

Ecological-trophic groups of microorganisms as indicators of the intensity of technogenic impact on soils adjacent to municipal solid waste landfills

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ABSTRACT

Under modern conditions of increasing volumes of municipal solid waste (MSW) generation and limited possibilities for its environmentally safe disposal, MSW landfills remain one of the most widespread sources of technogenic pressure on soil ecosystems. Long-term operation of landfills is accompanied by the accumulation of pollutants, including organic compounds, heavy metals, and leachate products, which alter the physicochemical properties of soils and, consequently, affect the structure and functioning of soil microbiota. In this context, microorganisms of various ecological–trophic groups are considered sensitive and informative indicators of the intensity of anthropogenic, particularly technogenic, impact, as they rapidly respond to changes in environmental conditions and reflect the direction of soil biochemical processes. Soil sampling was carried out taking into account the distance gradient from MSW landfills, which made it possible to trace the spatial differentiation of microbiological indicators depending on the level of technogenic load. For a comprehensive assessment of the functional state of the microbial community, the main indices of microbiological processes were calculated, including coefficients of mineralization and immobilization of organic matter, indicators of trophic orientation, and soil biological activity. The obtained results indicate that in soils located in close proximity to MSW landfills, significant changes in the structure of the microbial cenosis are observed. These changes manifest themselves in an increase in the abundance of microorganisms associated with intensive mineralization of organic compounds, accompanied by a simultaneous decrease in the proportion of oligotrophic and specialized forms. The detected shifts in microbiological indices indicate a disturbance of the balance of soil biochemical processes, a decrease in the stability of the soil ecosystem, and can be considered a consequence of increased technogenic pressure. Thus, ecological–trophic groups of microorganisms and indices of microbiological processes are effective indicators of the ecological state of soils within the zone of influence of MSW landfills. The application of microbiological indicators in environmental monitoring systems makes it possible to timely detect negative changes in soil ecosystems, assess the level of anthropogenic load, and can be used to substantiate environmental protection measures aimed at reducing technogenic impact and restoring disturbed soils.

Keywords: soil microbiota, microorganisms, technogenic load, municipal solid waste landfills.

INTRODUCTION

Municipal solid waste (MSW) landfills are widely used as a waste management tool. The main fraction of household waste contains biodegradable organic material, including paper, food waste, plant residues, as well as leather and textiles.

However, MSW landfills may also contain a significant amount of non-degradable waste, such as glass, metals, ceramics, and construction waste, as well as synthetic materials, including plastics and rubber. The chemical structure of these materials is characterized by polycyclic aromatic hydrocarbons and polychlorinated biphenyls, which are

resistant to degradation by most microorganisms (Sekhohola-Dlamini et al., 2020).

Municipal solid waste landfills represent the most common waste disposal method and are among the largest sources of anthropogenic greenhouse gas (GHG) emissions into the atmosphere (more than 20% of global GHG emissions and approximately 30% in the United States) (Remmas et al., 2023).

In the European Union, the percentage of municipal solid waste directed to recycling, incineration, landfilling, and composting is 30%, 27%, 24%, and 17%, respectively (Eurostat, European Commission, 2021. Municipal waste statistics). In the United States of America (USA), the share of household waste disposed of in landfills is twice as high compared to the EU. The proportion of MSW in the USA directed to recycling, incineration, landfilling, and composting amounts to 24%, 12%, 50%, and 8%, respectively (Environmental Protection Agency (EPA). National Overview, 2023).

Waste accumulation poses a serious threat to human life and health in many countries worldwide. According to the World Health Organization, approximately 88.0% of diseases arise as a result of waste of various origins. The problem of waste management is extremely relevant for Ukraine as well. In Ukraine, about 4.0% of household waste is recycled, of which 1.15% is incinerated and only 2.5% is delivered to secondary raw material collection points and waste processing facilities. The remaining waste is disposed of at landfills (Korobkova et al., 2024).

Another significant problem is that unsorted waste is disposed of at landfills, and the landfills themselves do not always meet established environmental standards. In addition, more than 33,000 MSW landfill and about 6,000 landfills that can hardly be considered controlled currently exist in Ukraine, posing a substantial threat to the environment. Under such conditions, the implementation of an effective municipal solid waste management system in every settlement, as well as the introduction of modern waste treatment technologies, is critically important. The introduction of centralized separate collection of MSW is particularly relevant (Koliada et al., 2024).

Ukraine lags behind developed countries in implementing effective systems for sorting and logistics of municipal solid waste, while simultaneously losing its valuable resource potential. At the same time, 94% of household waste in Ukraine has been disposed of in landfills, and

the total area of all operating landfills exceeds the area of the city of Ivano-Frankivsk (Nosova, 2024). MSW landfill exert a catastrophic impact on the environment, while the responsibility for their creation in Ukraine remains symbolic compared to the scale of technogenic pressure (Kolodiichuk, 2020). In recent years, only 5% of waste in Ukraine has been recycled, including glass, plastic, aluminum bottles, paper, cardboard, textiles, and other materials. Approximately 1% of waste is incinerated for energy recovery (Kolodiichuk, 2020).

One of the key components of MSW biodegradation is soil microbiota. Landfill conditions create unique ecological niches for microbial communities. Microbial activity in disposed waste plays a decisive role, particularly in greenhouse gas emissions (Wang et al., 2017).

As a result of reconnaissance studies of landfills within the Western Ukrainian forest-steppe zone, it was found that drainage systems for leachate removal are absent. Leachate accumulates in settling ponds and is not treated. At some landfills, leachate collection ditches are lacking, allowing leachate to infiltrate fertile agricultural lands and contaminate them with toxic elements. The relatively “safest” sites are inactive landfills undergoing natural phytomeliorative processes. In most countries worldwide, the concentrations of hazardous substances in landfill leachate and MSW landfill leachate exceed permissible limits, posing a detrimental threat to living organisms and ecosystems (Popovych et al., 2015).

The aim of this study was to assess the intensity of technogenic pressure on soils adjacent to MSW landfills by analyzing the dynamics of microorganism abundance within major ecological–trophic groups and determining key indices of microbiological processes. The study was conducted on soil samples collected within the impact zone of MSW landfills, taking into account the distance gradient from pollution sources, which made it possible to trace spatial changes in microbiological indicators.

The analysis of soil microbiota under MSW landfill conditions in Ukraine remains insufficiently studied. Therefore, the objective of this research was to investigate the effect of the distance gradient of technogenic pressure from municipal solid waste landfills on the dynamics of formation of ecological–trophic groups of microorganisms in the conditions of Chernihiv, Cherkasy, and Kirovohrad regions.

BACKGROUND

Using the high-throughput MiSeq sequencing method, the microbial diversity of cover soil and stored waste located at different depths (0–150 cm) at a typical MSW landfill was investigated. The abundance of microorganisms in the cover soil (0–30 cm) was the lowest among all samples, whereas in the stored waste it decreased from the upper to the middle layer (30–90 cm) and then increased from the middle to the lower layer (90–150 cm). Analysis of microbial diversity revealed 14 phyla and 18 genera of microorganisms. The dominant phyla were Firmicutes, Proteobacteria, and Bacteroidetes, while the dominant genera included *Halan-aerobium*, *Methylohalobius*, *Syntrophomonas*, *Fastidiosipila*, and *Spirochaeta*. *Methylohalobius* spp. (methanotrophs) were more prevalent in the cover soil layers than in stored waste, whereas *Syntrophomonas* and *Fastidiosipila*, which are involved in methane production, were more abundant in the middle and lower layers (90–150 cm) of stored waste. Microbial diversity at the MSW landfill strongly correlated with microbial biological activity, organic matter content, and moisture content of the stored waste (Wang et al., 2017).

The structure of microbial communities in landfill soils was investigated with a focus on fungal and bacterial composition in old (closed), active (operational), and leachate leakage zones compared with an undisturbed reference area. Molecular approaches demonstrated that bacterial phyla were most abundant in active landfill soils, particularly Actinobacteria (0.63 times higher), Firmicutes (0.17 times higher), and α -Proteobacteria (0.13 times higher), whereas *Nitrospira*, *Acidobacteria*, and *Chloroflexi* were present at minimal levels. The results indicate a correlation between bacterial groups and the age of the landfill zone. In addition, the type of buried waste, including medical and municipal solid waste, significantly affected the diversity and abundance of fungi in surface soil layers (Zabihollahi et al., 2024).

Over time, microorganisms decompose organic waste, releasing gases (mainly CH₄ and CO₂) and a complex mixture of soluble chemical compounds into leachate. Characterization of “landfill microbiomes” and their comparison across multiple landfills may allow the identification of ecological or operational factors that

influence the composition of these microbiomes and potentially their biodegradation capacity. The composition of landfill microbiomes was investigated within an ongoing national USGS study examining the chemical composition of leachate from 19 secure landfills across 16 states in the continental United States. The landfills differed in size, waste composition, management strategy, geography, and climatic zone. The diversity and composition of bacterial and archaeal populations in leachate samples were characterized using 16S rRNA gene sequence analysis and compared with various physical and chemical parameters. The most prevalent taxa were members of the phylum Campylobacterota and bacteria of the class Gammaproteobacteria. Their distribution was most strongly correlated with chloride and barium concentrations, water evaporation rate, waste age, and the number of detected household chemicals (Stamps et al., 2016).

Landfills represent a vast reservoir of lignocellulose-degrading bacteria that can potentially be utilized in biorefinery and industrial lignocellulose-based processes. The degradation of lignin and cellulose in nature is achieved through synergistic interactions among multiple microorganisms. Forty phyla were identified, with dominant groups including Proteobacteria, Firmicutes, Actinobacteria, and Bacteroidota, while *Aerococcus*, *Stenotrophomonas*, and *Sporosarcina* were the dominant genera. The activity of lignocellulolytic enzymes – namely cellulase, xylanase, esterase, and peroxidase – was detected in representatives of these bacteria (Chukwuma et al., 2021).

It was established that the plastisphere of MSW landfills contained a high concentration of phthalates and exhibited a distinct microbial structure. Significant plastic biodegradation was detected, primarily driven by bacteria of the genus *Pseudomonas*, along with increased activity in carbon metabolism and nitrification processes. The genera *Sporosarcina*, *Oceanobacillus*, and *Pelagibacterium* were found in high abundance on plastic surfaces, whereas *Ignatzschineria*, *Paenalcaligenes*, and *Oblitimonas* were enriched in the surrounding waste. Typical plastic-degrading bacteria of the genera *Bacillus*, *Pseudomonas*, and *Paenibacillus* were detected in both environments. However, *Pseudomonas* dominated plastic surfaces (up to 88.73%), while *Bacillus* prevailed in surrounding waste (up to 45.19%) (Lin et al., 2023).

In untreated landfill leachate, representatives of bacteria from the order *Bacteroidales* and *Pusillimonas*-like bacteria capable of degrading persistent compounds were identified, along with anaerobic fermentative bacteria of the class *Clostridia*. A substantial proportion of the microbial population in untreated leachate consisted of sulfate-reducing bacteria such as *Desulfobacter* spp. Landfill leachate contains high concentrations of organic matter as well as elevated levels of ammonium nitrogen. Heavy metals are consistently detected, together with a wide range of xenobiotics and pharmaceuticals, including chloroglycosides, perfluorocarbons, phenols, polyaromatic compounds, and plasticizers, which enhance the persistent nature of the wastewater and may exert toxic effects on living organisms even at extremely low dilutions (0.53% v/v). Physicochemical methods applied for leachate treatment can serve as pretreatment processes, facilitating subsequent biological methods such as activated sludge systems, which are mainly implemented using sequencing batch reactors (SBR) and membrane bioreactors (MBR). These activated sludge systems operate through specialized microbiota, including the genera *Thauera*, *Truepera*, *Pseudomonas*, *Paracoccus*, *Luteimonas*, and *Pusillimonas*, which are capable of coping with the persistent nature of landfill leachate (Remmas et al., 2023).

In Ukraine, four unauthorized MSW landfills located within the Carpathian Biosphere Reserve were studied, namely in the tracts Pidhirna, Stanyslav, Sterishory, and Feresok, with areas ranging from 0.15 to 1.5 ha, waste accumulation periods of 12–22 years, and different morphological compositions. Changes in the soil microbial cenosis under the direct influence of unauthorized MSW landfill were identified, including an increase in the abundance of organotrophic bacteria and micromycetes, a decrease in nitrogen-fixing microorganisms, and increased soil phytotoxicity. The highest numbers of bacteria utilizing nitrogen from organic compounds (25.36–28.61 million CFU g⁻¹ soil) and micromycetes (51.8–76.8 thousand CFU g⁻¹ soil) were recorded in soils from the Pidhirna and Feresok tracts, exceeding reference soils by 1.5–1.7 and 2.5–3.8 times, respectively. An increase in the abundance of pedotrophic and oligotrophic microorganisms and microorganisms assimilating organic forms of nitrogen, by an average of 2.70,

2.84, and 1.48 times, influenced the direction of major soil microbiological processes. The oligotrophic coefficient ranged from 0.21 to 0.30, the mineralization–immobilization coefficient from 1.22 to 1.38, and the pedotrophic coefficient from 0.55 to 0.96, with maximum values recorded in soils of the Feresok and Pidhirna dumpsites. This indicates intensified microbiological mineralization processes and enhanced decomposition of soil organic matter, including humic compounds. A strong relationship was established between the duration of MSW accumulation at a site and soil phytotoxicity level ($r = 0.92$). In soils of dumpsites located in the Pidhirna, Sterishory, and Feresok tracts, phytotoxicity exceeded 50%, indicating a high level of soil ecosystem contamination and increased environmental risks in areas of unauthorized MSW accumulation.

Saranenko, I. I. (2025) reported that the test plot near a dumpsite was significantly contaminated, with a phytotoxic effect (PE) reaching 69.6%, indicating substantial growth inhibition, while soil solution pH was 4.9. Under such conditions, most nutrients become poorly available to plants. Biotesting revealed characteristic morphological symptoms of toxic stress in *Capsicum annum* L. plants, including leaf curling, edge chlorosis, and root deformation.

OBJECTS OF THE STUDY

The objects of the study were four dumpsites/landfills located in different natural and geographical zones of Ukraine, which provides comprehensive coverage of regional features of technogenic pressure on the soil environment.

Landfill 1

Landfill 1 is located within Nizhyn district, Bakhmach territorial community of Chernihiv region (51°09'45"N, 32°42'14"E), at a distance of 17 km from the city of Bakhmach. The area of the technogenically disturbed territory is 2.25 ha. Soil sampling was carried out in two stages: in the third decade of July 2024 and again in October 2024, which made it possible to assess seasonal changes in the ecological state of soils.

The approximate volume of accumulated waste is about 120–180 thousand m³, based on an average waste body thickness of 5–8 m. Such a

volume is typical for unauthorized or semi-controlled dumpsites with a long period of operation. The accumulation of a significant mass of waste over approximately 30 years creates conditions for intensive mineralization processes, compaction, and leachate formation. This, in turn, causes increased technogenic pressure on adjacent soil and biotic components of the ecosystem.

Landfill 2

Landfill 2 is located within Uman district, Kniazho-Krynytska territorial community of Cherkasy region (49°06'22"N, 29°44'18"E), 4 km from the village of Kniazha Krynytsia. The area of the dumpsite is 0.2 ha. Soil sampling was conducted twice, in July and October 2024, for a comparable analysis of spatiotemporal transformations of soil characteristics.

With an average waste body thickness of 3–6 m, the approximate volume of accumulated waste may be 6–12 thousand m³. The dumpsite has been operated for approximately 15 years, which is a sufficient period for the formation of technogenically altered soils and for the activation of decomposition processes of the organic fraction of waste. The site is used as a scientific landfill (research polygon), which provides an opportunity to conduct systematic ecological and microbiological studies in order to assess the impact of waste on the state of soil ecosystems and adjacent natural components.

Landfill 3

Landfill 3 is located in Zolotonosha district of Cherkasy region, within the administrative boundaries of the Zolotonosha urban community, near the village of Krapyvna (49°37'46"N, 32°12'07"E). The area of the site is 0.4 ha. Soil sampling was performed in autumn, in October 2024.

With an average waste body thickness of 4–6 m, the approximate volume of accumulated municipal solid waste is estimated at 16–24 thousand m³. The dumpsite has been operated for approximately 17 years, which has contributed to the formation of technogenically transformed soils and the intensification of biochemical degradation processes in the waste mass. The site is used as a scientific landfill (research polygon), which enables comprehensive ecological and microbiological studies to assess the impact of waste on the

condition of soil ecosystems and adjacent natural components.

Landfill 4

Landfill 4 is located in the Onufriivka settlement community of Oleksandriia district, Kirovohrad region (48°53'03"N, 33°45'54"E), at a distance of 6.4 km from the village of Deriivka. The area of the contaminated site is 0.2 ha. Sampling was conducted in October 2024.

With an average waste body thickness of 2–4 m, the approximate volume of accumulated municipal solid waste is estimated at 4–8 thousand m³. The dumpsite has been functioning for approximately 5 years, which corresponds to the initial stages of soil transformation and activation of microbiological processes of decomposition of the organic fraction of waste. The studied site is used as a scientific landfill (research polygon), which provides an opportunity to assess early ecological changes in soil ecosystems under short-term technogenic pressure.

SOIL SAMPLING SCHEME

Soil sampling was carried out within the territories of anthropogenically transformed biogeocenoses in the impact zone of MSW landfill, from soil layers directly adjacent to the dumpsites, at a depth of 5–20 cm, which corresponds to the root-containing layer and the zone of the most intensive pollutant impact. The spatial organization of sampling was determined by the morphology of the dumpsite, local topography, and potential migration pathways of contaminants. For each site, three orientation directions were defined, ensuring representativeness of the data and enabling assessment of the pollution gradient.

At Site 1, samples were collected in the following directions: North – 5 m from the dumpsite, Northeast – 10 m from the dumpsite, and Southeast – 15 m from the dumpsite. In each direction, three point samples were established at a distance of 5 m from the dumpsite body, after which a composite (average) sample was prepared.

A similar approach was applied at Site 2: sampling was carried out in the directions West – 5 m from the dumpsite, North – 10 m from the dumpsite, and South – 15 m from the dumpsite.

At Sites 3 and 4, point sampling was applied: one sample in each of three directions – North-eastern localization – 5 m from the dumpsite, Central North – 10 m from the dumpsite, and Western direction – 15 m from the dumpsite. The selection of this scheme was determined by the smaller area of the dumpsites and physically limited access to their perimeter.

A control (background) point was established at a distance of about 200 m from the dumpsite boundary, on a site that had not undergone direct anthropogenic transformation. The control area is characterized by the absence of signs of economic activity, which allows these samples to be used for comparative analysis.

Determination of the dynamics of microorganism abundance in the main ecological–trophic groups and the main indices of microbiological processes, as well as microorganism identification, were performed in soil samples in the Laboratory of Industrial Biotechnology of NUBiP of Ukraine in accordance with DSTU 7847:2015 and generally accepted microbiological methods (DSTU 7847:2015, Volkohon V.V. et al., 2010).

Statistical processing of the data was performed using Microsoft Office Excel® 2010 for Microsoft Windows®; mean values were compared using analysis of variance (ANOVA) with $p \leq 0.05$.

RESULTS AND DISCUSSION

A differentiation in the dynamics of ecological–trophic groups of bacteria was established across different MSW landfills, at varying distances from the landfills, and depending on the sampling period.

The total bacterial abundance in summer at both landfills ranged from 17.3 to 132.7 CFU g⁻¹ dry soil (Table 1).

In the soil of Landfill 1 during summer, a moderate increase in the total bacterial abundance was observed at different distances (5, 10, and 15 m) from summer to autumn (from 17.3 to 20.7×10^5 CFU g⁻¹ soil), whereas at Landfill 2 a significant increase was recorded – almost 3.8-fold, reaching 132.7×10^5 CFU g⁻¹ soil (Figure 1).

An increase in bacterial abundance was also observed at different distances in autumn; however, the growth rate differed among landfills. The lowest increase was recorded at Landfill

3 (2.2-fold), while at Landfills 1 and 2 the increase amounted to 4.4- and 6.7-fold, respectively, and the highest increase was observed at Landfill 4 (8.5-fold). At Landfill 1, significant seasonal changes in bacterial abundance were recorded in autumn at distances of 10 and 15 m, particularly at 15 m, where the increase reached 5.8-fold. In contrast, at Landfill 2, bacterial growth was observed during summer and especially at a distance of 15 m in autumn, followed by a slight decrease in autumn regardless of distance (Figure 1).

The increase in total bacterial abundance in autumn compared to summer at MSW landfills results from the combined interaction of seasonal abiotic factors (temperature, moisture, availability of organic substrates) and the influence of waste composition and soil geochemical conditions, which form local niches with different levels of available energy for microbiological processes. The differing intensity of these factors at Landfills 1 and 2 explains the unequal ratios of summer-to-autumn bacterial abundance with distance, since the composition of organic and toxic components in waste, their decomposition, and migration within the soil profile determine the spatial availability of resources and stress conditions for microorganisms.

The composition and characteristics of MSW strongly affect bacterial abundance. It is known that certain bacteria are capable of degrading persistent compounds and utilizing methane; therefore, maintaining bacterial activity is of particular importance (Wang, X., et al., 2023).

In addition to landfill characteristics, seasonal factors such as moisture and temperature also influenced bacterial growth. In autumn, specific saprotrophic bacterial decomposers become more active, degrading fresh organic matter. The relatively low growth rate of bacteria at Landfill 1 in summer indicates the presence of toxic compounds (organic solvents and heavy metals, specifically Pb²⁺, Cd²⁺, Cu²⁺, and Zn²⁺, mg kg⁻¹), which selectively inhibit bacterial growth, as bacteria are more sensitive to toxicants than micromycetes.

Thus, the number of bacteria at a distance of 15 m at Landfill 1 increased only in autumn (up to 84.0×10^5 CFU g⁻¹ soil), whereas at Landfill 2 an increase was observed both in summer and autumn (up to 120.9 and 132.7×10^5 CFU g⁻¹ soil, respectively), indicating that Landfill 1 is more toxic than Landfill 2.

Table 1. Total abundance of microorganisms (CFU g⁻¹ dry soil) in soils of the sanitary protection zones of MSW landfills depending on the season

Distance from landfill	Total abundance of microorganisms, CFU g ⁻¹ dry soil					Oligotrophic coefficient	Pedtrophic coefficient
	Bacteria (MPA) ×10 ⁵	Fungi (Sabouraud) ×10 ³	Nitrogen-fixing microorganisms (Ashby) ×10 ⁵	Oligotrophs (Starvation agar) ×10 ⁵	Pedetotrophs (Soil agar) ×10 ⁴		
Summer 2024 – Landfill 1							
5 m	17.3±2.4	3.1±1.1	3.9±1.2	8.5±3.5	2.6±1.1	0.49	0.15
10 m	21.0±1.5	15.4±2.7	5.2±1.4	7.4±1.6	3.8±1.6	0.35	0.18
15 m	20.7±1.8	49.8±4.5	2.7±1.1	8.1±1.3	4.0±1.3	0.39	0.19
Summer 2024 – Landfill 2							
5m	35.1±4.9	14.4±2.9	5.7±2.4	21.0±3.4	7.3±2.7	0.60	0.21
10 m	52.9±4.6	5.3±1.1	3.3±1.6	2.8±1.5	12.7±2.4	0.05	0.24
15 m	132.7±5.7	7.5±1.8	8.4±2.8	2.5±1.1	15.6±4.5	0.02	0.12
Autumn 2024 Landfill 1							
5 m	18.5±4.5	50.3±4.8	2.7±1.4	5.0±1.1	15.1±1.8	0.27	0.82
10 m	47.6±3.0	12.5±2.7	5.2±1.1	26.4±2.7	8.8±1.5	0.55	0.18
15 m	84.0±4.9	10.0±2.4	7.0±3.5	6.1±2.9	12.5±3.7	0.07	0.15
Autumn 2024 Landfill 2							
5m	18.4±2.7	3.2±1.1	4.1±1.8	3.7±1.7	4.8±2.4	0.20	0.26
10 m	23.0±4.5	53.4±3.7	3.1±1.5	3.4±1.1	15.2±2.7	0.15	0.66
15 m	120.9±5.0	72.5±4.5	7.0±2.9	4.6±1.5	5.3	0.04	0.04
Autumn 2024 Landfill 3							
5 m	23.5±3.7	10.7±2.4	4.5±1.3	16.7±1.8	1.2±1.1	0.71	0.05
10 m	18.0±3.5	18.4±2.7	13.8±4.5	12.4±1.3	1.7±1.1	0.69	0.09
15 m	53.0±4.9	41.5±4.5	18.9±2.1	4.3±1.5	19.2±2.7	0.08	0.36
Autumn 2024 Landfill 4							
5 m	14.4±4.5	17.3±2.9	3.2±1.8	18.7±2.1	3.5±1.1	1.30	0.24
10 m	58.6±2.8	2.4±1.1	14.0±1.5	57.0±3.1	12.7±2.7	0.97	0.22
15 m	123.1±4.6	21.3±2.4	24.2±3.7	98.8±4.9	50.4±4.5	0.80	0.41

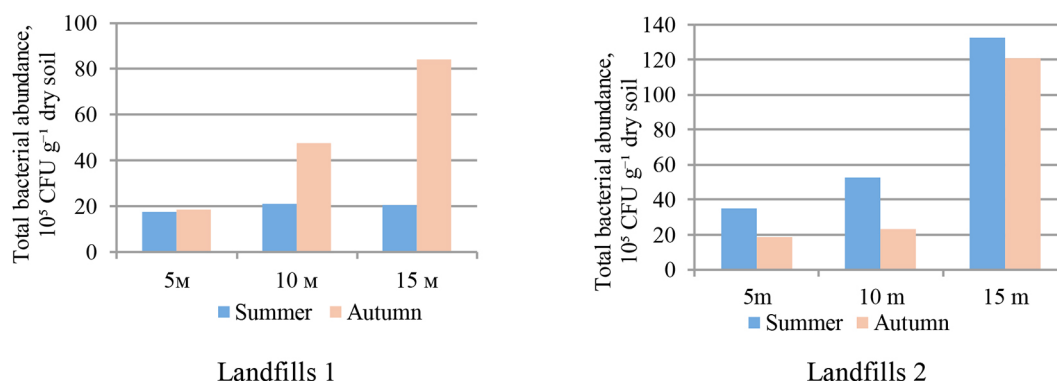


Figure 1. Dynamics of total bacterial abundance (summer–autumn) at MSW landfills 1 and 2

When comparing the total bacterial abundance in autumn across MSW landfills, the lowest bacterial numbers at a distance of 5 m were recorded at all sites. At a distance of 15 m, bacterial abundance was high at Landfill 1, highest at Landfills 2 and 4, and lowest at Landfill 3 (Figure 2).

At Landfill 3, a lower total bacterial abundance was observed in autumn compared to Landfills 2 and 4, which is likely due to a higher concentration of toxic components (heavy metals and toxic organic compounds) in the waste leachate that diffuse into the adjacent

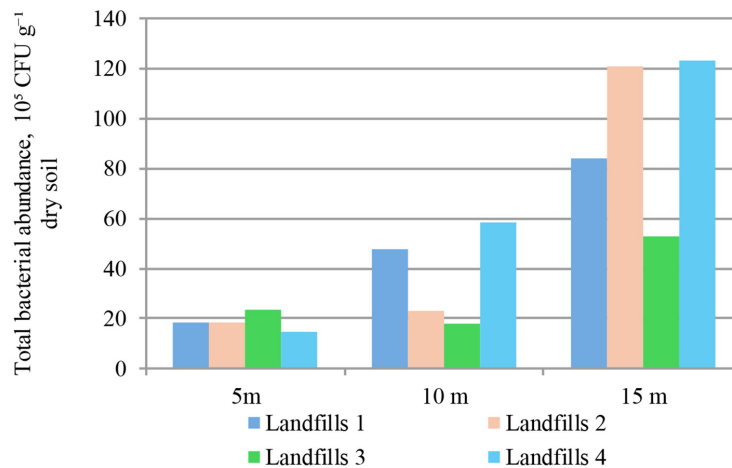


Figure 2. Total bacterial abundance in autumn at MSW landfills

soil and create unfavorable conditions for microbial growth. The high toxicity of these compounds leads to inhibition of microbial enzymatic activity and a reduced capacity for reproduction. At the same time, at Landfills 2 and 4, readily available organic substrates accumulate, conditions for active mineralization processes are formed, and the toxic impact of landfill leachate is weakened, as evidenced by the increase in bacterial populations in autumn.

The total abundance of micromycetes did not follow patterns similar to those observed for bacteria. In summer at Landfill 1, the number of micromycetes at different distances increased from 3.1 to 49.8×10^3 CFU g⁻¹ soil, whereas in autumn it decreased from 50.3 to 10.0×10^3 CFU g⁻¹ soil. At Landfill 2, during summer, micromycete abundance decreased from 14.4 to 7.5×10^3 CFU g⁻¹ soil, while in autumn it increased sharply from 3.2 to 72.5×10^3 CFU g⁻¹ soil (Figure 3).

A sharp 16.2-fold increase in micromycete abundance in autumn at Landfill 1 at a distance of 5 m indicates an increasing proportion of recalcitrant organic matter in the available fraction (as a result of weathering and partial decomposition), which stimulates fungal development, as fungi are more capable of degrading complex polymers such as lignin, cellulose, and polymeric components of waste.

It is precisely in autumn, under conditions of increased moisture and moderate temperature, that the development of most saprotrophic fungi is activated. In addition, certain fungal taxa exhibit high tolerance or the ability to degrade toxic organic compounds (e.g., polycyclic hydrocarbons) and may dominate in contaminated sites.

At Landfill 2, their proportion increased fivefold compared to summer (Figure 4).

In autumn, the number of micromycetes decreased from 5 m to 15 m at Landfill 1, whereas at Landfills 2 and 3 it increased with distance. The autumnal increase in micromycete abundance may also indicate their adaptation to xenobiotics, as well as enhanced degradation of complex organic compounds and toxicants.

The abundance of nitrogen-fixing microorganisms at distances of 5, 10, and 15 m showed a clear increasing trend in autumn at all landfills, and in summer at Landfill 2.

The highest abundance of nitrogen-fixing microorganisms was recorded at Landfills 3 and 4 in autumn at distances of 10 and 15 m and amounted to 13.8 – 24.2×10^5 CFU g⁻¹ soil (Figure 5).

An increase in their abundance at a distance of 15 m indicates the activation of biological nitrogen fixation processes, the formation of compensatory mechanisms in disturbed soils, and recovery processes in the soil cenosis, such as a reduction in the content of heavy metals or organic toxicants. In contrast, their low abundance at a distance of approximately 5 m indicates substantial soil contamination.

A sharp decrease in oligotrophic microorganisms in summer at Landfill 2 at distances of 10–15 m indicates a reduction in the toxic pressure of xenobiotics (Table 1). In autumn, at most landfills, the oligotrophic coefficient significantly decreased, especially at a distance of 15 m. Thus, a gradual adaptation of the microbiota to stressful conditions occurs, accompanied by the accumulation of organic substrates and activation of copiotrophic microflora. At

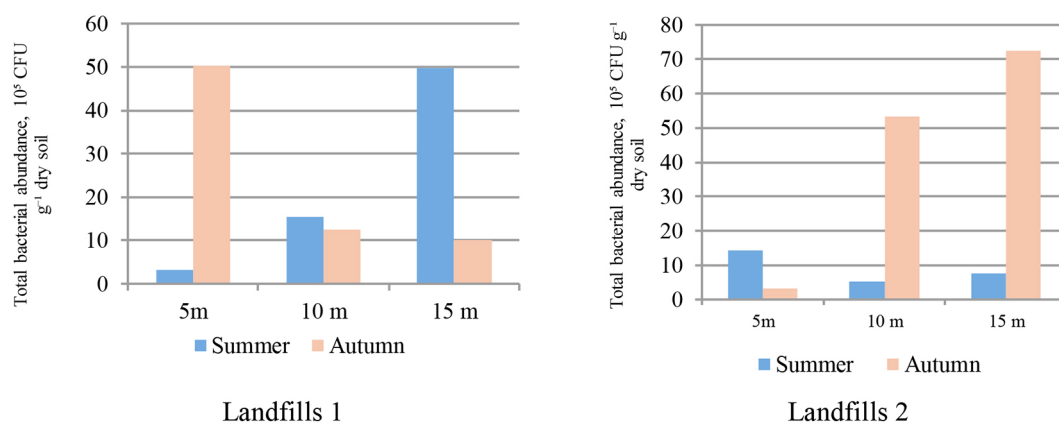


Figure 3. Dynamics of total micromycete abundance (summer–autumn) at MSW landfills

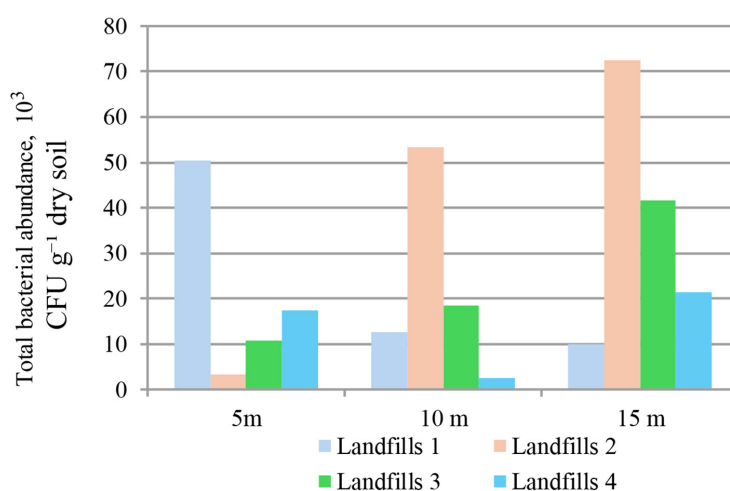


Figure 4. Total micromycete abundance in autumn at MSW landfills

Landfills 3 and 4, these values reached 0.69–1.30, which may be associated with specific waste fractions and leachates formed during the summer–autumn period.

Although the concentrations of heavy metals Pb^{2+} , Cd^{2+} , Cu^{2+} , and Zn^{2+} in the soils of the studied landfills did not exceed the established maximum permissible concentrations, their presence even at relatively low levels may have a biologically significant impact on soil microbial communities. It is well known that soil microorganisms are among the most sensitive bioindicators of chemical loading, and heavy metal ions are capable of interacting with cellular membranes and enzymatic systems of bacteria, disrupting metabolic processes even at subtoxic levels.

It should be noted that the quantitative content of heavy metals in MSW landfill soils is subject to seasonal variation within a fairly wide range. For example, the maximum exceedance

of permissible lead concentrations is observed in autumn and spring. It was also established that within a distance of up to 500 m from the dumpsite, the concentrations of heavy metals and metalloids in the investigated areas did not exceed the maximum permissible concentrations ($Pb^{2+} \leq 20 \mu g L^{-1}$; $Ni^{2+} \leq 40 \mu g L^{-1}$; $Cr^{2+} \leq 100 \mu g L^{-1}$; $Cu^{2+} \leq 100 \mu g L^{-1}$; and $As^{2+} \leq 20 \mu g L^{-1}$) (Baziene et al., 2020).

The pedotrophic coefficient in the summer period was low (0.12–0.24) at both landfills, indicating the dominance of mineralization processes in soils. In autumn, a sharp increase in this indicator was recorded (at Landfill 1 up to 0.82 at a distance of 5 m, at Landfill 2 up to 0.66 at 10 m, and at Landfill 4 up to 0.41 at 15 m). Thus, a gradual stabilization of microbial communities and an intensification of soil-forming processes are observed.

Analysis of the main morphotypes of soil bacteria and fungi under different levels of

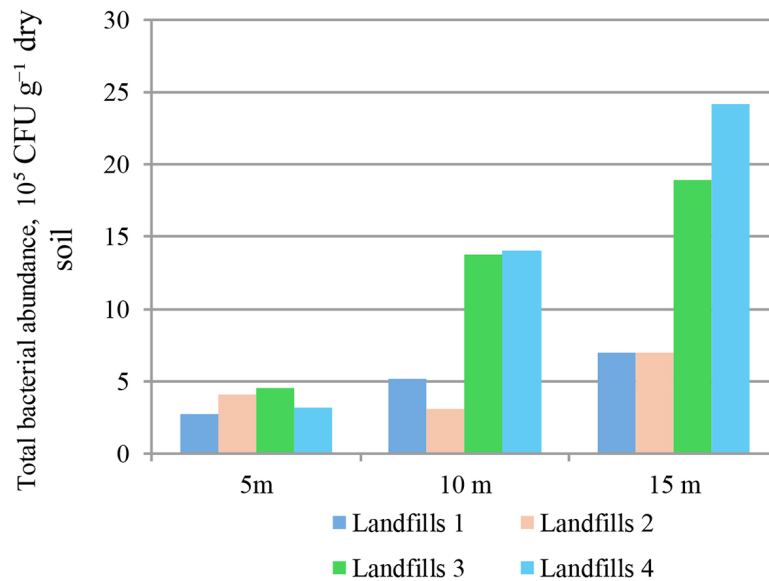


Figure 5. Total abundance of nitrogen-fixing bacteria in autumn at MSW landfills

technogenic pressure showed that in soils of all landfills and during all seasons, colonies morphologically characteristic of the genus *Pseudomonas* dominated: smooth, glossy, semi-transparent or light-yellow, medium-sized, sometimes pigmented (Table 2, Figure 6). It is known that many representatives of this genus exhibit high adaptability to xenobiotics and toxicants, degrade persistent xenobiotic compounds, possess the ability to degrade organic pollutants, and participate in biological antagonism (production of antibiotics and siderophores) (Lin et al., 2023).

The detection of *Pseudomonas aeruginosa* (Landfill 4, autumn, 10 m) indicates a sanitary–microbiological risk and increased anthropogenic pressure.

In biologically contaminated soils, pathogens of infectious diseases may be present, and natural self-purification processes are sharply weakened, which should be taken into account when disposing of waste at MSW landfills (Steffan et al., 2020). In addition, bacteria of the genus *Bacillus* were dominant morphotypes in most experimental variants; many representatives of this genus exhibit antagonistic properties, and their ability to form spores is an important indicator of microbial cenosis stability.

At the same time, the presence of *Bacillus mycoides* in soil in autumn (Landfill 1–10 and 15 m; Landfill 2–5 m; Landfill 4–15 m) is noteworthy, as this species is characteristic of soils

with elevated contents of toxic substrates. A significant abundance of antagonists, both among bacteria and fungi, was observed across different experimental variants (Figure 7).

The presence of *Bacillus mycoides* with atypical rhizoid, branched growth was detected in the soil of Landfill 1 at a distance of 5 m. It is known that strong selective pressure exerted by toxicants can induce the formation of mutant forms with altered morphological characteristics (Di Franco et al., 2002).

Among bacteria, micrococci also dominated in the experimental variants, and in the soil of Landfill 4 at a distance of 15 m, *Micrococcus luteus* was detected, the presence of which may indicate increased soil aeration.

The development of fungi of the genus *Penicillium* in soils may indicate processes of active toxicant degradation (He et al., 2023). In most soil samples, yeasts of the genus *Rhotorula* were identified, which are typical for soils with anthropogenic contamination due to their tolerance and ability to accumulate various heavy metal ions, contributing to soil remediation from heavy metal pollution (Krupieci, 2014; Deng et al., 2025).

Thus, the ecological–trophic structure of the microbial cenosis is a sensitive bioindicator of technogenic pressure, and microbiological parameters can be effectively used to assess the ecological state of soils within the impact zone of MSW landfills.

Table 2. Characteristics of cultivated ecological–trophic groups of soil microorganisms in the impact zone of municipal solid waste (MSW) landfills, 2024

Distance	Bacteria (MPA) 10 ⁵	Fungi (Sabouraud) 10 ³	Nitrogen-fixing microorganisms (Ashby) 10 ⁵	Oligotrophs (Starvation agar (SA)) 10 ⁵	Pedotrophs (Soil agar (SoA)) 10 ⁴
Summer (1 Landfill)					
5 m	Mainly bacteria the genus <i>Pseudomonas</i> , bacteria with atypical rhizoid growth, colonies bacteria light and bright yellow-colored	Yeasts, small slow-growing colonies fungi with grey concentric mycelium	Colonies medium-sized light semi-transparent, light-brown, medium-sized colonies	Small fine transparent colonies	Semi-transparent small colonies, colonies medium-sized
10 m	Dominated by colonies the genus <i>Pseudomonas</i> , are medium-sized light yellow bacteria, antagonists are present	There are yeasts pink, dominates fungus, light brown mycelium	Semi-transparent small colonies bacteria, typical for the genus <i>Azotobacter</i>	Small fine transparent colonies	Semi-transparent small colonies
15 m	Dominated by colonies of the genus <i>Pseudomonas</i> , are colony bacteria with atypical rhizoid growth, antagonists are present	Dominated by 32 colonies yeasts pink, are fungi the genus <i>Penicillium</i> , antagonists are present	Dominated by microcolonies light-pink colored	Dominated by colonies fungi small size with thin mycelium light colored	There are fungi the genus <i>Aspergillus</i> , are white pigmented microcolonies
Summer (2 Landfill)					
5 m	Dominated by bacteria of the genus <i>Pseudomonas</i> , are observed micrococci, antagonists are present	There are fungi the genus <i>Penicillium</i> , the genus <i>Aspergillus</i> , with light mycelium	Semi-transparent large colonies bacteria, typical for the genus <i>Azotobacter</i>	Small fine transparent colonies	White pigmented microcolonies
10 m	There are colonies the genus <i>Pseudomonas</i> , micrococci, colonies bacteria yellow colored	Several colonies yeasts	Light semi-transparent large colonies bacteria	White pigmented microcolonies	White pigmented microcolonies, semi-transparent small colonies, light mycelium fungi
15 m	There are colonies the genus <i>Pseudomonas</i> , the genus <i>Bacillus</i> , micrococci, antagonists are present	Several colonies yeasts, colonies bacteria yellow colored	Light semi-transparent large colonies, fine transparent or white colonies bacteria	White pigmented microcolonies	White pigmented microcolonies
Autumn (1 Landfill)					
5 m	Dominated by bacteria of the genus <i>Bacillus</i> and the genus <i>Pseudomonas</i> , atypical rhizoid growth bacteria, bacteria light-yellow colored, antagonists are present	There are yeasts pink, dominates fungus, light cream mycelium	Semi-transparent large colony bacteria, typical for the genus <i>Azotobacter</i>	Semi-transparent large colony, several small colonies	Semi-transparent small colonies, bacteria the genus <i>Pseudomonas</i>
10 m	Dominated by bacteria of the genus <i>Pseudomonas</i> , <i>Bacillus</i> , are observed <i>Bacillus mycoides</i>	Fungi with white mycelium, large colonies, with grey mycelium, small colonies, antagonists are present	Semi-transparent large colony bacteria, typical for the genus <i>Azotobacter</i> , small colonies bacteria cream colored	A large number of fine transparent microcolonies	White pigmented microcolonies, semi-transparent small colonies, bacteria the genus <i>Pseudomonas</i>

15 m	Bacteria dominate the genus <i>Bacillus</i> , are observed <i>Bacillus mycoides</i> , micrococci, bacteria yellow colored small, antagonists are present	There are yeasts pink, fungi genera <i>Penicillium</i> , <i>Aspergillus</i>	Light semi-transparent small colonies, typical for the genus <i>Azotobacter</i> , white pigmented microcolonies, small pink colony with dark brown pigment	Small fine transparent colonies	White pigmented microcolonies, semi-transparent small colonies, micromycete with light mycelium, bacteria the genus <i>Pseudomonas</i>
Autumn (2 Landfill)					
5 m	Bacteria dominate <i>Bacillus mycoides</i> atypical branching, are bacteria the genus <i>Bacillus</i> , antagonists are present	A small number of yeasts pink, fungi the genus <i>Penicillium</i>	Light semi-transparent large colonies	A small number of white pigmented microcolonies	White pigmented microcolonies, semi-transparent small colonies
10 m	Bacteria dominate predominantly the genus <i>Pseudomonas</i> , are bacteria the genus <i>Bacillus</i> , bacteria light-yellow colored	There are yeasts pink, fungi with mycelium white colored, fungi the genus <i>Aspergillus</i>	1 light colony large size, characteristic for <i>Azotobacter</i>	A small number of white pigmented microcolonies	Semi-transparent small colonies, colonies medium-sized, white pigmented microcolonies
15 m	Many bacteria the genus <i>Bacillus</i> , the genus <i>Pseudomonas</i> and micrococci, are light- and dark-yellow colonies bacteria	Dominated by light-colored fungi the genus <i>Penicillium</i> , are fungi the genus <i>Fusarium</i> , are fungi with light white mycelium, antagonists are present	Light colony large size, characteristic for <i>Azotobacter</i> , Light semi-transparent small colonies bacteria	Semi-transparent large colony, white pigmented colony, microcolonies semi-transparent, microbacteria light-yellow colored, fungus with dark reverse side	Small transparent colonies, bacteria the genus <i>Pseudomonas</i> ,
Autumn (3 Landfill)					
5 m	Bacteria dominate predominantly the genus <i>Pseudomonas</i> , are bacteria the genus <i>Bacillus</i>	Dominated by fungi of the genus <i>Penicillium</i> , the genus <i>Mucor</i> , are dark-colored colonies fungi, antagonists are present	Several light-brown colonies medium-sized, characteristic for <i>Azotobacter</i> , small round colonies cream colored, bacteria, which produce dark-brown pigment	Semi-transparent large colony	White pigmented microcolonies, semi-transparent small colonies, small (small number of)
10 m	Dominated by predominantly the genus <i>Pseudomonas</i> , are bacteria the genus <i>Bacillus</i>	Dominated by fungi of the genus <i>Mucor</i>	Several light colonies medium-sized, characteristic for <i>Azotobacter</i> , cream and semi-transparent small colonies bacteria	Semi-transparent large colony bacteria, microcolonies semi-transparent	White pigmented microcolonies, semi-transparent small colonies, small colonies fungi light colored
15 m	Bacteria dominate the genus <i>Bacillus</i> , micrococci, are bacteria the genus <i>Pseudomonas</i>	Very many morphotypes: mainly fungi the genus <i>Aspergillus</i> with mustard colored mycelium, fungi with light pigmented mycelium, fungi the genus <i>Penicillium</i> with light mycelium, antagonists are present,	Several light and light-brown colonies medium-sized, characteristic of <i>Azotobacter</i> , semi-transparent small colonies bacteria, cream small colonies bacteria	A large number of small transparent glossy colonies, several small semi-transparent colonies bacteria, white pigmented microcolonies	Semi-transparent small colonies, colonies medium-sized, white pigmented microcolonies
Autumn (4 Landfill)					
5 m	Mainly bacteria the genus <i>Bacillus</i> , <i>Pseudomonas</i>	Mainly fungi the genus <i>Penicillium</i> with light grey mycelium, the genus <i>Aspergillus</i> with pink brown mycelium	1 light colony medium-sized, characteristic for <i>Azotobacter</i> , small round colony cream colored	Several microcolonies light-grey colored, 1 transparent small glossy colony	semi-transparent small colonies, There are fungi the genus <i>Aspergillus</i>

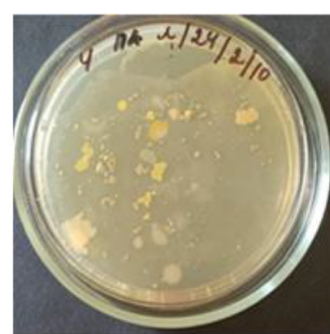
10 m	Bacteria dominate medium-sized genera <i>Bacillus</i> , <i>Pseudomonas</i> , <i>Pseudomonas aeruginosa</i> – <i>Pseudomonas aeruginosa</i>	Mainly fungi the genus <i>Aspergillus</i> , fungi with light pigmented mycelium, antagonists are present	Colonies medium-sized cream, white, semi-transparent,	Small transparent glossy colonies	White, pink microcolonies, bacteria the genus <i>Pseudomonas</i> ,
15 m	90% micrococci; are bacteria the genus <i>Pseudomonas</i> , are yellow colored small, <i>Bacillus mycoides</i>	Mainly fungi the genus <i>Aspergillus</i> with mustard colored mycelium, fungi with light pigmented mycelium	Colonies medium-sized cream, white, semi-transparent, colonies light-brown medium-sized, characteristic for <i>Azotobacter</i> , small yellow bacteria <i>Micrococcus luteus</i>	Small transparent glossy colonies	Fungal colonies are observed, glossy bacterial colonies, small and medium, light, white



Summer 24/1/15, nitrogen-fixing microorganisms



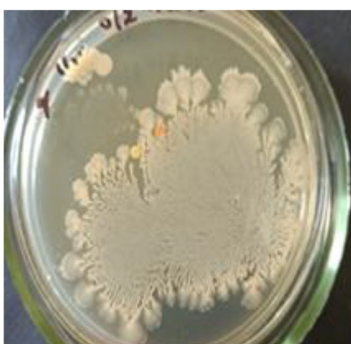
Summer 24/2/5, fungi



Summer 24/2/10, bacteria



Summer 24/1/15, fungi



Autumn 24/2/5, bacteria



Autumn 24/2/10, fungi



Autumn 24/4/5, fungi



Autumn 24/3/15, fungi



Autumn 24/4/15, bacteria

Figure 6. Main morphotypes of soil bacteria and fungi under different levels of technogenic pressure



Summer 24/1/15, bacteria



Autumn 24/1/15, fungi



Summer 24/1/10, fungi



Autumn 24/4/10, fungi

Figure 7. Antagonistic microorganisms of the studied soils

CONCLUSIONS

Soils within the sanitary protection zones of MSW landfills are characterized by high microbiological activity and a substantial restructuring of the ecological–trophic structure of the microbial cenosis. Quantitative and qualitative parameters of soil microorganisms largely depend on the distance from the landfill, seasonal conditions, and the composition of municipal solid waste.

Soils within the sanitary protection zones of municipal solid waste landfills exhibit increased microbiological activity and significant transformation of the ecological–trophic structure of the microbial cenosis. The quantitative and qualitative characteristics of soil microorganisms are largely determined by the distance from the landfill, seasonal conditions, and the morphological composition of municipal solid waste, which forms a specific set of organic and inorganic substrates in adjacent soils.

The presence of a substantial proportion of organic waste, paper, cardboard, wood, and textiles in MSW contributes to the input of readily available forms of organic carbon into the soil, which stimulates the development of copiotrophic bacteria and the intensification of mineralization processes.

At the same time, the presence of plastics, polyethylene, rubber materials, and metals (iron) in waste does not provide a direct input of nutrients; however, it indirectly affects soil microbiota through leachate formation, changes in the physicochemical properties of soils (pH, redox potential, electrical conductivity), and the input of heavy metal ions and other xenobiotics.

Seasonality further modulates these processes: in the autumn period, under conditions of increased moisture and accumulation of decomposition products of organic MSW fractions, microbial activity intensifies and the trophic structure shifts toward copiotrophic microorganisms, while

the proportion of oligotrophs decreases. Thus, the spatial–seasonal dynamics of microbiological indicators in soils of sanitary protection zones of MSW landfills result from the combined effects of waste composition, leachate formation processes, and abiotic environmental conditions.

An increase in the abundance of ecological–trophic groups of microorganisms at a distance of 15 m indicates the intensification of biological nitrogen fixation processes, activation of compensatory and recovery mechanisms in disturbed soils, and gradual stabilization of the soil cenosis, which may be associated with a decrease in heavy metal and toxicant content. Conversely, their low abundance in soils at a distance of approximately 5 m indicates a high level of technogenic contamination and suppression of soil biological activity.

The dominance of ecologically plastic bacteria (genera *Pseudomonas* and *Bacillus*), which possess mechanisms for the degradation of persistent xenobiotics and act as antagonists to many phytopathogens, as well as a diversity of micro-mycete decomposers (genera *Penicillium* and *Aspergillus*), was established.

An increase in the biodiversity of microbial morphotypes in the autumn period was revealed, which may indicate intensification of decomposition processes and adaptation of fungi and bacteria to the selective pressure of pollutants.

Analysis of the vegetation cover of the studied area indicates a profound transformation of phytocenoses under the influence of prolonged anthropogenic and pyrogenic pressure. Vegetation is predominantly ruderal in character and is characterized by a simplified species structure, low biodiversity, and dominance of species tolerant to pollution, mechanical soil disturbance, and chemical toxification. Such a structure is typical of areas with uncontrolled accumulation of household and construction waste and periodic thermal impacts.

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