Received: 20.12.2025 Revised: 18.04.2026 Accepted: 21.05.2026 Published: 27.05.2026

BIOLOGICAL SYSTEMS: Theory and Innovation

ISSN 2706-8382
e-ISSN 2706-8390

Journal homepage: https://bioscience.com.ua/en
Vol. 17, No. 2, 2026, 10-30

UDC 628.472:504.5

DOI: 10.31548/biologiya/2.2026.10

Unauthorised landfills as a source of heavy metals: The influence of waste morphological composition

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Abstract. Against the background of an increasing number of local uncontrolled landfills in Ukraine, the issue of their impact on the state of soils has become especially urgent, due to the high mobility of toxic elements and their long-term preservation in the environment. This study aimed to investigate the connection between the morphological composition of waste on unauthorised landfills and the degree of heavy metal content in soils of technogenically transformed territories. The standardised technique of sampling of municipal solid waste and soils was used, in accordance with national standards of Ukraine and international standards. Determination of the morphological composition of municipal solid waste was carried out by fractional sorting into the following morphological fractions: plastics, paper and cardboard, glass, metal, organic, textiles, building materials, and other mixed fractions. Soil sampling was carried out at a depth of 0-20 cm, where the maximum accumulation of anthropogenic metals takes place. Determination of the concentration of Cd2+, Cu2+, and Zn2+ was carried out by atomic absorption spectrometry, which provided a high accuracy of quantitative analysis. Statistical processing of the results consisted of correlation analysis, determination of the coefficients of determination and creation of regression models to establish the relationship between the share of separate morphological fractions and the degree of soil pollution. Additionally, the environmental risk was estimated by calculating the accumulation index, the contamination factor and the modified potential ecological risk index. The obtained results testified to the statistically significant relationship between the increased concentrations of heavy metals in the soil cover and the presence in the waste stream of such morphological fractions, as metal scrap, fine-dispersed plastics, electronic and electrical waste, building materials with paints, varnishes and other mixtures based on polymers. The highest mobility to soils was shown by Pb2+ and Cd2+, which correlated with the morphological fractions that included used batteries, small metal items and electrical and electronic

Suggested Citation:
Leliushok, S., & Naumovska, O. (2026). Unauthorised landfills as a source of heavy metals: The influence of waste morphological composition. *Biological Systems: Theory and Innovation*, 17(2), 10-30. doi: 10.31548/biologiya/2.2026.10.

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waste. The organic morphological fraction is not a direct source of heavy metals; however, it contributes to their mobilisation during the mineralisation process and formation of organic acids

Keywords: concentration factor; pollution index; mobile forms of elements; adsorption; leachates

INTRODUCTION

Illegal dumping is one of the most serious environmental problems in today's urbanised society. The environmental risk posed by illegal dumping sites is not only due to the stock of waste but also to the absence of artificial impermeable layers, leachate collection systems and monitoring systems, which allows the interaction of the waste with the soil profile and the hydrological network. In urban and periurban environments, the dumping sites are frequently located in micro depressions, gullies, roadsides and along the boundaries of agrocenoses, that is, areas that receive surface run-off and occasional inundation, which facilitates the flow of pollutants to the soil and water bodies. This implies that the environmental risk does not stop at the spatial limits of the dump, but extends to other areas with different land uses. In the physical disintegration of waste and biodegradation of the organic fraction, and after rainfall, the leachates are generated. Leachates can be enriched with heavy metal soluble and colloidal fractions and may flow through the soil and into the groundwater. This mechanism transfers contaminants from the waste to the environment, expanding the spatial scale of the risk and the complexity of remediation actions.

W. Ahmad *et al*. (2021) pointed out that soil pollution in the surrounding areas of dumping sites usually shows higher concentrations compared to the background values and poses higher environmental and health risks. Recent environmental studies have evidenced that the movement of leachate is one of the key sources of metal pollution in the soil and water of dumping sites. Thus, J.K. Drall *et al*. (2025) in an integrated study on an uncontrolled dumping site (soil and groundwater study and application of pollution indexes) concluded that the mobility of leachate components causes metal pollution in the environmental components and suggests the need for control of infiltration, monitoring and minimising the dispersal of leachates. Notably, the influence of leachate is not limited to abiotic compartments. J. Chen *et al*. (2025) studied the environmental impacts of illegal dumping (slag and sewage sludge) and found that heavy metal pollution was associated with significant changes in the structure of the bacterial soil community, such as a decrease in bacterial diversity and changes in the relative abundance of the bacterial groups. The authors indicated that the illegal dumping acts as a disturbance factor of the soil microbiome and consequently could affect the soil processes of matter transformation.

The morphological composition of municipal solid waste (MSW), the percentage distribution of organic matter, polymeric materials, metals, glass, textiles, and construction debris, determines not only the physical properties of a landfill (such as porosity and permeability) but also the chemical processes occurring within it. For example, the predominance of the polymer fraction promotes the prolonged persistence of organic and inert components, while also potentially enhancing the accumulation of metallic impurities through adsorption and the mechanical release of fillers and additives from plastics. Conversely, a substantial proportion of batteries, cables, printed circuit boards, and metal fragments directly increases the risk of Pb^{2+} and Pb^{2+} ions entering soils and leachate. I. Hölzle *et al*. (2022) concluded that environmental control is a critical factor in the risk assessment and planning of landfill management measures. Q. Wang *et al*. (2021) found that the morphological composition of waste is closely related to the species and contents of elements that are likely to be dissolved or extracted. A. Podlasek *et al*. (2023), discussing the pollution potential of MSW landfill leachate (case studies and worldwide overview), stated that leachate properties are influenced by the percolation of atmospheric precipitation through the waste mass and the set of physicochemical and biological processes occurring in the landfill body. With regard to morphological composition, they pointed out the large variability of leachate and the need to take into account the context of waste formation and transformation conditions when evaluating environmental risk. Another issue is the chemical bioavailability and mobility of metals in the soil, which depend on multiple factors, such as pH, content of organic matter, sorption and desorption processes, redox conditions, and the presence of complexing agents. The morphological structure of waste indirectly affects these factors. For example, the organic component accelerates the formation of low-molecular-weight organic acids during decomposition, which increases the solubility and mobility of some metals. The polymeric component can serve as a matrix for the adsorption or dispersion of particles with metallic impurities. Therefore, the correct interpretation of the content of metals in soils requires simultaneous analysis of both the morphological structure of waste and soil properties, as indicated by K. Godyń *et al*. (2023).

This article aimed to investigate the effect of the morphological composition of unauthorised landfills on the accumulation of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}) in the upper soil horizon of technogenically impacted areas, to reveal statistically significant correlations, and to develop practical recommendations for monitoring and remediation. The scientific novelty of the research is the mandatory consideration of the actual morphological structure of waste as an independent factor in the interpretation of soil properties, while in previous studies, this issue was considered separately or only partially. The proposed approach is of practical importance for regional waste management programmes and ecologically optimal planning of remediation activities.

MATERIALS AND METHODS

The research was carried out on two landfill sites in different physiographic zones of Ukraine, which made it possible to comprehensively study the regional features of anthropogenic pressure on the soil environment. Site 1 was placed in Nizhyn district, Bakhmach territorial community, Chernihiv region (51°09'45"N, 32°42'14"E) at a distance of 17 km from the town of Bakhmach. The area of technogenically disturbed land is 2.25 ha. Soil samples were collected twice: in spring 2025 (the third ten-day period of April) and again in summer 2025 (the third ten-day period of August), which permitted evaluation of the seasonal changes in soil ecological state. Site 2 was placed in Uman district, KniazhoKrynytsia territorial community, Cherkasy region (49°06'22"N, 29°44"18"E), 4 km from the village of Kniazha Krynytsia. The landfill area was 0.2 ha. The soil samples collection was done in the same order and terms as at Site 1: in spring 2025 (the third ten-day period of April) and repeated in summer 2025 (the third ten-day period of August), which allowed comparison of spatial and temporal transformations of soil properties. Both sites are characterised by chernozem soils. According to regional features, in Nizhyn district, chernozems prevail (together with marsh soils in the floodplains), whereas in Cherkasy region, typical chernozems prevail (together with podzolised and dark grey podzolised soils), with typical and degraded chernozems being a significant part of the regional soil cover. Climatic characteristics of the regions are presented according to the data of Climate-Data.org (n.d.).

Site 1:

- climate type: humid continental with warm summers (Dfb according to the Köppen-Geiger classification);
- mean annual air temperature: approximately 8.3°C;
- mean annual precipitation: approximately 671 mm/year; for Nizhyn district, a range of 550-660 mm/year is reported, with a maximum during the warm season.

Site 2:

- climate type: humid continental with warm summers (Dfb);
- mean annual air temperature: 9.6°C;
- mean annual precipitation: approximately 618 mm/year.

Land use of the area surrounding Site 1 is characterised by a mixed economy structure with agriculture being a leading component and forest and shelterbelt components. The district is also characterised as a district where the leading sectors are agricultural production and forestry (Baranovska *et al*., 2000). Therefore, the surrounding areas are classified as agricultural landscapes (arable land/fields) with elements of forest vegetation and floodplain areas. Cherkasy region is characterised by a very high degree of land cultivation. According to the data of R. Podzerei (2024), in some regions of Ukraine, among them the Cherkasy region, the ploughed lands' share may be about 90%. Thus, for areas surrounding Site 2, intensive agricultural (arable land) use is the prevailing land use type, which enhances the relevance of production soils risk evaluation. Rationale for the selection of these sites and regions:

1. Representativeness of two different natural and climatic situations within the forest-steppe/transitional zone of Ukraine: Chernihiv region is characterised by a lower mean annual temperature and (according to reference data) higher or comparable precipitation in comparison with Uman district. This results in different soil moisture regimes and different conditions for contaminants migration.

2. A common soil basis, chernozem soils, was preserved at both sites, but a higher bulk density is observed at Site 2, which allows comparing the possible effects of compaction and permeability on contaminants migration without changing the soil type.

3. Types of anthropogenic land use: Site 1 is agricultural, with a significant proportion of forest and floodplain areas in the district; Site 2 has a very high proportion of cultivated land and intensive agricultural land use.

4. The similar sampling scheme (same seasons and sampling dates: third ten-day periods of April and August 2025) guarantees the comparability of the sites in terms of seasonal changes in the region (climate, land use), without any methodological differences.

Waste samples were collected from each landfill. The optimal mass of a single sample was 7 kg of dry or mixed waste. The selected sample sizes provide a representative sample of the total mass of waste, taking into account the diversity of fractions. The samples were selected manually, that is, the fractions were separated based on visual and tactile assessment, type of material, structure, density, type of packaging and other characteristics. Three 7 kg composite samples were collected at each Site 1 and Site 2. To reduce methodological error and the effect of point waste accumulation, the sampling was carried out at several points, spread over the area of the landfill body. Randomisation was provided as follows:

1. Before sampling, the visible surface of the landfill was divided into three conditional sectors;

2. One sample was taken from each sector;

3. Samples were not taken from obviously anomalous places (for example, recent local dumping of a single fraction, separate accumulations of construction waste, large objects).

To maintain representativeness at the stage of sample preparation for sorting and laboratory analysis, the quartering method was used:

1. The 7 kg composite sample was placed on a clean sheet or tray and mixed as much as possible for the most uniform distribution of fractions;

2. A conical pile of waste was formed, levelled to a uniform thickness and divided into four equal sectors;

3. Two opposite quarters were removed, and the remaining two were combined.

The sample was sorted into standard fractions by hand; each fraction was weighed, and its proportion (%) of the total sample mass was determined. No waste transportation was carried out, since the morphological composition was determined directly in the field on the day of sampling. In this research, the characterisation of solid waste flows in the study areas was carried out by analysing the morphological composition of the samples taken, identifying the main components that make up the material composition of the waste. The fractions were determined as follows: paper and cardboard, iron, rubber waste, organic, plastic waste, textiles, glass, wood, and polyethene. This morphological classification system allows the analysis of both the material parts of interest (paper, plastics, glass, metals) and the parts that influence the intensity of biological processes and the risk to the environment (organic matter, rubber, textiles, wood). The obtained data on the composition of the wastes were used as the basis for the study of the seasonal dynamics and interpretation of the patterns of formation of technogenic pressure, in particular, for the accumulation of heavy metals in the surrounding soils. The following waste components were distinguished: polymeric materials (plastics), rubber, organic fraction, paper and cardboard, wood, as well as inert fractions, including glass. The classification is in accordance with ASTM D5231-92 (2016). After manual sorting, each fraction was weighed separately, and the mass percentage of each fraction to the mass of the total sample was calculated:

$$\%\,\text{fraction} = \frac{m_{\text{fraction}}}{m_{\text{total sample}}} \times 100\%, \qquad (1)$$

where m_{fraction} is the mass of the fraction after sorting, is the mass of the total sample.

Before weighing, the samples were dried (or their humidity was standardised) in order to prevent the distortion of the results due to humidity differences, especially in the organic fraction. The soils were sampled in technogenically transformed areas adjacent to the unauthorised landfills at a depth of 5-20 cm, corresponding to the root zone and the layer most intensively affected by pollutants. The spatial scheme of sampling was determined by the morphology of the landfill, relief, and the presumed direction of contaminant spread. Three directionally oriented profiles were chosen for each site to ensure representativeness and trace the gradient of pollution. At Site 1, samples were collected in the north, north-east, and south-east directions. Three point-like samples were taken in each direction at a distance of 5 m from the body of the landfill, and then merged into a combined sample. The same scheme was applied at Site 2, where the sampling was performed in the west, north, and south directions; three pointlike samples were taken in each direction at a distance of 5 m. A control (background) point was chosen at a distance of about 200 m from the landfill boundary in an area not affected by direct technogenic impact. The control site is represented by the absence of economic activity signs, which makes it possible to use these samples for comparative analysis. The statistical processing of the data was performed in Microsoft Excel 2019 using the built-in functions and tools of descriptive statistics. Descriptive statistics for each variable, including mean, minimum, maximum and standard deviation, were calculated. Spearman's rank correlation was used to determine the correlation between heavy metal concentration and morphological composition of the waste. Differences and correlation coefficients were considered statistically significant at $p < 0.05$.

RESULTS AND DISCUSSION

Site 1 is a technogenically transformed territory with a long history of intensive anthropogenic impact. The site was formed due to an uncontrolled deposition of MSW of diverse morphological composition. The morphological structure of the landfill surface is represented by anthropogenic relief of mounds and local depressions filled with leachate. The natural water regime is broken, and the infiltration of atmospheric precipitation is disturbed, causing the formation of anaerobic conditions in the soil profile. Main waste fractions are represented by polymers, polyethene, organic residues, glass, paper, wood, rubber and metal, which indicates the complex nature of the pollution. Soil cover within the landfill and in the adjacent area is subject to complex degradation caused by the migration of leachate and the accumulation of heavy metals (Cd^{2+}, Pb^{2+}, Zn^{2+}, Cu^{2+}, Ni^{2+}), organic acids, ammonium nitrogen, phenolic compounds and polymeric substances. According to U. Wydro *et al*. (2022), the leachate of landfills significantly changes the physical, chemical, biological and biochemical properties of soils, which manifests itself in the transformation of the microbial structure and changes in the enzymatic activity of soils. Similar processes were studied by M. Malovanyy *et al*. (2023) and H. Kachmar *et al.* (2023), who highlighted the importance of leachate as a factor for the spread of pollutants and soil degradation of adjacent shelterbelts.

The vegetation cover on the landfill is characterised by fragmentation and mosaic distribution. Within the landfill body, vegetation is virtually absent, whereas on its periphery, zones of secondary vegetation develop. These are mainly represented by grass species of the *Poaceae* family, as well as ruderal and invasive species from the *Asteraceae*, *Amaranthaceae*, and *Chenopodiaceae* families. Dominant species are represented by scentless mayweed (*Tripleurospermum inodorum*), common ragweed (*Ambrosia artemisiifolia*), dock (*Rumex* spp.), stinging nettle (*Urtica dioica*), creeping thistle (*Cirsium arvense*), couch grass (*Elytrigia repens*), and common reed (*Phragmites australis*). The listed species indicate the initial stages of secondary succession and the high ecological plasticity of the flora under conditions of toxic and physical stress. Grasses and some ruderal species have a dual ecological function; on the one hand, they ensure partial stabilisation of the soil surface, reducing the risk of erosion, and on the other, they are actively involved in the bioaccumulation of heavy metals in the root system and aboveground mass. This is in line with the research of L. Štofejová *et al*. (2021) and M.T. Samadi *et al.* (2024), who showed the high potential of couch grass and common reed for metal phytostabilisation. Data of A. Cakaj *et al.* (2023) about the role of representatives of the families *Poaceae* and *Asteraceae* as bioindicators of degraded soils are also confirmed. A particular environmental threat is posed by the presence, in the immediate vicinity of the landfill, of agrocenoses, in particular soybean (*Glycine max*) and wheat (*Triticum* L.) crops. As shown in the studies of X. Liu *et al.* (2024) and S. Razanov *et al.* (2022), these crops are capable of accumulating heavy metals in their biomass, thereby creating a risk of their entry into the food chain. The dichotomy between natural ruderal vegetation of the landfill and agrogenic soils calls for a comprehensive approach to environmental status assessment. Therefore, Site 1 is a point of multi-factor anthropogenic pollution affecting soil, biota, surface and ground water, and atmospheric air simultaneously. The anthropogenic relief formation, soil cover degradation, microbiological activity inhibition and a peculiar ruderal flora development give evidence for drastic changes in natural processes. The data obtained prove the relevance of this site as a reference zone of maximal anthropogenic impact for further soil-ecological and microbiological investigations.

Site 2 is a technogenically transformed territory demonstrating persistent manifestations of intensive anthropogenic impact, which developed as a consequence of long-term uncontrolled storage of household, construction, polymeric, organic, as well as hazardous and medical waste. The morphological heterogeneity of waste and the absence of any engineering infrastructure have led to the formation of a multi-component focus of chronic environmental risk. The landfill surface has a disturbed structure and anthropogenic microrelief with mounds, compacted areas, charred soil and ash layers. Periodic waste burning is one of the major factors that induce changes in the soil cover. The thermal impact causes the destruction of the structural-aggregate state of the soil, humus horizon degradation and organic matter destruction. According to G. Pathak *et al*. (2024), combustion of mixed municipal and polymeric waste results in ash, aerosol and leachate formation with an increased content of heavy metals, polycyclic aromatic hydrocarbons, dioxins and furans, which predominantly accumulate in the surface soil horizon. The soil environment of the landfill is characterised by high variability of chemical composition caused by mechanical contamination, pyrogenic loading and infiltration of waste decomposition products.

The accumulation of heavy metal cations (Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}) and organic toxicants has been registered, which may cause secondary pollution of the soil-water system. As was underlined by J. Szulc *et al*. (2024), uncontrolled landfills are persistent sources of metals, dust and potentially toxic compounds capable of long-term soil retention. The microbiological status of the landfill soil is characterised by signs of imbalance: inhibition of mesophilic and cellulolytic microflora, decrease in enzymatic activity and increase in the share of micromycetes and bacteria tolerant to toxic and thermal stress. The changes in the balance of the main trophic groups of microorganisms indicate loss of the soil system's capacity for self-regulation, which agrees with the data by M. Zhan *et al.* (2025) on α-diversity decrease of microbiota under conditions of metal and organic stress. The vegetation cover of the landfill is undergoing a profound transformation. In areas of direct waste accumulation, an almost complete degradation of the soil-vegetation complex is observed. The peripheral part is presented with fragmented ruderal and synanthropic coenoses dominated by species of the *Asteraceae* and *Amaranthaceae* families and invasive species. The prevalence of common ragweed (*Ambrosia artemisiifolia*), stinging nettle (*Urtica dioica*), burdock (*Arctium* spp.), and mallow (*Malva* spp.) indicates the involvement of degraded and technogenically affected ecotopes. Woody and shrub vegetation has signs of chronic stress (partial necrosis of crowns, decrease of assimilating surface, necrotic damage of leaves). Ecological danger is presented by the presence of animal biological and medical waste, which, in the course of decomposition, contributes to the formation of toxic gaseous products (ammonia, hydrogen sulphide, phenolic compounds) and the development of pathogenic microflora. The combination of organic, polymeric and hazardous waste creates a long-term toxicological and ecological tension, which complicates the natural process of rehabilitation. Thus, Site 2 functions as a pyrogenic-technogenic pollution focus, where mechanical soil degradation, chemical pollution, thermal influence and microbiological destabilisation are combined. Their interactions lead to a deep transformation of the soil-plant system, a decrease in the ecological stability of the territory and the appearance of potential threats to the adjacent agroecosystems and natural ecosystems.

The analysis of morphological (fractional) composition of MSW is the basis for understanding both the potential environmental impact and the prospects for further disposal, recycling or neutralisation. The morphological composition characterises which of the fractions is dominated (organic, polymeric, papercardboard, glass, metal, textile, construction, hazardous and others) and what is the mass proportion of each of them in the total mass of waste. This is important when studying the pollution of soils, since different fractions have different release rates of potentially toxic compounds (heavy metals, organic compounds), different decomposition abilities, filtration and formation of leachate. For the representativeness and standardisation of the results, it is necessary to plan the sampling, sorting, fraction separation and calculation of mass. Particular attention should be paid to the mass of the sample, the number of repetitions, representativeness, weighing and documentation. The morphological composition of the waste is the initial characteristic, which determines the potential for the formation of leachate and the conditions for the migration of pollutants. Thus, polymeric and rubber components can serve for a long time inside the landfill body as a medium for the accumulation of impurities, and the organic component contributes to the activation of microbiological processes and the change in physicochemical parameters (pH conditions, solubility of compounds). Glass, along with paper and cardboard and wood, demonstrates the potential of waste as a resource and the different rates of processing of the various components over time. Overall, this allows for a more justified association between the composition of waste and the spatio-temporal features of soil pollution and clarifies the causes of high concentrations of heavy metals in territories affected by these facilities.

In the framework of the study, the morphological composition of waste in Site 1 was investigated for the spring season of 2025 in order to establish the structure of the main components and their proportion in the total waste flow. This made it possible to determine which components predominate in the waste and what proportion of the materials can be recycled as secondary raw materials or need separate processing. The data obtained are necessary for the environmental evaluation of the level of anthropogenic load, for the prediction of possible environmental risks, and for the justification of priority measures of waste management. The results of the morphological analysis serve as a basis for comparison of seasonal dynamics and for the development of recommendations for the optimisation of sorting complexes and reduction of the volume of burial. Figure 1 shows the morphological composition of the waste at Site 1.

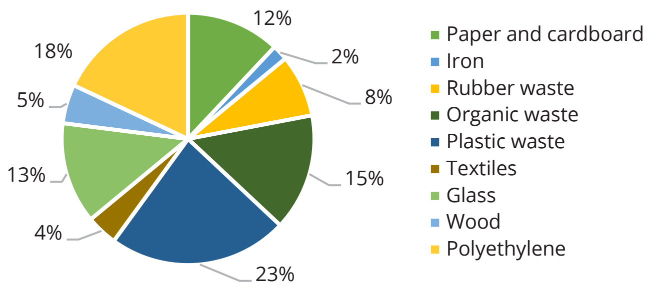

Figure 1. Average morphological composition of collected waste samples at Site 1, %, spring 2025
Source: developed by the authors

The composition of waste presented in Figure 1 is characterised by the dominance of polymeric and packaging fractions. The greatest part is represented by plastic waste (23%), which determines the general structural pattern of the waste. A significant part is also played by polyethene (18%), while the proportion of organic waste is 15%. A significant role is played by glass (13%) and paper and cardboard (12%), which, together with the aforementioned fractions, make up a significant part of the total waste. The sum of the polymeric components (plastic waste 23% + polyethylene 18%)

is 41% and accounts for almost half of the entire morphological composition. This indicates a prevalence of materials typical of packaging and having a long persistence in the environment. The significant proportion of paper and cardboard (12%), along with the polymeric fractions, also indicates the significant role of packaging materials in the structure of the waste. At the same time, the presence of an organic fraction (15%) indicates a significant contribution of biogenic components to the structure of the waste in this period. The least significant are the fractions that make up the secondary component of the morphological composition. These include rubber waste (8%), wood (5%), textiles (4%), and iron (2%). Overall, these components account for 19% of the structure and, therefore, contribute less than the first component. However, these are necessary to evaluate the diversity of the material composition and the potential complexity of the waste management. The lowest percentage of iron (2%) denotes the lowest presence of the metallic fraction in the waste in the spring of 2025 at this site. In the summer of 2025, the morphological composition of the waste in Site 1 was also determined, allowing the characterisation of the real distribution of fractions in the collected samples for this period. Figure 2 shows the morphological composition of the waste at Site 1.

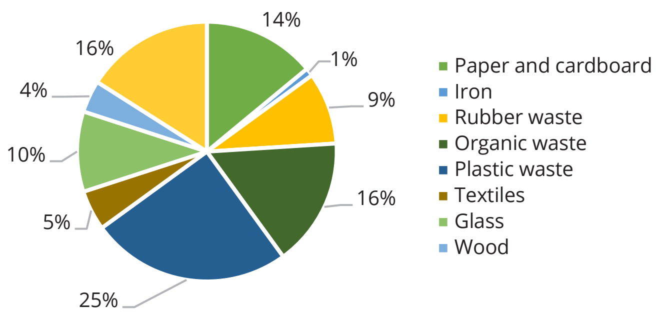

Figure 2. Average morphological composition of collected waste samples at Site 1, %, summer 2025
Source: developed by the authors

The morphological composition of the collected samples of waste in Site 1 (summer 2025) is marked by the prevalence of the polymeric fraction. The highest percentages are of plastic waste (25%) and polyethene (16%), which together represent 41% of the total composition. A large percentage is also occupied by the organic waste (16%), which constitutes a distinct and significant biodegradable fraction. The paper and cardboard (14%) also have a high expression and are part of the main structural fractions. Among the other components, fractions of inert and anthropogenic materials are found. The glass represents 10%, which indicates a stable presence of the mineral (inert) fraction in the samples. The rubber waste represents 9% and constitutes a moderate percentage of materials with slow decomposition, and that require specific management approaches. Lower percentages are registered for the textiles (5%) and wood (4%), which together represent 9% of the morphological composition. The lowest fraction in the summer structure is iron (1%), which indicates the lowest expression of the metallic fraction. In general, the percentages of paper and cardboard (14%), glass (10%), iron (1%), plastic waste (25%), and polyethene (16%) together add 66% and characterise the waste with an expressive presence of components with the potential to be recovered as secondary raw materials. The organic fraction (16%) is highlighted as a significant fraction that requires specific management within the waste management systems. The remaining components, rubber (9%), textiles (5%) and wood (4%) complete the general profile and denote the heterogeneity of the morphological composition in the summer season. In the spring of 2025, the morphological composition of the waste in Site 1 was marked by a high percentage of polymers, since plastic waste and polyethene represented 23% and 18%, respectively (totalising 41%). In the summer of 2025, the total percentage of the polymeric fraction remained the same (41%); however, an internal redistribution was registered, with the percentage of the plastic fraction increasing to 25% (+2%) and the polyethene fraction decreasing to 16% (-2%). The percentage of the organic fraction increased slightly from 15% to 16% (+1%), and paper and cardboard from 12% to 14% (+2%). On the contrary, glass showed a drop from 13% to 10% (-3%), being the most significant decrease among inert fractions. Concerning the secondary fractions, a small variation was observed during the summer: rubber waste increased from 8% to 9% (+1%), textiles from 4% to 5% (+1%), while wood decreased from 5% to 4% (-1%). The metallic fraction was reduced in both periods and decreased again, from 2% to 1% (-1%). The share of principal materials with potential for recovery (paper and cardboard, glass, iron, plastic, and polyethene) was reduced from 68% in spring to 66% in summer, showing a slight decrease due to the drop in glass and metallic fractions. However, the general trend is the same: a constant dominance of polymers in the waste composition at Site 1 in both seasons.

In the context of preparing this article, a study of the morphological composition of waste at Site 2 was carried out for the spring season of 2025, allowing for the quantification of the structure of the main fractions that make up the waste flow. The determination of the proportions of the polymeric, organic, rubber, and inert fractions is necessary to understand the real composition of the waste and the environmental impact that its stockpiling can generate. The data collected served as a basis for evaluating materials with recovery potential through sorting, as well as identifying fractions that require specific management strategies. The results of the spring analysis of Site 2 were also used as raw material for subsequent seasonal comparisons and for supporting actions focused on mitigating the environmental impact of waste. A.E. Peter *et al.* (2019) analysed the composition of both fresh and aged waste in an open-air dump: the fresh MSW contained ~36% of biowaste (food, garden, and organic waste), and around 30% of recyclable materials (plastics, paper, cardboard, and metals). The aged waste showed a prevalence of plastics (25-33%) with high energy value, while the organic matter was practically decomposed. This is related to the state of the dump after several years of operation, where the plastics and polyethene (43% together) are predominant, and the organic fraction reaches only 12%. In this case, the organic fraction is much lower, which, according to F.A. Osra *et al.* (2021), may be related to the age of the dump, the decomposition of organic matter, or the specific composition of the waste, which is mainly packaging, plastics, and inorganic material. Figure 3 shows the morphological composition of the waste at Site 2 (spring 2025).

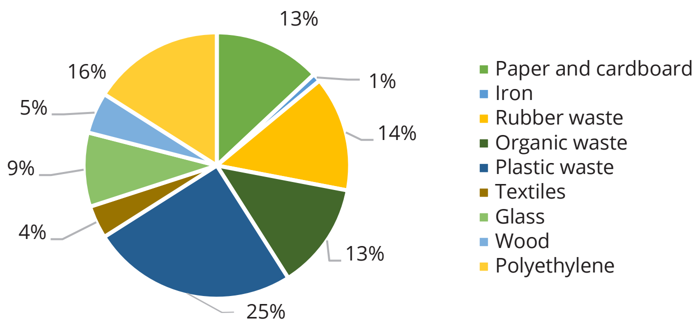

Figure 3. Average morphological composition of collected waste samples at Site 2, %, spring 2025
Source: developed by the authors

The morphological composition of the collected samples of waste, presented in Figure 3, is characterised by the predominance of the polymer fraction. The greatest proportion is represented by plastic waste (25%) and polyethene (16%), which together account for 41% of the morphological composition. A significant share is occupied by rubber waste (14%), which indicates the rather high content of elastomeric materials in the waste. The organic share is 13%, which corresponds to the share of biodegradable components. Among the fractions of materials traditionally considered recyclable, paper and cardboard occupy 13%, and glass 9%, which indicates a rather high content of packaging and inert components in the composition of the waste. The share of wood is 5%, and that of textiles is 4%, which together make up 9% of the morphological composition. The smallest share is occupied by iron (1%), which indicates the rather low content of the metal fraction. In general, the morphological composition of the waste at Site 2 in the spring of 2025 is shifted towards polymeric materials, which make the greatest contribution to its structure. Simultaneously, rubber and organic shares (14% and 13%, respectively) remain significant, which affects the environmental hazard and need for management. The paper and cardboard shares and the glass share (13% and 9%, respectively) indicate the presence of the fractions which can potentially be recovered. On the whole, the morphological composition is rather complex but with a clear dominance of the polymer group in the spring season. In the summer of 2025, a study of the morphological composition of the waste at Site 2 was also carried out with the aim of establishing the real structure of the fractions in the collected samples under the conditions corresponding to the seasonal maximum of waste formation. The data of the summer period at Site 2 are the basis for the seasonal analysis of the morphological structure dynamics and development of practical recommendations for optimising the sorting of waste and reducing the anthropogenic impact on the environment (Fig. 4).

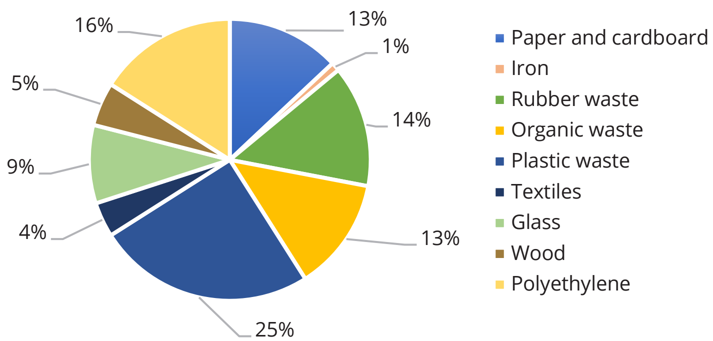

Figure 4. Average morphological composition of collected waste samples at Site 2, %, summer 2025
Source: developed by the authors

The morphological composition of the collected samples of waste at Site 2, presented in Figure 4, is characterised by the dominance of the polymer fraction. The greatest proportion is represented by plastic waste (25%) and polyethene (16%), which together account for 41% of the morphological composition. A significant component is occupied by rubber waste (14%), which indicates a rather high content of elastomeric materials in the waste in the summer season. The share of the organic component is 13%, which corresponds to the share of the biodegradable components. In the list of fractions that could potentially be recovered as secondary raw materials are paper and cardboard (13%) and glass (9%), which indicate the presence of packaging materials and an inert component, typical for mixed waste. The rest of the morphological composition consists of wood (5%) and textiles (4%), which together constitute 9%. The metallic fraction is represented in insignificant quantities (iron is 1%). Briefly, the morphological structure of Site 2 for summer indicates the prevalence of polymers and a significant proportion of rubber and organic components (14% and 13%, respectively). Such a structure is characterised by the high content of slowly degradable materials in nature (polymers and rubber) and a rather significant proportion of biodegradable waste. Paper and cardboard (13%) and glass (9%) form a significant part of the waste, which can be recovered in case of appropriate sorting. In general, the structure is heterogeneous, but with a clear lumping of the main mass in the polymer and related technogenic fractions.

Morphological composition of the studied areas reflects the real structure of the materials entering the landfill body and allows for the identification of the possible sources of pollutants formation in the surrounding environment. The prevalence of polymeric and packaging components, the presence of the organic fraction, as well as the proportion of rubber, textile, wood, and inert materials, determine the intensity of biochemical decomposition processes, formation of leachates, and migration behaviour of substances in the waste-soil system. The morphological structure has a significant impact on the rate of transformation of waste, on acid-base and redox conditions, and on the ability of the medium to accumulate or mobilise toxic substances. In this regard, the morphological structure is considered a key characteristic that determines the subsequent processes of soil contamination. O. Kravchenko *et al.* (2018) characterise the morphological composition of MSW at landfills and dumpsites in Ukraine (the cities of Khmelnytskyi and Kryvyi Rih). The authors demonstrated that the composition of mixed, unsorted waste largely determines the microbiocenosis within the landfill body, and that a high proportion of "bioavailable" organic matter leads to the dominance of bacteria of the genera *Bacillus*, *Micrococcus*, *Sarcina*, and others. However, in samples where polymers and plastics predominate, the activity of such biocenoses decreases. It explains the observed situation: the predominance of plastic and polyethene indicates that the biological activity of the landfill may be low or changed. O.M. Trofymchuk *et al.* (2020) showed that long-term landfills of MSW lead to an accumulation of heavy metals in the soil, with the concentration of copper, lead, nickel, and tin in some cases exceeding the background values by 2-10 times. However, if such a landfill predominantly consists of polymeric, rubber, textile, plastic, and inert wastes, they can serve as potential future sources of pollution, e.g. as a result of the formation of leachates, biogeochemical transformations, and heavy metal migration. According to the presented data (metals 2%, rubber 7%, textiles 5%), there are fractions in the landfill that may contribute to the contamination of soil and groundwater.

The second stage of the research was to assess the accumulation of heavy metals, which are among the most dangerous and durable pollutants that can persist in soils for a long time and penetrate into trophic chains. The various components of waste may serve as direct metal-carriers (especially some components of anthropogenic origin), as well as indirect factors contributing to their enhanced migration due to changes in the physico-chemical parameters of the medium. Therefore, the determination of the content of heavy metals in soils in the areas affected by the studied objects allows quantifying the level of anthropogenic impact and comparing it with the morphological characteristics of the waste in different seasons. This comparison is necessary for understanding the pollution formation mechanisms and for subsequent environmental conclusions and recommendations. Table 1 shows the results of soil analysis at Site 1 in the spring-summer period of 2025. The table shows the parameters obtained from the collected samples for the corresponding season.

Table 1. Content of mobile forms of heavy metals in soils (mg/kg), Site 1, spring-summer 2025

Sample code	MPC, mg/kg	North			North-East			South-East		
		1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Spring 2025										
Cu, mg/kg	3.00	0.461	0.681	0.575	0.566	0.715	0.43	0.63	0.387	0.361
Zn, mg/kg	23.00	8.075	5.412	6.875	4.645	1.785	1.86	6.924	8.565	1.91
Cd, mg/kg	0.70	0.898	0.768	0.575	0.505	0.609	0.65	0.49	0.407	0.397
Pb, mg/kg	6.00	1.195	1.53	1.576	1.451	2.19	2.755	1.067	2.115	2.145
Summer 2025										
Cu, mg/kg	3.00	0.354	0.67	0.77	0.611	0.632	0.548	0.63	0.49	0.453
Zn, mg/kg	23.00	8.67	9.625	3.955	5.985	8.405	9.47	2.12	2.125	1.59
Cd, mg/kg	0.70	0.282	0.338	0.433	0.347	0.437	0.492	0.45	0.518	0.35
Pb, mg/kg	6.00	1.91	1.278	2.03	1.89	1.375	0.644	0.95	1.775	1.844

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

In the spring of 2025, the maximum concentration of Cu^{2+} was observed in sample 2.2 (North-Eastern direction) and was equal to 0.715 mg/kg (for comparison, the remaining values of Cu^{2+} in the spring season were lower and ranged from 0.361 to 0.681 mg/kg). In the summer of 2025, the maximum concentration of Cu^{2+} was recorded in sample 1.3 (North direction) and was equal to 0.770 mg/kg (summer Cu values ranged from 0.354 to 0.770 mg/kg). When comparing the maxima of the seasons, it can be seen that the summer maximum (0.770 mg/kg) exceeded the spring maximum (0.715 mg/kg) by 0.055 mg/kg. At the same time, in the location of the spring maximum (2.2), the summer concentration decreased to 0.632 mg/kg (a change of -0.083 mg/kg). In the location of the summer maximum (1.3), there was an increase in the content of Cu^{2+} from 0.575 mg/kg in spring to 0.770 mg/kg in summer (a change of +0.195 mg/kg), which indicates a seasonal redistribution of this element within the object. The maximum concentration of Zn^{2+} in the spring of 2025 was found in sample 3.2 (South-East direction) and was equal to 8.565 mg/kg (the remaining spring values of Zn^{2+} were in the range from 1.785 to 8.075 mg/kg). In the summer of 2025, the maximum value of Zn^{2+} was observed in sample 1.2 (North direction) with 9.625 mg/kg (range of summer values: 1.590-9.625 mg/kg). A seasonal comparison of peak values shows that the summer maximum exceeded the spring maximum by 1.060 mg/kg; however, at the location of the spring maximum (3.2), Zn^{2+} decreased sharply in summer to 2.125 mg/kg (a change of -6.440 mg/kg). At the location of the summer maximum (1.2), by contrast, Zn^{2+} increased from 5.412 mg/kg in spring to 9.625 mg/kg in summer (a change of +4.213 mg/kg), indicating a summer concentration of peak values in the Northern direction alongside a peak in the southeast.

The maximum value of Cd^{2+} in the spring of 2025 was observed in sample 1.1 (Northern direction) with 0.898 mg/kg (range of other values of Cd^{2+} in the spring: 0.397-0.768 mg/kg). In the summer of 2025, the maximum value of Cd^{2+} was observed in sample 3.2 (South-Eastern direction) with 0.518 mg/kg (range of summer values: 0.282-0.518 mg/kg). A comparison of seasonal maxima indicates that the spring peak of Cd^{2+} was higher than the summer peak by 0.380 mg/kg. At the spring maximum location (1.1), the summer concentration decreased to 0.282 mg/kg (a change of -0.616 mg/kg). At the location of the summer maximum (3.2), Cd^{2+}, in contrast, increased from 0.407 mg/kg in spring to 0.518 mg/kg in summer (a change of +0.111 mg/kg), indicating a seasonal shift in the zone of elevated concentrations from the north towards the south-east. For Pb^{2+}, the maximum value observed in the spring of 2025 was in sample 2.3 (North-Eastern direction) with 2.755 mg/kg (range of other values of Pb^{2+} in the spring: 1.067-2.190 mg/kg). In the summer of 2025, the maximum value of Pb^{2+} was observed in sample 1.3 (Northern direction) with 2.030 mg/kg (range of summer values: 0.644-2.030 mg/kg). A seasonal comparison of maxima shows that the spring peak exceeded the summer peak by 0.725 mg/kg. At the location of the spring maximum (2.3), Pb^{2+} decreased in summer to 0.644 mg/kg (a change of −2.111 mg/kg). At the location of the summer maximum (1.3), Pb^{2+} increased from 1.576 mg/kg in spring to 2.030 mg/kg in summer (a change of +0.454 mg/kg), reflecting a redistribution of the most pronounced Pb^{2+} values across seasons and study sectors.

A significant conclusion is presented in the study by B. Bernardo *et al*. (2025), who examined soils around a landfill during two seasons of the year. They concluded that in the wet period, washing out predominates, which, on the one hand, decreases some indicators of element accumulation in the soils, and, on the other hand, increases the potential mobility of the contaminants, while in the dry period, there is a greater tendency to accumulation and retention. In relation to the object of this study, this means that interseasonal dynamics of moisture content and direction of surface and intra-soil runoffs can change not only the average background contents of Pb^{2+}, but also the redistribution between the sectors. This is also indicated by the pattern described above: the spring maximum is noted in sample 2.3, and the summer maximum in sample 1.3.

Concentrations of Cu^{2+}, Zn^{2+}, Cd^{2+} and Pb^{2+}, which were obtained for the spring-summer period of 2025, can affect the morphological features of the soil cover indirectly, through the changes in soil microbial activity, the intensity of humus formation and the condition of the plant root system. Even without significant exceedances, spatial "peaks" of these elements can cause local differences in the structure (aggregation state) of the soil, its bulk density and in the stability of the surface horizon against degradation. In the areas with relatively higher concentrations of metals, a decrease in the biological activity is more likely, which can be reflected in such morphological features as poorer aggregation, a lower proportion of water-stable aggregates and higher susceptibility to surface sealing. Such an effect, as a rule, has a mosaic nature, corresponding to different degrees of element accumulation in the sectors and points of sampling presented in Table 1. As for the content of MPC, the contents of Cu^{2+} (MPC 3.00 g/kg), Zn^{2+} (MPC 23.00 g/kg) and Pb^{2+} (MPC 6.00 g/kg) in all the points of sampling in the spring and summer periods are below the permissible limits. At the same time, for Cd^{2+} (MPC 0.70 g/kg), the value of 0.898 mg/kg was observed in sample 1.1 in the spring period, which exceeds the indicated standard; the rest of the summer values of Cd^{2+} (0.282-0.518 mg/kg) are below the MPC. Thus, most of the indicators do not exceed the permissible concentrations, although there is a local excess of Cd^{2+} in the spring. From the scientific point of view, such single exceedances are of special interest for the interpretation of possible morphological changes, since they testify to localised areas of potential environmental risk. In Figure 5 below, it can be seen that the excess of MPC is in samples 1.1 and 1.2 in the spring period. The values of Cd^{2+} registered in both samples are higher than the established MPC, which confirms the presence of excesses.

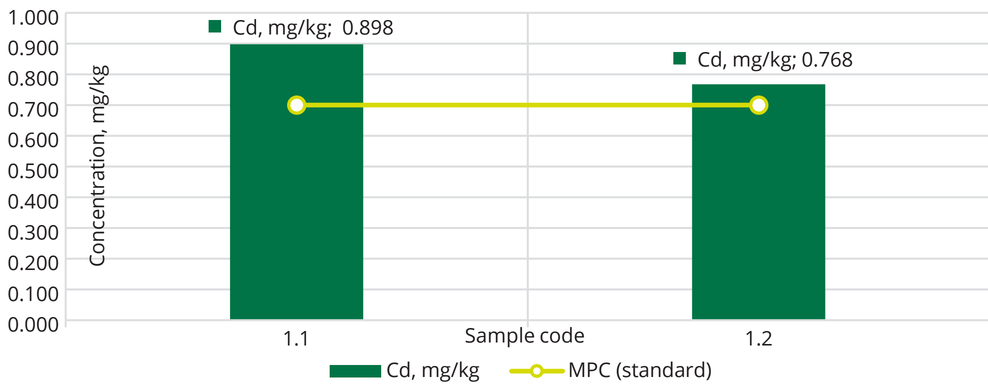

Figure 5. Exceedance of Cd, mg/kg, above the MPC at Site 1, spring 2025
Source: developed by the authors

The comparison of maxima in spring and summer shows that for Cu^{2+} and Zn^{2+}, the summer maxima are higher (0.770 mg/kg vs. 0.715 mg/kg for Cu^{2+} and 9.625 mg/kg vs. 8.565 mg/kg for Zn^{2+}, respectively), whereas the maxima of Pb^{2+} and Cd^{2+} in spring are higher than in summer (2.755 mg/kg vs. 2.030 mg/kg for Pb^{2+} and 0.898 mg/kg vs. 0.518 mg/kg for Cd^{2+}, respectively). This could be due to the seasonal condition of the soil, depending on the moisture content and biological activity. In the summer period, the transformation of organic matter and root activity is more intensive, which results in a change of fixation and mobility of elements within the upper soil horizon. Local summer maxima of Cu^{2+}/Zn^{2+} could be linked to the changes in the conditions of enzymatic activity in the soil, which in turn may affect the structure and aggregate stability of the topsoil. A higher contrast in spring for Pb^{2+} and especially for Cd^{2+} (with a local excess in sample 1.1) indicates the necessity of more detailed consideration of these points concerning morphological (compaction, structure, and aeration) manifestations, even when other metals are within the permissible limits. M. Tziouvalekas *et al.* (2024) found experimentally that the temperature of DTPA extraction influences the mobility and extractability of the elements; with an increase in temperature, the DTPA-extracted element concentration increases (especially for Cu^{2+} and Zn^{2+}, as well as for Pb^{2+}). The authors concluded that temperature may cause systematic biases between batches of determinations and should be taken into consideration when the "bioavailable/mobile" pool is interpreted. Within the framework of the present data, this means that the summer maxima of Cu^{2+} (0.770 mg/kg vs. 0.715 mg/kg in spring) and Zn^{2+} (9.625 mg/kg vs. 8.565 mg/kg) could be influenced not only by the input sources but also by an increase in the share of extractable (labile) forms in the topsoil under conditions of higher temperatures and more intensive transformation of organic matter.

M.S. El-Komy *et al.* (2025) in the study of DTPA-extractable metals found that season (wet and dry periods) and drying and wetting cycles have a significant impact on metal bioavailability and extractability, and stressed that for Cu^{2+}, Pb^{2+}, and Zn^{2+}, ion exchange is one of the key mechanisms controlling metal availability, along with spatial variation of soil characteristics. In the case of the present study, this means that the summer drying and rewetting regime, along with more intensive biological transformation of organic matter and root activity, could cause the shift of Cu^{2+}/Zn^{2+} into more labile extractable forms, which manifests itself as higher summer maxima. The results obtained show the multicomponent composition of the data. Firstly, they serve as a reference point for further monitoring, based on which a comparison of the indicators in subsequent seasons and years can be carried out. Secondly, the distribution of heavy metals over space, which allows tracing areas with high concentrations and assigning specific monitoring points (in particular, for Cd^{2+} in sample 1.1 in spring). Thirdly, the results characterise the environmental risk to soil organisms, vegetation, and the potential entry of pollutants into the trophic chain. Fourthly, the amount of data obtained makes it possible to assess the state of the object at the level of the facility itself and the surrounding territories, which can be used as a basis for developing management and nature protection measures. Thus, the distribution of metals has a mosaic character, maxima for each element are located at different points and sectors, which indicates heterogeneity of the conditions of accumulation. According to the MPCs indicated, the concentrations of Cu^{2+}, Zn^{2+}, and Pb^{2+} during the spring and summer period do not exceed the maximum permissible concentrations at any sampling point, while for Cd^{2++}, a local excess was registered in the spring in sample 1.1 (0.898 mg/kg vs. MPC 0.70 mg/kg). A seasonal shift of maximum values is observed: Cu^{2+} and Zn^{2+} have higher maxima in the summer, while Pb^{2+} and Cd^{2+} have higher maxima in the spring, which may be due to the seasonality of the conditions of migration and fixation of elements in the upper soil horizon. In connection with the potential impact on the morphological properties of the soil, special attention should be paid to points with high or maximum values, especially for Cd^{2+} in sample 1.1 in spring, as a sign of a local strengthening of the anthropogenic factor or soil geochemical features. Table 2 shows the concentrations of mobile forms of heavy metals in soils of Site 2 during the spring and summer period.

Table 2. Content of mobile forms of heavy metals in soils (mg/kg), Site 2, spring-summer 2025

Sampling period/ sample code	MPC, mg/kg	West			North			South		
		1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Spring 2025										
Cu, mg/kg	3.00	0.53	0.497	0.463	0.29	0.587	0.609	0.63	0.387	0.361
Zn, mg/kg	23.00	1.185	0.87	1.09	0.825	1.49	0.81	6.924	8.565	1.91
Cd, mg/kg	0.70	0.219	0.412	0.429	0.182	0.445	0.381	0.49	0.407	0.397
Pb, mg/kg	6.00	2.409	2.11	2.245	1.35	0.82	1.635	1.067	2.115	2.145
Summer 2025										
Cu, mg/kg	3.00	0.557	1.25	1.568	0.756	0.518	0.637	36.8	0.366	0.478
Zn, mg/kg	23.00	1.29	3.45	4.47	6.651	1.005	3.828	10.39	1.556	0.837
Cd, mg/kg	0.70	0.518	0.651	0.698	0.756	0.495	0.6255	0.28	0.352	0.38
Pb, mg/kg	6.00	1.595	2.854	2.652	1.79	1.37	1.58	1.415	1.485	1.728

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

In the spring of 2025, the maximum content of Cu^{2+} (mobile forms) was observed in the Southern direction in sample 3.1, which was 0.63 mg/kg (at other sampling points, the values of Cu^{2+} were in the range of 0.29-0.609 mg/kg). In the summer of 2025, the maximum value of Cu^{2+} was also noted in sample 3.1, where it was 36.8 mg/kg, while the rest of the summer values of Cu^{2+} were in the range of 0.366-1.568 mg/kg. Thus, at the point with the highest values (3.1), the concentration of Cu^{2+} increased from 0.63 mg/kg in the spring to 36.8 mg/kg in the summer (a change of +36.17 mg/kg), which indicates a sharp seasonality at this point. Of the rest, the Western direction shows higher summer concentrations than in the spring, in samples 1.3 (1.568 mg/kg) and 1.2 (1.25 mg/kg), but much lower than the maximum concentration registered in sample 3.1. In the case of Zn^{2+}, the maximum spring 2025 concentration is registered in the Southern direction in sample 3.2 with a value of 8.565 mg/kg. The rest of the samples show spring concentrations between 0.81 and 6.924 mg/kg. For summer 2025, the maximum concentration of Zn^{2+} is registered in sample 3.1 (Southern direction) with a value of 10.39 mg/kg; the rest of the summer concentrations of Zn^{2+} are between 0.837 and 6.651 mg/kg. The maximum summer concentration (10.39 mg/kg) is 1.825 mg/kg higher than the maximum spring concentration (8.565 mg/kg). At the point corresponding to the spring maximum, in sample 3.2, a decrease was observed in summer from 8.565 mg/kg to 1.556 mg/kg (a change of -7.009 mg/kg). At the same time, at the point of the summer maximum, in sample 3.1, Zn^{2+} increased from 6.924 mg/kg in spring to 10.39 mg/kg in summer (a change of +3.466 mg/kg), indicating a seasonal reconfiguration of the spatial distribution of elevated values. In spring 2025, the Cd^{2+} content across all points at Site 2 ranged from 0.182 mg/kg to 0.490 mg/kg: the minimum was recorded in sample 2.1 (Northern direction) at 0.182 mg/kg, while the maximum was recorded in sample 3.1 (Southern direction) at 0.490 mg/kg. For summer 2025, the maximum concentration of Cd^{2+} is registered now in sample 2.1 (Northern direction) with a value of 0.756 mg/kg. The minimum summer concentration is registered in sample 3.1 (Southern direction) with a value of 0.280 mg/kg (the rest of the samples, except 2.1, are between 0.3520.698 mg/kg).

Comparison of seasonal maxima shows an increase in the peak Cd^{2+} level from 0.490 mg/kg (spring, 3.1) to 0.756 mg/kg (summer, 2.1), i.e. by 0.266 mg/kg, indicating a pronounced seasonal and spatial reconfiguration of the "zone of maximum values". At the same time, at the point of maximum spring concentration (3.1), the content of Cd^{2+} decreased from 0.490 mg/kg to 0.280 mg/kg (a change of -0.210 mg/kg), and at the point of maximum summer concentration (2.1), it increased from 0.182 mg/kg to 0.756 mg/kg (an change of +0.574 mg/kg), which directly indicates the redistribution of the main area of high concentrations. Regarding Pb^{2+} for spring 2025, the maximum concentration is registered in the Western direction in sample 1.1 with a value of 2.409 mg/kg. The rest of the spring concentrations of Pb^{2+} are between 0.82 and 2.245 mg/kg. For summer 2025, the maximum concentration of Pb^{2+} is registered in sample 1.2 (Western direction) with a value of 2.854 mg/kg. The rest of the summer concentrations are between 1.37 and 2.854 mg/kg. The maximum summer concentration (2.854 mg/kg) is 0.445 mg/kg higher than the maximum spring concentration (2.409 mg/kg). At the same time, at the point of the spring maximum (1.1), a decrease was observed from 2.409 mg/kg to 1.595 mg/kg (a change of -0.814 mg/kg). On the other hand, at the point of maximum summer concentration (1.2), the content of Pb^{2+} increased from 2.11 mg/kg in spring to 2.854 mg/kg in summer (a change of +0.744 mg/kg), which directly indicates the redistribution of the accumulation intensity in the Western direction.

The registered concentrations of mobile Cu^{2+}, Zn^{2+}, Cd^{2+}, and Pb^{2+} (spring-summer 2025, Site 2) can affect the morphological condition of the soil, first of all, due to changes in biological processes and the stability of aggregates in the upper horizons. Mobile forms of metals are most accessible for migration and sorption complex interaction; thus, they can change humus formation conditions, microbial activity, and root system development. At the morphological level, the difference will manifest as local variation of soil structure, bulk density, surface stability against sealing and compaction, and cracking upon drying. It is worth noting that local "peaks" at individual points can generate a mosaic of morphological features, even if the majority of indicators remain within the limits. In this data set, the most "contrasting" areas relate to the Southern direction (3.1) and the Northern direction (2.1) in the summer. According to the MPC standards presented in the table, no exceedances are noted for most elements at most points; however, there is an exception. For Cu^{2+} (MPC 3.00 mg/kg), the value is 36.8 mg/kg in sample 3.1 in the summer; thus, it significantly exceeds the MPC (for comparison, the maximum Cu^{2+} content in the spring is 0.63 mg/kg, which does not exceed the standard). For Zn^{2+} (MPC 23.00 mg/kg), the maximum values in the spring (8.565 mg/kg, 3.2) and in the summer (10.39 mg/kg, 3.1) do not exceed the permissible level. For Pb^{2+} (MPC 6.00 mg/kg), the maximum in the spring (2.409 mg/kg, 1.1) and the maximum in the summer (2.854 mg/kg, 1.2) also do not exceed the MPC. Figure 6 shows the exceedance of the MPC in sample 3.1 in the summer. The values of Cu^{2+} registered in both samples are higher than the established MPC, which confirms the presence of excesses.

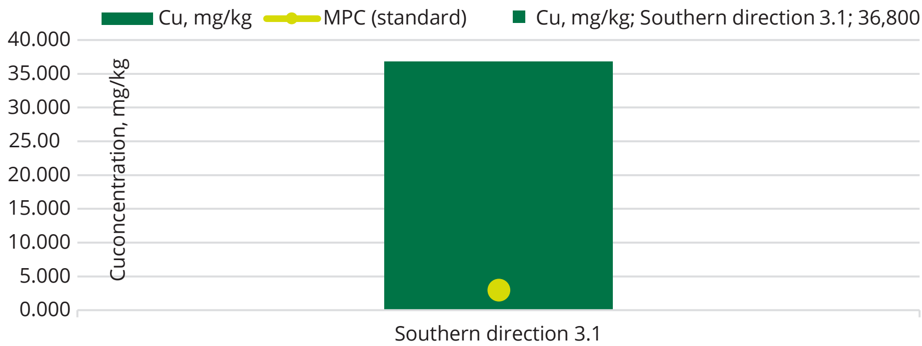

Figure 6. Exceedance of Cu^{2+}, mg/kg, above the MPC (Site 2, summer 2025)
Source: developed by the authors

The sharp increase in the content of the mobile form of Cu^{2+} in the summer in sample 3.1 (up to 36.8 mg/kg) is likely due to a combination of local input of copper and a change in the soil chemical conditions for the transition of copper into more mobile, extractable forms. In the summer, at high temperatures and varying humidity (drying and rewetting cycles), the processes of mineralisation of organic matter and transformation of Cu^{2+} complexes with humic substances are activated, which can temporarily increase the share of mobile compounds. In addition, the local variation often comes from point anthropogenic pollution (input of waste, dust/sludge, metal particles, or wastewater with copper) or redistribution of pollutants by surface flow into microdepressions of the relief, where fine particles are concentrated. L. Filipović *et al.* (2023) showed on a field lysimeter experiment (with a monthly frequency of sampling during two years) performed on the soils of a vineyard slope, that Cu^{2+} concentrations in the leachates are statistically linked to dissolved organic carbon (DOC) concentrations, with a stronger correlation found at the footslope position where the substances tend to accumulate and the redistribution by the flow of water is more pronounced. The authors pointed out in their discussion that the organically complexed forms control the copper mobility: according to the modelling of speciation, the majority of Cu^{2+} in leachate was found as Cu^{2+} – DOC (the sum of humic-complexed forms), whereas the molar fraction of free Cu^{2+} in the aqueous phase is very low (tenths to hundredths of a per cent). This suggests that a seasonal variation in the DOC pool or dissolved organic matter (DOM) might significantly affect the mobile pool of Cu^{2+} in the soil-solution system. In the framework of this research, this statement straightforwardly supports the interpretation of the summer maximum in sample 3.1: if, during the summer period, the input or formation of dissolved organic matter is increased or its composition is changed (e.g. due to the mineralisation of organic matter and drying-rewetting cycles), then part of copper can be mobilised into more mobile, extractable forms due to complexation with DOM/DOC. At the same time, for Zn^{2+} and Pb^{2+}, which do not exceed the MPC values at any points, the morphological effect is generally less pronounced and manifests itself mainly in the form of background seasonal fluctuations without a marked disturbance to the soil profile. In general, it is a combination of "local peaks" with seasonal dynamics that creates conditions for a heterogeneous morphological pattern of the site.

The obtained results allow characterisation of the environmental status of the territory and the spatial distribution of the potential risk. They can be used as a basis for the environmental impact assessment, monitoring of the working environment, and development of scientific models of the migration and accumulation of mobile metal forms in the soil during different seasons. The indicators reflect the possible scheme of the spatial distribution of the contamination and allow identifying objects that require a more detailed morphological description of the soil profile, first of all, at the "contrasting" points. The data indicate a spatial heterogeneity in the distribution of mobile forms of metals. The maximum values of different elements are concentrated in different sectors and points: Cu^{2+} is in sample 3.1 in summer, Zn^{2+} is in sample 3.1 in summer and in sample 3.2 in spring, Cu^{2+} is in sample 2.1 in summer, Pb^{2+} is in sample 1.2 in summer and in sample 1.1 in spring. Zn^{2+} and Pb^{2+} concentrations during the spring-summer period at all points of both sites do not exceed the MPC values. However, Cu^{2+} in sample 3.1 in the summer season exceeds the norm. The most significant seasonal variations were registered for Cu^{2+}: in sample 3.1, the concentration increased from 0.63 mg/kg in spring to 36.8 mg/kg in summer, which significantly changed the environmental interpretation of the site's summer status. The general conclusion that follows from the above data is that, for the assessment of potential morphological transformations, local maxima and their seasonal dynamics are of greater interest than average site concentrations since they determine the areas of priority interest for further study. The comparison of both sites revealed that the risk degree is different: the maximum risk at Site 1 is caused by a sharp increase in the concentration of Cd^{2+} in spring at the Northern direction in samples 1.1 and 1.2 (0.898 mg/kg and 0.768 mg/kg, respectively), while at Site 2, the maximum risk is caused by a sharp increase in the concentration of Cu^{2+} in summer in sample 3.1 (36.8 mg/kg) and the summer maximum of Cd^{2+} concentration in sample 2.1 (0.756 mg/kg). Zn^{2+} and Pb^{2+} concentrations at both sites during both seasons are significantly below the MPC and are subject to local seasonal maxima (Zn^{2+} up to 9.625 mg/kg at Site 1 and up to 10.39 mg/kg at Site 2; Pb^{2+} up to 2.755 mg/kg at Site 1 and up to 2.854 mg/kg at Site 2). The points of priority interest for further monitoring and repeated sampling are 1.1-1.2 (Cd^{2+}, spring) at Site 1, as well as 3.1 (Cu^{2+}, summer) and 2.1 (Cd^{2+}, summer) at Site 2, since they determine the maximum excess of MPC within the framework of the presented data.

Over the spring-summer period of 2025, the morphological structure of wastes at Site 1 is generally represented by the prevalence of the polymer fraction (plastics: 23-25%, polyethylene: 16-18%, the total share is approximately 41%), a considerable share of organic waste (15-16%), and components potentially recoverable (paper/cardboard: 12-14%, glass: 10-13%). Against the background of the recorded morphological structure of waste, the cases of excess of the maximum permissible concentration were registered: in the spring period, the concentration of Cd^{2+} in the Northern direction (samples 1.1: 0.898 mg/kg and 1.2: 0.768 mg/kg) exceeded the MPC (0.70 mg/kg). In summer, a pronounced local excess was registered for Cu^{2+} in sample 3.1 (Southern direction), which is 36.8 mg/kg (MPC 3.00 mg/kg). This fact indicates the formation of a focal zone of high anthropogenic pollution. At Site 2, the morphological composition of waste in the spring and summer of 2025 was the same and consisted of the following: plastics: 25%, polyethylene: 16%, rubber waste: 14%, organic waste: 13%, paper and cardboard: 13%, glass: 9%, wood: 5%, textiles: 4%, ferrous metals: 1%. Such a composition indicates the prevalence of long-lived materials (polymers and rubber) and the presence of a biodegradable fraction, which determines the intensity of the transformation processes in the body of the landfill. The constancy of the morphological composition is a necessary condition for the correct seasonal comparison of the processes of migration and risks of toxicant accumulation in the soils adjacent to the landfill. The likely causes of the revealed excesses of the MPC should be interpreted in the relationship between the morphological composition of the waste and the processes of formation of leachate and migration of contaminants.

The increased content of polymer and rubber fractions can serve as a source or carrier of impurities due to the presence of technological additives, fillers, and pigments, as well as contribute to the sorption/desorption of metals on the surface of materials during degradation. On the contrary, the presence of an organic component (13-16%) contributes to biochemical transformations and the formation of leachate, which changes the physicochemical parameters of the environment (solubility of compounds, mobility of metal forms) and can contribute to their migration and accumulation. Local maxima (of Cd^{2+} in samples 1.1-1.2 and Cu^{2+} in sample 3.1) are associated with point sources of pollution in combination with non-uniform distribution and filtration of moisture in the contaminated areas.

CONCLUSIONS

In the framework of the study, it was found that in 2025, for both landfills, the characteristic feature of the morphological structure of waste is the prevalence of the polymer fraction. At Site 1, in the spring-summer period, the total content of plastics and polyethene in the waste remained at the same level, 41%, and a significant content of the organic fraction (15-16%) and the components, which are potentially recyclable (paper/cardboard and glass), was noted. At Site 2, the morphological composition of waste in the spring and summer was the same in terms of the proportion of fractions, which indicates a constant waste flow and reproducibility of structure. Morphological results validate the high potential of the waste stream both as a resource and environmental threat, as they are mostly composed of long-lifetime materials (polymers and rubber). At Site 1, slight seasonal structural variations were registered (increase of plastics and paper/cardboard and decrease of glass), which might be linked to changes in packaging materials during the spring-summer season. At Site 2, the relatively constant proportions of the main fractions allow considering the morphological profile as a reference characteristic for the interpretation of migration processes and related pollution risks.

The investigation of the soil samples revealed the exceedance of maximum permissible concentrations of heavy metals in certain directions and periods of sampling. For Site 1, in the spring season, MPC exceedance for Cd^{2+} (0.70 mg/kg) was found in the Northern direction in samples 1.1 (0.898 mg/kg) and 1.2 (0.768 mg/kg). In the summer season at the same site, a sharp local MPC exceedance for Cu^{2+} (3.00 mg/kg) was registered in the Southern sample 3.1 (36.8 mg/kg), which indicated the formation of a localised zone of anthropogenic pollution. The reasons for the registered MPC exceedances are related to the morphological features of the waste and processes caused by them in the waste-leachate-soil system. Elevated proportions of the polymer and rubber fractions may act as sources or carriers of impurities and participate in the retention and transport of pollutants, while the organic fraction enhances the formation of leachates and changes the physicochemical conditions that influence the mobility and accumulation of metals in the soil. The local character of the MPC exceedances (for Cd^{2+} in the 1.1-1.2 direction and for Cu^{2+} in sample 3.1) agrees with the spatial heterogeneity of the composition and moisture content of the waste, as well as with the varying intensity of filtration, which controls the focal accumulation of heavy metals. Further investigations are recommended for a deeper analysis of the influence of different waste fractions on heavy metal migration in soils and for the development of efficient measures to mitigate anthropogenic pollution through proper management and treatment of the waste.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Несанкціоновані сміттєзвалища як джерело важких металів: вплив морфологічного складу відходів

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Анотація. В умовах зростання кількості локальних, неконтрольованих місць розміщення відходів в Україні проблема оцінки їх впливу на стан ґрунтів набуває особливої актуальності, зважаючи на високий потенціал міграції токсичних елементів та тривалий період їхньої екологічної активності. Метою дослідження був аналіз взаємозв'язку між морфологічною структурою відходів на несанкціонованих сміттєзвалищах та рівнями накопичення важких металів у ґрунтах техногенно навантажених територій. У дослідженні застосовано стандартизовану методику відбору проб твердих побутових відходів та ґрунтів згідно з національними та міжнародними вимогами. Морфологічний склад твердих побутових відходів визначали шляхом фракційного сортування за категоріями: пластик, папір і картон, скло, метали, органічні відходи, текстиль, будівельні матеріали та інші змішані фракції. Відбір ґрунтових зразків здійснювався з глибини 0-20 см, що відповідає зоні найбільшої акумуляції техногенних металів. Концентрації Cd2+, Cu2+ та Zn2+ визначали із застосуванням атомно-абсорбційної спектрометрії, що забезпечило високу точність кількісного аналізу. Для статистичної обробки результатів використано кореляційний аналіз, оцінку коефіцієнтів детермінації та побудову регресійних моделей для визначення зв'язку між часткою окремих морфологічних фракцій та рівнями забруднення ґрунтів. Додатково проведено оцінку екологічного ризику за індексами накопичення, коефіцієнтом забруднення та модифікованим індексом потенційної екологічної небезпеки. Отримані дані виявили статистично значущі зв'язки між підвищеним вмістом важких металів у ґрунтовому покриві та наявністю у складі відходів таких фракцій, як металобрухт, дрібнодисперсний пластик, електронні та електротехнічні компоненти, а також будівельні матеріали, що містять фарби, лаки та інші полімерні суміші. Найбільш інтенсивно до ґрунту мігрують Pb2+ та Cd2+, що корелюють з фракціями старих батарейок, дрібних металевих предметів та електронних відходів. Органічна фракція, хоча і не є прямим джерелом важких металів, сприяє їх мобілізації внаслідок процесів мінералізації та утворення органічних кислот

Ключові слова: коефіцієнт концентрації; індекс забруднення; рухомі форми елементів; адсорбція; фільтрати