filter pollutants from soil and water. Meanwhile, fruticaceous and ruderal communities can aid in reducing pollution and enhancing the overall appearance of the area.

Site 1 is situated on the western side of the Bronytsia landfill, adjacent to the access road and natural forested areas. Three main types of plant communities were documented at this site: single-tier silvaceous (sv_1), fruticaceous (f) and ruderal (r). The percentage distribution of the area of these communities is as follows: single-tier silvicolous (sv1) occupies 10% of the area; frutocenoses (f) occupy 5% of the area; ruderal (r) occupies 40% of the area. The coefficient of phytomelioration efficiency (K_{FM}) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_f \cdot b + S_r \cdot b}{S} \quad (2)$$

The assessment shows that site 1 has the following average scores (b) for each vegetation type: single-tier silvicolous (sv_1) – 4 points; fruticolous (f) – 3 points; ruderal (r) – 2 points.

The coefficient of phytomeliorative efficiency of site 1 is 2.45. This indicates that this site has an average level of phytomeliorative activity. A high proportion of ruderal cenoses indicates a significant number of weeds, which may reduce the overall phytomeliorative potential of the site.

The presence of single-tier silvicolonies and fruticolonies indicates the potential for further development and improvement of the environment at this site through the implementation of additional phytomelioration measures. For example, an increase in the share of sylvatic and fruticaceous vegetation may contribute to an increase in the overall phytomeliorative effect.

In general, site 1 has a moderate phytomeliorative potential, which can be increased by targeted planting measures and improving the structure of the vegetation cover. Site 2 is located on the northern side of the landfill, bordering agricultural land. Three main types of plant communities were recorded at this site: single-tier silvicolous (sv_1), ruderal (r) and agrocenoses (a). The percentage distribution of the area of these communities is as follows: single-tier silvicultural communities (sv1) occupy 5% of the area; ruderal communities (r) occupy 10% of the area; and agrocenoses (a) occupy 10% of the area.

The coefficient of phytomelioration efficiency (K_{FM}) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_r \cdot b + S_a \cdot b}{S} \quad (3)$$

As assessed, site 2 has the following average scores (*b*) for each vegetation type: single-tier silvicultural communities (sv_1) – 4 points; ruderal communities (*r*) – 2 points; agrocenoses (*a*) – 3 points.

The coefficient of phytomeliorative efficiency of site 2 is 2.8. This indicates that this site has a lower average level of phytomeliorative activity compared to site 1. The high proportion of ruderal cenoses indicates a significant amount of weeds, which may reduce the overall phytomeliorative potential of the site.

The presence of single-tier silvicolonies and agrocenoses indicates the potential for further development and improvement of the environment at this site through the implementation of additional phytomelioration measures. For example, an increase in the share of silvicultural and agrocenoses may contribute to an increase in the overall phytomeliorative effect. In general, site 2 has a moderate phytomelioration potential, which can be increased through targeted landscaping measures and improvement of the vegetation structure.

Site 3 is located on the eastern side of the landfill, where it borders the adjacent forest plantations. Three main types of plant communities were recorded at this site: single-tier silvaceous (sv1), ruderal (r) and fruticaceous (f). The distribution of the area for each vegetation type is as follows: single-tier silvicolous (sv1) – 35% of the area; ruderal (r) – 30% of the area; frutocenoses (f) – 10% of the area. The coefficient of phytomelioration efficiency (K_{FM}) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_f \cdot b + S_r \cdot b}{S} \quad (4)$$

The average values of scores (*b*) for each type of vegetation in site 3 are as follows: single-tier silvicolous (sv_1) – 4 points; ruderal (*r*) – 2 points; frutocenoses (*f*) – 3 points.

Thus, the coefficient of phytomeliorative efficiency of site 3 is 3.07. This indicates a relatively high level of phytomeliorative activity in this area compared to site 2.

The high percentage of single-tier silvicolous plants indicates a significant potential for improving the ecological condition of this part of the landfill. Silvicultural communities provide important ecological functions, such as improving the microclimate and reducing erosion. However, a significant proportion of ruderal communities also indicate the presence of weeds, which can negatively affect the overall ecological condition of the site. Fruit communities, although occupying a smaller portion of the area, also contribute to the phytomelioration process by improving the structural diversity of vegetation and providing additional environmental benefits.

Site 3 demonstrates moderately high phytomelioration potential, which makes it one of the most promising for further reclamation and improvement of the landfill's environmental condition.

Site 4 is situated on the southern side of the landfill, adjacent to forest plantations. Three main types of plant communities were recorded at this site: single-tier silvaceous (sv1), fruticaceous (f), and ruderal (r). The distribution of the area for each vegetation type is as follows: single-tier silvicolous (sv_1) – 30% of the area; frutocenoses (f) – 25% of the area; ruderal (r) – 40% of the area.

The coefficient of phytomelioration efficiency (KFM) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_f \cdot b + S_r \cdot b}{S} \quad (5)$$

The average values of points (*b*) for each vegetation type in site 4 are as follows: single-tier silvicolous (sv_1) – 4 points; ruderal (*r*) – 2 points; fruticolous (*f*) – 3 points.

The coefficient of phytomeliorative efficiency of site 4 is 2.89. This indicator indicates a relatively low phytomeliorative potential of this part of the landfill compared to other areas, for example, to site 3.

Site 4 has a significant share of ruderal communities, which indicates the dominance of weeds, which have a lower impact on improving the ecological condition compared to other vegetation types. Single-tier silvacenoses occupy one third of the area, which indicates the potential for environmental improvement, as they have a positive impact on the microclimate and prevent soil erosion. Fruit trees cover 25% of the area and also contribute to the overall ecological condition.

In general, site 4 demonstrates a lower phytomelioration potential compared to other areas of the studied landfill. However, even at this level, this part of the territory has the potential for further improvement if the appropriate vegetation cover is developed. Implementation of measures to reduce the number of ruderal communities and increase the proportion of salt marsh communities can help improve the phytomeliorative characteristics of this site.

Site 5 is located in the central part of the landfill, where most of the household waste is concentrated. Three main types of plant communities were identified at this site: single-tier silvaceous (sv_1), frutocenoses (f) and ruderales (r). The distribution of the area between these vegetation types is as follows: single-tier silvicolous (sv_1) – 2% of the area; frutocenoses (f) – 1% of the area; ruderal (r) – 40% of the area.

The coefficient of phytomelioration efficiency (K_{FM}) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_f \cdot b + S_r \cdot b}{S} \tag{6}$$

The mean scores (*b*) for each type of vegetation on site 5 are as follows: single-tier silvicolous (sv_1) – 4 points; ruderal (r) – 2 points; fruticolous (f) – 3 points.

The coefficient of phytomeliorative efficiency of site No. 5 is 2.12. This indicator demonstrates one of the lowest levels of phytomeliorative efficiency among the studied landfill sites. Site 5 is characterized by the dominance of ruderal communities, which occupy a significant part of the area (40%). Ruderal communities, as weed communities, have a limited role in improving the ecological condition of the territory. Only 2% of the area is occupied by single-tier silvacenoses, which indicates an insignificant share of forest communities in this area. Fruit communities occupy only 1% of the area, which further limits the potential for improving the phytomeliorative condition.

With significant waste accumulation, this site demonstrates a low level of environmental improvement. The low phytomeliorative efficiency coefficient indicates the need for specialized measures to improve the environmental quality of the territory. In particular, it is important to focus efforts on increasing the area occupied by silvicolous and fruticolous vegetation to improve the overall phytomeliorative efficiency of the site. Implementation of these measures can help reduce the negative impact of waste on the environment and improve the overall environmental condition of the landfill. Site 6 is located at a distance of 100 meters from the landfill boundaries in the northwest, which serves as a control object for assessing phytomeliorative efficiency in comparison with areas directly contaminated by waste. The following functional categories of vegetation were identified at this site: single-tier silvicenoses (sv1), ruderalenoses (r), frutocenoses (f), and pratocenoses (p). The distribution of the area between these vegetation types is as follows: single-tier silvaceous (sv_1) – 15% of the area; frutocenoses (f) – 10% of the area; ruderales (r) – 20% of the area; pratocenoses (p) – 30% of the area. The coefficient of phytomelioration efficiency (K_{FM}) was calculated using the following formula:

$$K_{FM} = \frac{S_{sv1} \cdot b + S_f \cdot b + S_f \cdot b + S_r \cdot b}{S} \tag{7}$$

The mean scores (*b*) for each vegetation type in site 6 are as follows: single-tier silvaceous plants (sv_1) – 4 points; ruderal plants (r) – 2 points; frutocenoses (f) – 3 points; pratocenoses (p) – 3 points.

The coefficient of phytomeliorative efficiency of the control site 6 is 2.93. This indicator is one of the highest among all the studied sites.

The analysis of the results shows that the control site has relatively good conditions for vegetation compared to other parts of the landfill. A significant area occupied by pratocenoses (30%) and a moderate share of single-tier sylvan cenoses (15%) contribute to a positive ecological effect. In addition, frutocenoses and ruderalenoses, although occupying smaller areas, also contribute to the overall phytomeliorative state of the territory.

As shown in Figure 8, the phytomeliorative efficiency coefficients (KFM) vary significantly across the landfill. The eastern side exhibits the highest efficiency (KFM = 3.07), correlating with a higher density of silvicultural vegetation. Given the high assessment of phytomeliorative effectiveness, the control site demonstrates significant potential to serve as a baseline for comparison with other landfill sites. This allows us to assess the effectiveness of various phytomelioration measures at contaminated sites and make adjustments to remediation strategies. At the control site, a relatively stable and positive impact of vegetation on the ecological state of the territory is observed, which confirms the importance of further research and improvement of phytoremediation practices to improve the environmental quality of other landfill sites.

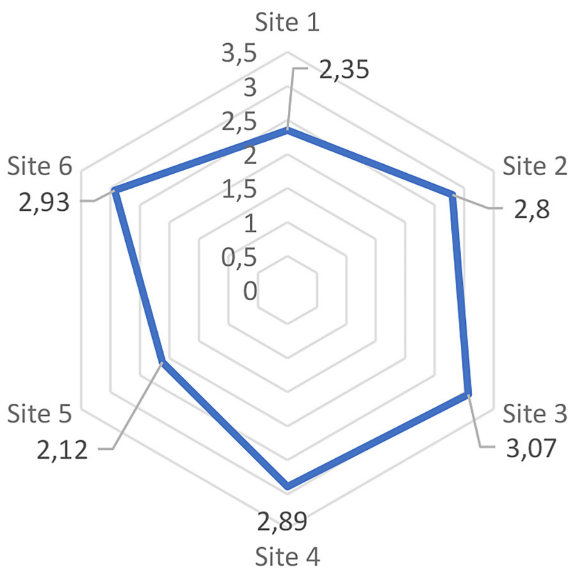

Figure 8. Graphical visualization of K_{FM} in the investigated sites

CONCLUSIONS

An assessment of the phytomelioration potential at the Bronytsia landfill indicated that vegetation plays a crucial role in enhancing the environmental conditions. The analysis of heavy metals in tree roots revealed significant exceedances of the maximum permissible concentrations (MPC) for Pb, Cd, and Co, highlighting a high level of contamination at the site. The results demonstrated variability in contamination levels across different areas of the landfill, with the highest concentrations of heavy metals found at the eastern and central sections.

The assessment of phytomeliorative efficiency showed different results for the studied sites. The identified functional categories of plantations, such as silvacenoses, frutocenoses and ruderalenoses, have different effects on phytomelioration of the territory. For example, high coefficients of phytomeliorative efficiency were found on the southern and eastern sides of the landfill, which indicates a significant potential of plants to improve environmental conditions. The research paper presents a detailed study of the phytomeliorative effectiveness of vegetation cover in different parts of the Bronytsia landfill, located in the southwestern part of the Lviv region. The efficiency assessment is based on the analysis of phytomeliorative potential, which allows determining an extent of positive impact of vegetation on devastated areas. The results of the research indicate that some areas of the landfill already have significant phytomelioration potential, while others require further measures to improve the environmental condition. Site 4, with the highest phytomeliorative efficiency coefficient, is the most promising for further reclamation work.

Thus, the use of vegetation for ecosystem restoration at the Bronytsia landfill is a promising way to improve the environmental situation. Recommendations for the further use of phytomelioration measures may include the introduction of specific plant communities that are most suitable for the conditions of this landfill, as well as continuous monitoring of the effectiveness of their impact on ecosystem restoration. The phytomeliorative effectiveness of the species composition of vegetation on devastated landscapes, including landfills, is an extremely important component of improving the environment on a local and regional scale. The results of the research indicate that some areas of the landfill already have significant phytomelioration potential, while others require further measures to improve the environmental condition. Site 4, with the highest phytomeliorative efficiency coefficient, is the most promising for further reclamation work.

Thus, the use of vegetation for ecosystem restoration at the Bronytsia landfill is a promising way to improve the environmental situation. Recommendations for the further use of phytomelioration measures may include the introduction of specific plant communities that are most suitable for the conditions of this landfill, as well as continuous monitoring of the effectiveness of their impact on ecosystem restoration. The phytomeliorative effectiveness of the species composition of vegetation on devastated landscapes, including landfills, is an extremely important component of improving the environment on a local and regional scale.

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