RESEARCH ON URBAN WASTE LANDFILLS FOR THE PURPOSE OF IMPROVING THE QUALITY OF ENVIRONMENTAL COMPONENTS

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ABSTRACT: This article contains recent theoretical and experimental research on the design and construction methods of municipal waste landfills, with a focus on geomembrane liners, compacted clay liners, composite geosynthetics, leachate management, gas capture, and advanced monitoring. The aim is to evaluate how these technical solutions can improve the quality of environmental components, water, soil, and air, and to propose lines of work for sustainable design and operation. The results demonstrate that modern composite systems, together with active strategies, such as leachate recirculation, bioreactors, and IoT monitoring, significantly reduce the risk of contamination and increase energy recovery.

KEYWORDS: landfill, geomembrane, clay layer, bioreactor, IoT monitoring

1. INTRODUCTION

Sustainable management of municipal waste is one of the most important environmental challenges of the 21st century, with direct implications for soil, groundwater, air and human health. Landfills, although they constitute the inevitable final solution for a significant part of the urban waste stream, can become major sources of pollution if they are not designed and operated properly [1, 2]. Leachate, landfill gases (CH_4, CO_2, H_2S) and mechanical instability of the waste body can lead to contamination of natural resources and greenhouse gas emissions, affecting the balance of local and global ecosystems. The transition from uncontrolled landfills to mechanized landfills has reduced risks, but challenges persist due to the degradation of barrier materials, the generation of complex leachate and methane emissions. In this context, theoretical and experimental research on modern methods of landfill design and construction is gaining strategic importance.

Innovative approaches – such as waste-leachate bioreactors**,** Controlled leachate recirculation **,** optimized drainage, the use of composite geomembranes and the integration of sensors for real-time monitoring – allow the landfill to be transformed from a pollution source into a controlled biological conversion system [3]. Thus, the risk of contaminants infiltration into soil and groundwater is significantly reduced, and biological degradation processes are accelerated, shortening the stabilization time and

increasing the production of biogas that can be used for energy.
The importance of this research is emphasized by the need to align with European directives on the circular economy (EU 2018/851) and the reduction of greenhouse gas emissions (European Green Deal). In addition, by optimizing the design, a reduction in post-closure costs is ensured, a extension of the lifespan of the landfill cells and an increase in geotechnical safety [6, 7]**.** The research results thus contribute not only to environmental protection, but also to the substantiation of efficient public policies in the field of waste management. In conclusion, the in-depth study of the technologies and constructive principles applied to municipal landfills is not only a technical-scientific approach, but also an investment in the health of the environment and communities. By implementing these research-based solutions, landfills become integrated elements of the circular waste management system, actively contributing to the global objective of improving the quality of environmental components.

2. THEORETICAL FRAMEWORK

2.1 Insulation systems
In modern practice, landfills use composite systems: HDPE geomembranes, geosynthetics for drainage, and geosynthetic clay liners (GCLs) or compacted clay as a base. These layers provide redundancy and reduce leachate flow to the substrate. Recent literature confirms the high efficiency (>98% in some configurations) of well-designed and installed systems, although long-term performance depends on the quality of the installation and local hydraulic conditions. Among the containment systems that use modern materials and have recently achieved performance are:

- *GM-GCL-AL composites* (geomembrane - clayey geosynthetic - attenuation layer); recent studies show that triple-layer systems offer significantly improved control of pollutants, especially metals, soluble organic compounds and oxidants, compared to single or double ones. According to the “Review of the Anti-Pollution Performance of Triple-Layer GM/GCL/AL Composite Liners” (Membranes, 2022), these triple systems reduce the migration of toxic substances by combining physical barriers (geomembrane), adsorption properties (GCL) and biological/physical attenuation effects of the attenuation layer.
- *Local mixtures with modified clay / fly ash* : In "Exploring the geotechnical and microstructural properties of composite mixtures for landfill liner materials: an experimental investigation" (2024) mixtures of localized soil, bentonite, and fly ash in different proportions are studied, with tests of compressive strength, permeability, microstructure (SEM, XRD). The results suggest that the optimal proportions allow for low permeability, satisfactory mechanical strength, and increased adsorption capacity.

Defects in geomembranes can compromise their effectiveness, necessitating non-destructive testing and continuous monitoring. A key aspect is the effect of temperature on the compacted clay liner – exceeding the threshold of 45°C leads to cracking and increased permeability.

2.2 Active technologies

Bioreactors (leachate recirculation, humidity control) accelerate organic degradation and increase biogas production, facilitating energy recovery;

they also reduce long-term persistent emissions. A landfill bioreactor is a municipal waste landfill designed to accelerate biological processes (hydrolysis → acidogenesis → methanogenesis) by controlling humidity, temperature and leachate circulation. It has been found that the use of vertical wells and uniform leachate distribution are more effective for rapid organic degradation, VFA (volatile acid) reduction and biogas generation. Also, reactors with more frequent recirculation reduce the COD half-life significantly; stabilization is accelerated, internal temperature increases and gas generation begins earlier.

Clogging of the drainage layer or perforations can drastically reduce recirculation performance and increase internal pressure, affecting slope stability. Early detection of clogging areas can be done through geophysical imaging (ERI) or flow monitoring [7]. The influence of clogging should be managed through drainage grading design and maintenance plans.

In bioreactors the internal temperature can increase (microbes produce heat), control is necessary to prevent drying of the clay liner and to maintain optimal conditions for methanogens (mesophilic temperatures 30–40°C or thermophilic ~50–55°C in some contexts) [8]. At excessive temperatures there is a risk of cracking of the clay, if the liner is not properly protected.

Recirculation can alter leachate chemistry (pH, redox conditions) and can mobilize metal species or organic compounds if not controlled. Therefore, some projects practice leachate pretreatment (neutralization/biological oxidation) before recycling or partially treated recirculation [9]. Recent examples are investigating pretreatment by alkalization or the addition of stabilizing agents.

2.3 Monitoring and control

New IoT applications, pressure sensors, automated gas capture well network optimization systems and detection technologies (thermal imaging, remote mapping) improve leak detection and capture performance [4]. Monitoring integration (ERI, drones, IoT) uses combinations of methods, geophysics for distribution, drones for emissions, sensors for process parameters, to obtain a complete picture of performance.

Recent studies show that variations in electrical resistivity can be correlated with variations in the moisture and ionic content of the leachate within the waste mass, representing a non-invasive method for real-time monitoring of leachate distribution. The advantages of using unmanned aerial vehicles equipped with miniaturized methane sensors are emphasized. These platforms allow relatively detailed spatial estimates of emissions, detection of hot spots and evaluation of gas capture efficiency over large areas.

Thanks to these technologies, operators can identify anomalies in real time, reducing the risk of groundwater contamination [11,12] .

Table 1 presents a representative summary of the results from 6 pilot studies on the main indicators of leachate recirculation efficiency, COD , BOD_5 , CH_4 % increase. and stabilization time, in the context of improving the quality of the environmental components of urban landfills.

Table 1 Main indicators of leachate recirculation efficiency

Research study	Discount_CODE _%	BOD5_reduction _%	CH4_increase_ % (vs control)	Stabilization_time _years
Study A (pilot, column)	55	68	30	2.5

Study B (pilot scale)	62	72	28	1.8
Study C (field pilot)	48	60	34.5	3.4
Study D (pilot bioreactor)	70	78	40	1.2
Study E (column, LR)	58	69	33	1.6
Study F (pilot-scale LR)	65	74	35	1.4

The definition of the experimental indicators used in the pilot studies in Table 1 is:

- **COD (Chemical Oxygen Demand**) – expresses the total amount of oxygen required to oxidize organic and inorganic compounds in the leachate. It is a global indicator of the pollutant load.

- **BOD_5 (Biochemical Oxygen Demand, 5 days**) – indicates the oxygen consumed by microorganisms for the decomposition of biodegradable organic matter. The BOD_5/COD ratio shows the degree of biodegradability.

- **CH_4 % increase** – represents the percentage increase in methane produced in the bioreactor compared to the conventional landfill. It is an indicator of the biological and energy efficiency of the system.

- **Stabilization time** – the period required until the biological processes reach equilibrium and the parameters (COD, BOD_5, CH_4) stabilize, marking the maturity of the landfill.

3. METHODOLOGY AND EXPERIMENTAL ELEMENTS

The research focused on: barrier system performance, leachate treatment efficiency, bioreactor results and monitoring innovations. Laboratory tests were analyzed to obtain special clay mixes, local soil + bentonite + fly ash, measuring hydraulic permeability, compressive strength, mechanical behavior (cohesion, friction angle) and microstructure for different cleaning/wetting phases. The behavior of controlled volume bioreactors with organic waste was studied, applying different leachate recirculation regimes (volumes, frequency, type of leachate – raw vs. treated) for monitoring: COD, BOD5, VS (volatile solids), BOD5/COD ratio, methane potential (BMP), cumulative CH_4 production [9]. To detect moisture/leachate variations, to disprove the existence of dry areas or accumulation points, geophysical images were used, methane emission estimates using drones equipped with small-sized sensors, targeting detailed spatial data. A comparative synthesis was also carried out to capture the most recent innovations and experimental data, represented in Table 2.

Table 2. Comparative synthesis of the main methods of construction and management of urban waste landfills

Method	Advantages	Disadvantages/risks	Impact on environmental quality
HDPE geomembrane + GCL	Waterproof, durable barrier	Vulnerable to pinching/interlocking ; requires careful installation	Reduces leachate infiltration, protects groundwater
Compacted clay	Natural, stable material	Requires large thickness; susceptible to cracking	Good protection if well compacted

Composite systems (multi-layer liner)	Redundancy, high performance	Increased cost and complexity	Maximum protection against leaks
Bioreactor + leachate recirculation	Accelerates stabilization; increases biogas	Requires humidity control; risk of contaminant mobilization	Reduces long-term emissions, energy generation
IoT monitoring and remote detection	Early detection, gas capture optimization	Infrastructure & data dependency	Reduces emissions and the risk of undetected leaks

The comparative analysis and performance evaluation was based on the definition of performance indicators: hydraulic conductivity, permeability, pollutant migration coefficient (metallic and organic), BOD5/COD, VS, methane potential (BMP), CH_4 emission rates, mechanical stability (cohesion, friction), durability of barriers under temperature/humidity/seasonal wear conditions, evaluation of short and medium term effects (1-5 years). Figure 1 presents a diagram of the estimated efficiency for different methods of construction and management of waste landfills.

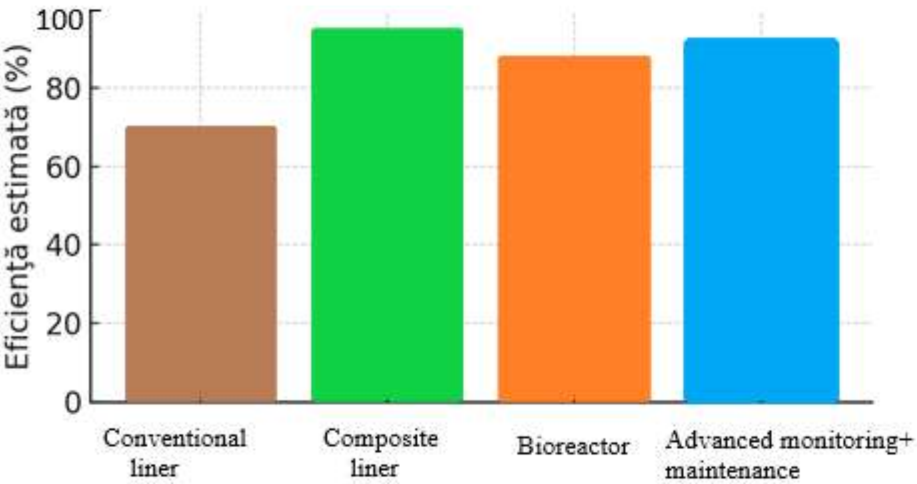

Figure 1. Efficiency of strategies to reduce the polluting impact of urban waste landfills

4. RESULTS AND DISCUSSIONS

Experimental research shows that well-designed composite systems (HDPE geomembrane over GCL/compacted clay) offer the best groundwater protection, with efficiencies reported in recent studies of over 98% under ideal conditions, while soil-bentonite-ash mixtures achieve permeabilities of the order of 10^{-9} m/s. However, recent work emphasizes the importance of installation and continuous monitoring to maintain long-term performance. Leachate treatment remains a challenge; recent reviews present advanced solutions (MBR, ozonation, advanced oxidation treatments) to treat complex leachate.

The GM/GCL/AL composite barrier was shown to have superior performance in the migration of heavy metals and soluble organic pollutants; for example, significant reductions in the migration of Pb, Cd, and low molecular weight compounds were observed, compared to the single geomembrane or geomembrane + GCL.

The study of compacted clay liners under high temperature conditions shows that, if the temperature is not controlled (e.g. by passive methods or cooling/ventilation pipes), desiccation occurs leading to cracking, with degradation of impermeability.

Numerical modeling for wastes with high food waste content shows that recirculation of treated leachate reduces the time to reach low C/L (carbon/liquid) ratios, reduces VFA peaks, and accelerates the methanogenic phase, compared to water injection-only scenarios. For example, in the biochem-hydro-mechanical model simulations, without recirculation, the time to decay of the C/L ratio to 0.5 is ~3.4 years; with treated recirculation, ~1.4 years; with simple water injection, ~1.9 years.

Bioreactors and leachate recirculation have proven effective in accelerating organic degradation and increasing biogas production by 34.5%, but must be carefully designed to avoid the mobilization of soluble pollutants. In terms of monitoring, the adoption of IoT sensors and remote sensing methodologies (thermal imaging, remote sensing) improves leak detection and optimization of gas capture.

The use of 2D electrical resistivity (ERI) in the applied study of leachate injection has allowed visualization of fluid distribution and early identification of areas of increased moisture and potential leaks. Poor insulation or defects can be inferred from resistivity models.

Although the use of drones to estimate methane emissions is still in its infancy, significant progress has been made. These platforms allow for the capture of emissions in inaccessible locations, providing thermal imaging combined with methane sensors, which allows for spatial estimation of hot spots. Limitations still include sensor accuracy, atmospheric conditions, and logistics.

In liner materials, recent studies on metal retention using improved clay mixes have shown that additions (fly ash, compost, other mineral materials) can improve adsorption capacity and reduce toxic metal migration considerably, but the efficiency depends on pH, humus/organic matter content, ionic charge and initial concentration.

5. CONCLUSIONS

Modern methods of landfill construction (composite systems, active technologies and advanced monitoring) offer the possibility of substantial improvement of the quality of environmental components when properly designed and operated. Challenges remain related to the durability of materials, the complexity of leachate treatment and the need for continuous monitoring. Future research should aim at long-term assessments, robust leak testing methods and integrated gas and leachate management strategies. Proposals for sustainable design and operation could be:

- Adopting multi-layer composite systems as the standard for new warehouses, with clear specifications for thicknesses and materials.
- Implementation of robust quality assurance programs during installation (inspection, testing of geomembrane welds).
- Integration of active strategies: bioreactor at pilot areas, controlled leachate recirculation and optimized gas capture for energy recovery.
- Large-scale implementation of continuous monitoring: sensor networks for pressure, leachate level, gas composition, plus

periodic analyses with advanced technologies.
- Ongoing research on the long-term durability of geomembranes and liner/fill interfaces, including under seismic loads.

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