Proceedings of the 13th International Scientific Conference

ENVIRONMENTAL ENGINEERING

April 23–24, 2026, Vilnius, LITHUANIA

eISSN 2029-7092
eISBN 978-609-476-444-8
Article ID: enviro.2026.2281
https://doi.org/10.3846/enviro.2026.2281

POST-RECLAMATION CHANGES IN RADIATION DOSE EQUIVALENT RATE AND LEACHATE PROPERTIES: A CASE STUDY OF THE LVIV MUNICIPAL LANDFILL

Abderrahim BOUYNK[1*], Aušra MAŽEIKIENĖ[2], Kateryna STEPOVA[3], Oleksandra ZHORINA[4], Tetiana SKYBA[5], Iryna FEDIV[6]

[1,2]Department of Environmental Protection Technology and Management, Environmental Engineering Faculty, Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania
[3,4,5,6]Department of Environmental Safety, Lviv State University of Life Safety, 35 Kleparivska str., 79000 Lviv, Ukraine

Received 15 January 2026; revised 29 January 2026; accepted 24 February 2026

Abstract. Reclamation of municipal solid waste landfills is a critical environmental measure aimed at reducing radiological and hydrochemical risks associated with long-term waste disposal. This study evaluates post-reclamation changes in radiation dose equivalent rates and the physicochemical characteristics of raw landfill leachate at the Lviv Municipal Landfill (Ukraine), one of the most environmentally hazardous waste disposal sites in the region. Ambient equivalent dose rates were measured in 2025 at the landfill summit and along the main cardinal directions and compared with pre-reclamation data from 2012. The results indicate a substantial decrease in equivalent dose rate following reclamation measures, with current values ranging from 0.089 to 0.101 μSv/h, remaining well below the regulatory limit of 0.3 μSv/h and significantly lower than pre-reclamation levels of 0.41–0.42 μSv/h. At the same time, pronounced spatial heterogeneity of radiation levels persists, with the highest values recorded in the western sector of the landfill. In parallel, the chemical composition of raw landfill leachate collected from a dedicated leachate accumulation pond was analyzed. This pond receives leachate generated by drainage from the waste body and serves as temporary storage prior to treatment by an on-site reverse osmosis system implemented as part of the landfill reclamation project. The leachate is characterized by extremely high concentrations of ammonium nitrogen (3844 mg/l), chemical oxygen demand (8960 mg O_2/l), chlorides (4000 mg/l), phosphates (88 mg/l), and total dissolved solids (14,625 mg/l), indicating severe organic and mineral contamination typical of mature landfill leachate. The results demonstrate that, despite the effectiveness of reclamation measures in mitigating radiological hazards, the generation of highly concentrated raw leachate remains a significant environmental challenge. The chemical composition of the leachate clearly confirms the necessity of its advanced treatment, which provides a scientific justification for the implementation of a reverse osmosis-based leachate treatment system at the landfill. The findings emphasize the importance of continuous monitoring of both radiation dose equivalent rate and leachate quality to ensure long-term environmental safety during and after landfill reclamation.

Keywords: landfill, leachate, pollution, equivalent dose rate, reclamation.

1. Introduction

Landfilling remains one of the most widely used methods for Municipal Solid Waste (MSW) disposal worldwide, particularly in regions where waste sorting and recycling infrastructures are still under development. One of the most critical environmental challenges associated with landfills is the generation of landfill leachate, defined as liquid wastewater formed either by the intrinsic moisture of waste or by the percolation of precipitation through waste layers (Laner et al., 2012). In many cases, especially at older or inadequately engineered landfills, leachate collection and treatment systems are insufficient, resulting in the release of contaminated effluents into surrounding soil, surface water, and groundwater systems. Such contamination poses serious risks to ecosystems and human health, including carcinogenic and genotoxic effects (Ma et al., 2022; Huang et al., 2024).

The chemical composition of landfill leachate is highly variable and depends on multiple factors, including landfill age, waste composition, landfilling technology, design features, and local climatic and hydrogeological conditions (Al-Yaqout & Hamoda, 2020). Among these factors, landfill age has been identified as a key

* Corresponding author. E-mail: *abderrahim.bouynk@vilniustech.lt*

determinant influencing leachate characteristics, particularly the transition from readily biodegradable organic matter to more persistent and refractory compounds such as humic and fulvic acids (Luo et al., 2020; Khan & Vohra, 2025). As a result, older landfills often generate leachate with high Chemical Oxygen Demand (COD), elevated ammonium concentrations, and reduced biodegradability, significantly complicating treatment processes.

In addition to chemical pollution, landfills may represent a source of radiological risk due to the uncontrolled disposal of materials containing Naturally Occurring Radioactive Materials (NORM), industrial by-products, medical waste, or radioactive consumer goods. Although municipal landfills are not typically designed for radioactive waste management, the accumulation of such materials over long operational periods can lead to elevated equivalent dose rates. These risks are further exacerbated by landfill fires, waste decomposition, and gas migration, which may redistribute radionuclides within the landfill body and into surrounding environmental compartments. Therefore, systematic monitoring of the equivalent dose rate at landfill sites is an essential but often underestimated component of environmental safety assessments, particularly during and after landfill reclamation.

Despite advances in waste management policies, landfill-related environmental impacts remain significant. The EU Landfill Directive 1999/31/EC (Council of the European Union, 1999) establishes strict requirements for landfill operation, including engineered liners, leachate collection systems, and final sealing. Although the volume of waste disposed of in landfills across the European Union decreased by nearly 28% between 2010 and 2020, and landfill management practices have improved overall, effective control of leachate pollution and long-term radiological safety continues to pose substantial challenges.

Currently, landfill leachate treatment relies on combinations of biological, physico-chemical, and membrane-based technologies. Biological treatment processes are economically attractive due to their relatively low cost, high throughput, and energy efficiency; however, they are often unstable and difficult to control when treating mature leachates with low biodegradability (Ji et al., 2021). Physico-chemical methods may be effective for specific contaminants but frequently demonstrate limited efficiency in reducing COD and ammonia in aged leachate. Consequently, no single universal treatment strategy exists, and multi-stage, site-specific treatment schemes are typically required (Renou et al., 2008; Yu et al., 2022).

In recent years, membrane-based technologies, particularly Membrane Bioreactors (MBRs), have gained increasing attention as alternatives to conventional activated sludge processes. By integrating biological degradation with membrane filtration, MBRs provide improved effluent quality, higher biomass retention, and a reduced spatial footprint (Ahmed & Lan, 2012). Nevertheless, membrane fouling, operational complexity, and sensitivity to variations in leachate composition remain critical issues requiring further research, especially under post-reclamation conditions.

These challenges are particularly relevant for regions with a high dependence on landfilling. In western Ukraine, the Lviv region generates more than 2 million tonnes of non-hazardous waste annually, most of which remains unsorted. The waste stream is dominated by biodegradable organic fractions (approximately 44%), followed by plastics (15%), glass (11%), and paper/cardboard (10%), creating favorable conditions for intensive leachate formation and long-term pollutant accumulation (Ministry of Health of Ukraine, 1988).

The Lviv municipal solid waste landfill operated by the municipal enterprise "Zbyranka" represents an example of a long-term environmental hotspot. Prior to reclamation, the landfill accumulated approximately 9 million tonnes of waste and untreated leachate, resulting in severe soil and water contamination, recurrent landfill fires, and elevated equivalent dose rates reaching 0.41–0.42 μSv/h. These conditions led to the closure of the landfill and the initiation of a comprehensive reclamation program, including leachate treatment, landfill gas collection, and technical and biological remediation measures. Since 2022, a biogas plant has been operating at the site, contributing to methane recovery, odor reduction, and fire prevention.

In this context, post-reclamation monitoring of both leachate properties and equivalent dose rate is of critical importance. While reclamation measures are primarily aimed at reducing chemical pollution and stabilizing the landfill body, their effectiveness in mitigating radiological risks remains insufficiently studied. Comprehensive assessment of equivalent dose rate dynamics alongside changes in leachate composition provides a more complete understanding of the environmental recovery of reclaimed landfill sites and supports evidence-based decision-making for long-term environmental monitoring and risk management.

Accordingly, this study aims to evaluate post-reclamation changes in equivalent dose rate and landfill leachate properties at the Lviv municipal landfill, offering an integrated assessment of chemical and radiological factors that influence environmental safety following landfill closure and reclamation.

2. Methodology

2.1. Radiation dose equivalent rate monitoring

Measurements of the ambient dose equivalent rate (μSv/h) were conducted at the landfill site and within adjacent ecosystems. Field measurements were performed using a GAMMA-SCOUT STANDARD dosimeter-radiometer, which complies with the U.S. standard FCC 15 and is capable of detecting α-, β-, and γ-radiation. To verify measurement reliability, parallel measurements were carried out using a MKS-05 TERRA-P dosimeter–radiometer. The close agreement between the two instruments confirmed the high accuracy and reproducibility of the obtained data.

Radiation measurements at the landfill were performed using the envelope (transect) method, with control points located on all four cardinal directions (north, south, east, and west) relative to the landfill body. Measurements were repeated 5–10 times at each point. For comparative purposes, additional measurements were conducted at a background reference site, defined as a clean area located at a distance of no less than 1 km from landfill-related or other anthropogenic sources, ensuring minimal human impact.

2.2. Determination of radionuclide activity in environmental samples

The activity of beta-emitting radionuclides in soil and plant samples was determined using a SEB-01 beta radiation spectrometer (serial No. 12602; calibration certificate UA01 No. 179, dated 08.02.2023). Measurements were performed in accordance with the methodology MI 12-08-99 "Activity of radionuclides ^{90}Sr and ^{90}Y in counting samples obtained by radionuclide separation", approved by the State Standard of Ukraine.

Gamma-emitting radionuclide activity in soil and vegetation samples was analyzed using a SEG-001 "AKP-S" gamma spectrometer (serial No. 16-2000; calibration certificate UA01 No. 178, dated 08.02.2023). Measurements followed the certified procedure "Measurement methodology using scintillation gamma-ray energy spectrometers with AkWin software" (Certificate of attestation MVI No. 07-119:2011), approved by the National Scientific Center "Institute of Metrology".

2.3. Sample preparation and mineralization

Mechanical processing and preparation of soil and plant samples for subsequent analyses were performed in accordance with DSTU ISO 11464:2007 (Soil quality – Pretreatment of samples for physico-chemical analysis) (State Enterprise of Ukraine, 2007).

Mineralization (ashing) of soil and vegetation samples was conducted at the Research Laboratory of Environmental Safety of Lviv State University of Life Safety following DSTU 7670:2014 (Raw materials and food products – sample preparation. Mineralization for the determination of toxic elements) (State Research and Design Institute "Konservpromcomplex", 2014). This procedure ensured complete decomposition of organic matter and accurate determination of radionuclide and heavy metal contents.

3. Results

3.1. Radiation dose equivalent rates

The results demonstrate a statistically significant reduction in ambient equivalent dose rate at the Lviv municipal landfill following reclamation. In 2012, all monitoring locations exhibited radiation levels exceeding both local (0.08 μSv/h) and regional background values (0.085 μSv/h), with pronounced spatial heterogeneity and maximum dose rates observed in the southern and northern sectors of the landfill. Such variability may be attributed to heterogeneous waste composition, historical disposal of materials containing naturally occurring radioactive substances, and repeated landfill fires that likely contributed to radionuclide redistribution.

In contrast, post-reclamation measurements conducted in 2025 revealed a substantial decrease in equivalent dose rate across all sectors, with mean values approaching natural background levels. The most pronounced reductions (up to 68%) were recorded in areas previously characterized by elevated radiation exposure. Statistical analysis confirmed the significance of these changes (Wilcoxon signed-rank test, $p = 0.031$), indicating effective stabilization of radiological conditions as a result of reclamation measures, including waste isolation, surface sealing, and landfill gas management. Table 1 shows the ambient equivalent dose rates at the Lviv municipal landfill before and after reclamation.

Table 1. Ambient equivalent dose rates at the Lviv municipal landfill before and after reclamation

Location	2012 (Mean±SD), μSv/h	2025 (Mean±SD), μSv/h	Change (%)
West	0.145 ± 0.049	0.100 ± 0.001	−30.3
East	0.130 ± 0.014	0.090 ± 0.003	−30.8
South	0.275 ± 0.106	0.089 ± 0.004	−67.6
North	0.245 ± 0.092	0.098 ± 0.001	−60.0
Summit	0.225 ± 0.078	0.097 ± 0.001	−56.9

Note: Background radiation level = 0.085 μSv/h; local reference level = 0.08 μSv/h.

Figure 1 shows comparison of ambient equivalent dose rates (μSv/h) measured at different sectors of the Lviv municipal landfill in 2012 (pre-reclamation) and 2025 (post-reclamation).

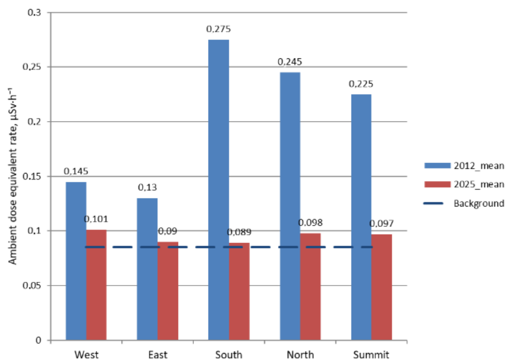


Figure 1. Comparison of ambient equivalent dose rates (μSv/h) measured at different sectors of the Lviv municipal landfill in 2012 (pre-reclamation) and 2025 (post-reclamation). The dashed line indicates the regional radiation dose equivalent rate (0.085 μSv/h)

Spatial analysis revealed a clear reduction and homogenization of equivalent dose rate following landfill reclamation. In 2012, elevated dose rates were unevenly distributed, with maximum values recorded in the southern and northern sectors as well as at the landfill summit. In contrast, post-reclamation measurements in 2025 demonstrated consistently lower and more uniform radiation levels across all monitoring points, approaching regional background values.

The equivalent dose rate measured at the Lviv municipal landfill are consistent with patterns reported for municipal solid waste landfills in Ukraine and other countries. In the pre-reclamation period (2012), mean ambient equivalent dose rates at the Lviv site (approximately 0.20 μSv/h averaged over four cardinal directions) were substantially higher than those reported for most stabilized Ukrainian landfills in recent years. For instance, a comprehensive survey of four municipal landfills in Western Ukraine reported average gamma radiation levels ranging from 0.100 to 0.119 μSv/h, while background areas did not exceed 0.080–0.105 μSv/h (Skyba & Popovych, 2025). Earlier monitoring campaigns summarized in the same study documented higher spatial variability and local maxima reaching 0.30–0.33 μSv/h, particularly at landfill summits and active zones, which is comparable to the elevated sectoral values observed at the Lviv landfill in 2012.

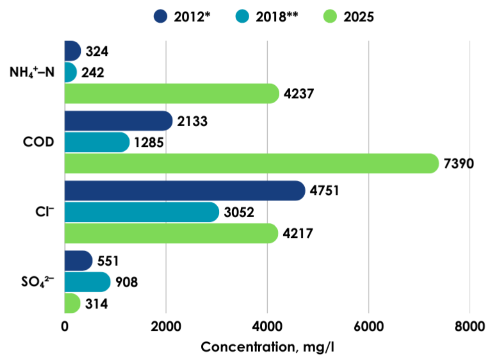
Following reclamation, equivalent dose rate at the Lviv landfill in 2025 (0.089–0.101 μSv/h, mean ≈ 0.094 μSv/h) became comparable to, or lower than, values reported for stabilized municipal landfills in Ukraine (Popovych et al. 2020). Similar ranges have been reported at European landfill sites. For example, a radiological characterization of the Lo Uttaro municipal landfill in southern Italy showed ambient equivalent dose rates between 0.079 and 0.268 μSv/h, with a mean value of approximately 0.16 μSv/h, reflecting substantially higher spatial heterogeneity than that currently observed at the reclaimed Lviv site (Ambrosino et al., 2020). Comparable external gamma radiation levels have also been reported for municipal landfill areas and surrounding environments in Turkey, where typical field values range from ~0.10 to 0.22 μSv/h, with local maxima reaching ~0.25 μSv/h (Taskin et al., 2009).

Overall, this comparison indicates that the post-reclamation equivalent dose rate at the Lviv municipal landfill lies in the lower part of the range reported for municipal landfills both in Ukraine and internationally, confirming the effectiveness of reclamation measures and highlighting the importance of long-term radiation monitoring as an integral component of environmental safety assessment at landfill sites.

3.2. Landfill leachate

The leachate composition at the Lviv municipal landfill demonstrates pronounced temporal variability associated with landfill aging and reclamation processes. During the pre-reclamation period (2012–2018), a gradual decrease in ammonium nitrogen and COD was observed, indicating partial stabilization of biodegradable organic matter. In contrast, post-reclamation measurements in 2025 revealed a sharp increase in ammonium nitrogen (up to 4237 mg/l) and COD (7390 mg/l), characteristic of mature landfill leachate dominated by refractory organic compounds. The relative stability of chloride concentrations confirms the conservative nature of this indicator, while the substantial decrease in sulfate concentrations suggests enhanced anaerobic conditions and sulfate-reducing processes within the reclaimed landfill body.

It should be noted that the observed increase in leachate contaminant concentrations after reclamation does not necessarily indicate an overall increase in pollutant loads. Following landfill reclamation, the installation of impermeable capping systems and surface sealing significantly reduces the infiltration of atmospheric precipitation into the waste body, leading to a decrease in the total volume of generated leachate. As a result, reduced dilution and concentration effects may occur, causing higher concentrations of dissolved organic and inorganic constituents in raw leachate, despite a lower overall leachate yield. Similar trends have been reported for reclaimed and capped municipal landfills, where leachate volumes decrease while concentrations of ammonium nitrogen, COD, and conservative ions remain high or even increase (Ma et al., 2022; Council of the European Union, 1999). Figure 2 illustrates temporal dynamics of leachate composition.



Notes: * Haidin et al., 2013; ** Grynchyshyn, 2019.

Figure 2. Temporal dynamics of leachate composition

The composition of landfill leachate at the Lviv municipal landfill shows both common features and pronounced deviations when compared with international datasets. According to a global review of municipal landfill leachates, typical concentrations of ammonium nitrogen range from 200 to 3000 mg/l, while COD values commonly vary between 2000 and 20,000 mg/l, depending on landfill age and operational conditions (Ma et al., 2022). In this context, the post-reclamation ammonium concentration observed at the Lviv landfill in 2025 (4237 mg/l) exceeds the upper range typically reported for stabilized landfills, indicating a highly concentrated and mature leachate. Similarly, the COD value of 7390 mg/l falls within the upper-middle range of global observations and confirms the dominance of refractory organic matter. Table 2 shows the comparison of landfill leachate composition with international ranges and regulatory limits.

Table 2. Comparison of landfill leachate composition with international ranges and regulatory limits

Parameter (mg/l)	2025	Typical international range (Ma et al., 2022)	EU / UA regulatory limits*
NH_4^+–N	4237	200–3000 (aged leachate may exceed 3000)	≤ 30–50 (discharge to surface waters)
COD	7390	2000–20,000	≤ 125 (EU UWWTD); ≤ 80–150 (UA)
Cl^-	4217	3000–10,000	≤ 250–350 (discharge to surface waters)
SO_4^{2-}	314	500–2000	≤ 250–500 (discharge to surface waters)

Note: * Regulatory limits: EU Urban Wastewater Treatment Directive 91/271/EEC (Council of the European Union, 1991); EU Water Framework Directive 2000/60/EC (European Parliament & Council of the European Union, 2000); Ukrainian sanitary and environmental discharge standards.

Chloride concentrations at the Lviv landfill (4217 mg/l in 2025) are consistent with values reported for aged landfill leachates worldwide, where chloride levels commonly exceed 3000 mg/l and may reach 10,000 mg/l due to their conservative behavior (Ma et al., 2022). In contrast, sulfate concentrations at the Lviv site (314 mg/l) are relatively low compared with typical international ranges (500–2000 mg/l), suggesting intensive sulfate reduction under anaerobic conditions within the reclaimed landfill body.

The comparison with international ranges and regulatory limits clearly demonstrates that the post-reclamation leachate from the Lviv municipal landfill remains highly concentrated and exceeds EU and Ukrainian discharge standards by one to two orders of magnitude, particularly for ammonium nitrogen and COD, necessitating advanced multi-stage treatment technologies.

4. Conclusions

This study assessed post-reclamation changes in radiation dose equivalent rate and landfill leachate composition at the Lviv municipal landfill based on long-term monitoring data collected before and after reclamation. The results demonstrate that reclamation measures were effective in significantly reducing ambient radiation levels and spatial heterogeneity across the landfill site. Average ambient equivalent dose rates decreased from elevated pre-reclamation values in 2012 (≈0.20 μSv/h) to near-background levels in 2025 (≈0.094 μSv/h), indicating a substantial improvement in radiological safety and alignment with values reported for stabilized municipal landfills in Ukraine and other European countries.

In contrast, the chemical composition of landfill leachate exhibited an opposite trend. Post-reclamation leachate in 2025 was characterized by extremely high concentrations of ammonium nitrogen and chemical oxygen demand, reaching 4237 mg/l and 7390 mg/l, respectively, which exceed typical regulatory discharge limits in the European Union and Ukraine by one to two orders of magnitude. These concentrations are indicative of a mature, highly mineralized leachate dominated by refractory organic compounds and intensive anaerobic processes within the reclaimed landfill body. The relative stability of chloride concentrations and the marked decrease in sulfate levels further support the prevalence of anaerobic conditions and sulfate-reducing processes after reclamation. At the same time, although leachate concentrations increased, the total volume of generated leachate is expected to decrease as a result of landfill reclamation, due to the isolation of the waste body from direct precipitation infiltration.

The combined analysis of radiation dose equivalent rate and leachate chemistry highlights that landfill reclamation effectively mitigates external environmental and radiological risks but does not necessarily reduce internal contaminant concentrations in leachate. Therefore, reclaimed landfills may remain significant sources of highly concentrated wastewater requiring advanced, multi-stage treatment technologies. The findings underline the importance of integrating long-term radiation monitoring with comprehensive leachate characterization as part of post-reclamation environmental control strategies. Such an integrated approach is essential for ensuring the sustainable management and environmental safety of reclaimed municipal solid waste landfills. (Federal Communications Commission, n.d.)

References

Ahmed, F. N., & Lan, C. Q. (2012). Treatment of landfill leachate using membrane bioreactors: A review. *Desalination*, *287*, 41–54. https://doi.org/10.1016/j.desal.2011.12.012

Al-Yaqout, A., & Hamoda, M. F. (2020). Long-term temporal variations in characteristics of leachates from a closed landfill in an Arid region. *Water*, *Air*, & *Soil Pollution*, *231*, Article 319. https://doi.org/10.1007/s11270-020-04688-7

Ambrosino, F., Stellano, L., & Sabbarese, C. (2020). A case study on possible radiological contamination in the Lo Uttaro landfill site (Caserta, Italy). *Journal of Physics*: *Conference Series*, *1548*, Article 012001. https://doi.org/10.1088/1742-6596/1548/1/012001

Council of the European Union. (1991). *Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment* (1991, May 21, No. 31991L0271). Official Journal of the European Communities. https://eur-lex.europa.eu/eli/dir/1991/271/oj/eng

Council of the European Union. (1999). *Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste* (1999, April 26, No. 31999L0031). Official Journal of the European Communities. https://eur-lex.europa.eu/eli/dir/1999/31/oj/eng

European Parliament & Council of the European Union. (2000). *Directive 2000/60/EC establishing a framework for Community action in the field of water policy* (2000, October 23, No. 32000L0060). Official Journal of the European Communities. https://eur-lex.europa.eu/eli/dir/2000/60/oj/eng

Federal Communications Commission. (n.d.). *47 CFR Part 15*: *Radio frequency devices*. eCFR. https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15

Grynchyshyn, N. M. (2019). Properties of leachate formed after the closure of a municipal solid waste landfill. *Bulletin of Lviv State University of Life Safety*, (19), 122–127. https://doi.org/10.32447/20784643.19.2019.14

Haidin, A. M., Diakiv, V. O., Pohrebennyk, V. D., & Pashuk, A. V. (2013). Chemical composition of leachate from the Lviv municipal solid waste landfill. *Pryroda Zakhidnoho Polissia ta prylehlykh terytorii [Nature of Western Polissya and adjacent territories]*, (10), 43–49.

Huang, Z., Liu, G., Zhang, Y., Yuan, Y., Xi, B., & Tan, W. (2024). Assessing the impacts and contamination potentials of landfill leachate on adjacent groundwater systems. *Science of the Total Environment*, *930*, Article 172664. https://doi.org/10.1016/j.scitotenv.2024.172664

Ji, Z., Tang, W., & Pei, Y. (2021). Constructed wetland substrates: A review on development, function mechanisms, and application in contaminants removal. *Chemosphere*, *286*, Article 131564. https://doi.org/10.1016/j.chemosphere.2021.131564

Khan, S., & Vohra, M. S. (2025, October 27–30). A critical review of landfill leachate and its treatment by electrochemical oxidation: A future energy-oriented approach for sustainable liquid waste treatment. In *Proceedings of the 14th International Conference on Renewable Energy Research and Applications* (*ICRERA*) (pp. 1222–1235). Vienna, Austria. IEEE. https://doi.org/10.1109/ICRERA66237.2025.11284037

Laner, D., Crest, M., Scharff, H., Morris, J. W. F., & Barlaz, M. A. (2012). A review of approaches for the long-term management of municipal solid waste landfills. *Waste Management*, *32*(3), 498–512. https://doi.org/10.1016/j.wasman.2011.11.010

Luo, H., Zeng, Y., Cheng, Y., He, D., & Pan, X. (2020). Recent advances in municipal landfill leachate: A review focusing on its characteristics, treatment, and toxicity assessment. *Science of the Total Environment*, *703*, Article 135468. https://doi.org/10.1016/j.scitotenv.2019.135468

Ma, S., Zhou, C., Pan, J., Yang, G., Sun, C., Liu, Y., Chen, X., & Zhao, Z. (2022). Leachate from municipal solid waste landfills in a global perspective: Characteristics, influential factors and environmental risks. *Journal of Cleaner Production*, *333*, Article 130234. https://doi.org/10.1016/j.jclepro.2021.130234

Ministry of Health of Ukraine. (1988). *Sanitary rules and norms for the protection of surface waters from pollution* (SanPiN No. 4630-88). https://zakononline.ua/documents/show/157524___528513

Popovych, V., Telak, J., Telak, O., Malovanyy, M., Yakovchuk, R. & Popovych, N. (2020). Migration of Hazardous components of municipal landfill leachates into the environment. *Journal of Ecological Engineering*, *21*(1), 52–62. https://doi.org/10.12911/22998993/113246

Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., & Moulin, P. (2008). Landfill leachate treatment: Review and opportunity. *Journal of Hazardous Materials*, *150*(3), 468–493. https://doi.org/10.1016/j.jhazmat.2007.09.077

Skyba, T., & Popovych, V. (2025). Radioecological analysis of landfill ecosystems in the Western Forest-Steppe (Ukraine). *IOP Conference Series*: *Earth and Environmental Science*, 1499, Article 012060. https://doi.org/10.1088/1755-1315/1499/1/012060

State Enterprise of Ukraine. (2007). *Iakist hruntu*. *Pidhotovka prob do fizyko-khimichnoho analizu* [Soil quality – Pretreatment of samples for physicochemical analysis] (DSTU ISO Standard No. 11464:2007). https://online.budstandart.com/ua/catalog/doc-page?id_doc=52911

State Research and Design Institute „Konservpromcomplex". (2014). *Syrovyna i produkti kharchovi*. *Pidhotovka prob*. *Mineralizatsiia dlia vyznachennia vmistul toksychnykh elementiv* [Raw materials and food products – Sample preparation. Mineralization for the determination of toxic elements] (DSTU Standard No. 7670:2014). https://online.budstandart.com/ru/catalog/doc-page?id_doc=85544

Taskin, H., Karavus, M., Ay, P., Topuzoglu, A., Hindiroglu, S., & Karahan, G. (2009). Radionuclide concentrations in landfill environments. *Journal of Environmental Radioactivity*, *100*(1), 49–53. https://doi.org/10.1016/j.jenvrad.2008.10.012

Yu, D., Pei, Y., Ji, Z., He, X., & Yao, Z. (2022). A review on the landfill leachate treatment technologies and application prospects of three-dimensional electrode technology. *Chemosphere*, *291*, Article 132895. https://doi.org/10.1016/j.chemosphere.2021.132895