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# A comprehensive review of landfill leachate treatment technologies

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The management of landfill leachate presents a significant environmental challenge, necessitating a comprehensive and dynamic treatment approach. This comprehensive review delves into the critical issue of landfill leachate treatment, exploring its environmental impact, treatment technologies, regulatory frameworks, and the path towards sustainable management practices. This review explores the complexities of landfill leachate, emphasizing the need for sustainable waste management practices to safeguard environmental health. Our analysis highlights the evolution of conventional and advanced treatment technologies designed to mitigate these risks, focusing on membrane technologies, advanced oxidation processes, and the promising potential of emerging techniques such as adsorption and biological nutrient removal. These technologies are evaluated for their efficiency, cost implications, and sustainability impacts, underscoring the challenges and opportunities within the current landscape of leachate treatment. The review aims to provide insights into designing efficient and effective treatment systems through a detailed analysis of conventional and advanced treatment methods. By examining a case study in Changsha City, the effectiveness of a comprehensive treatment system integrating various technologies is demonstrated. The review underscores the interconnectedness of human activities, environmental health, and waste management, emphasizing the importance of a holistic approach. It stresses the continuous improvement of leachate treatment technologies and the adoption of sustainable practices to reduce the environmental footprint of landfills. Ultimately, it calls for integrating multiple treatment processes, economic considerations, and readiness to address future challenges in landfill leachate treatment, contributing to the advancement of sustainable waste management practices.

## KEYWORDS

landfill leachate, treatment technologies, membrane technologies, advanced oxidation processes, waste treatment

## 1 Introduction

Landfill leachate, a liquid byproduct of the decomposition process in landfills, represents a significant environmental challenge that encapsulates the complexity of modern waste management and the imperative of safeguarding environmental health (Teng et al., 2021). As rainfall or other sources of moisture percolate through the waste material accumulated in landfills, they dissolve and suspend a myriad of substances present

in the waste, creating a potent mixture known as leachate (Mor and Ravindra, 2023). This concoction's composition can vary widely but typically includes dissolved organic matter, inorganic macro-components like salts and metals, and a range of xenobiotic organic compounds, reflecting the diverse nature of disposed materials (Kumar et al., 2023). Organic components, measured in terms of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), indicate the leachate's potential impact on water bodies, while inorganic macro-components, such as ammonia, chlorides, sulfates, and heavy metals like arsenic, cadmium, chromium, lead, and mercury, underline the toxicological concerns associated with leachate (Al-Yaqout and Hamoda, 2020). Furthermore, the presence of xenobiotic compounds, which include pesticides, pharmaceuticals, and industrial chemicals, adds to the complexity of leachate, given their resistance to degradation and potential for bioaccumulation (de Oliveira et al., 2020). The environmental impacts of uncontrolled landfill leachate are profound and far-reaching. Leachate can seep into groundwater and surface water, contaminating aquatic ecosystems, wildlife, and human health (Essien et al., 2022). The infiltration of pollutants into water supplies can disrupt aquatic habitats, harm species diversity, and bioaccumulate the food chain, presenting significant risks to public health through consuming contaminated water and food (Sharma et al., 2023). Moreover, the heavy metals and persistent organic pollutants found in leachate are particularly concerning due to their toxicity, environmental longevity, and potential to cause long-term ecological damage (Hussein et al., 2021).

Recognizing the environmental hazards of landfill leachate, its treatment and management have become critical components of sustainable waste management practices (El-Saadony et al., 2023). Effective leachate treatment aims to neutralize its harmful components, making it safe for discharge or further use (Kumar et al., 2023). This necessitates a multifaceted approach that combines physical, chemical, and biological treatment processes tailored to the specific composition of the leachate and local regulatory requirements (Torretta et al., 2017). Physical treatments, such as sedimentation and filtration, remove suspended solids and particulate matter (Siddiqi et al., 2022). Chemical treatments, including precipitation, coagulation, and advanced oxidation, target dissolved pollutants, reducing their concentration to safer levels (Kurniawan et al., 2006). Biological aerobic and anaerobic treatments further degrade organic substances, transforming them into less harmful compounds (Kurniawan et al., 2010). The importance of landfill leachate treatment extends beyond the immediate goal of pollution control. It embodies the broader principles of environmental protection and sustainable waste management (Mukherjee et al., 2015). By mitigating the adverse impacts of leachate on ecosystems and human health, effective treatment practices contribute to the preservation of water quality, protect biodiversity, and ensure the wellbeing of communities (Senathirajah and Palanisami, 2023). Furthermore, advancements in leachate treatment technologies offer opportunities for resource recovery, such as the extraction of valuable materials or the reuse of treated water, aligning with the principles of the circular economy and resource efficiency (Puyol et al., 2017).

Treating landfill leachate is not just a technical challenge but a fundamental aspect of environmental stewardship and public health protection (Nath and Debnath, 2022). It reflects the evolving

understanding of waste not merely as a byproduct to be disposed of but as a potential source of pollution that must be managed with foresight and responsibility. As such, the continuous improvement of leachate treatment technologies, alongside adopting more sustainable waste management practices, is essential to reducing the environmental footprint of landfills. This includes the development of more efficient and cost-effective treatment solutions and the implementation of waste reduction, reuse, and recycling initiatives that can minimize leachate generation in the first place (Kamaruddin et al., 2017).

Ultimately, the comprehensive management and treatment of landfill leachate highlight the interconnectedness of human activities, environmental health, and the need for a holistic approach to waste management (Torretta et al., 2017). This review aims to provide an integrated analysis of both conventional and advanced treatment technologies, emphasizing recent advancements and emerging techniques such as adsorption and biological nutrient removal. Unlike previous reviews that may focus solely on specific technologies or methodologies, this review evaluates a broad spectrum of treatment methods, offering a practical guidance for designing and optimizing treatment systems by evaluating the efficiency, cost implications, and sustainability impacts of various methods. Additionally, we incorporate a detailed case study from Changsha City, demonstrating the practical application and effectiveness of a comprehensive treatment system that integrates various technologies. This real-world example bridges the gap between theoretical discussions and practical implementation, providing actionable insights for practitioners and policymakers. By addressing the interconnectedness of human activities, environmental health, and waste management, our review advocates for a holistic approach that emphasizes continuous improvement of leachate treatment technologies and the adoption of sustainable practices. This comprehensive perspective makes our review an invaluable resource for engineers, environmental scientists, and waste management professionals seeking to implement effective and sustainable treatment solutions in diverse contexts.

## 2 Characteristics of landfill leachate

### 2.1 Physical and chemical properties of landfill leachate

Leachate embodies a dynamic concoction of substances, each contributing to its hazardous nature. Landfill leachate's physical, chemical, and biological characteristics delineate a complex and multifaceted environmental challenge that requires a nuanced understanding for effective management and treatment (Table 1) (Andreottola and Cannas, 2024; Castrillón et al., 2010; Naveen et al., 2017; Luo et al., 2020; Subiza-Pérez et al., 2023).

Physically, leachate is primarily a liquid matrix. However, its appearance, viscosity, and other physical properties can vary greatly depending on the landfill's age, the composition of waste, and the amount of precipitation the landfill receives (Anjum et al., 2023). Typically, young leachate is characterized by a high organic load, evident in its dark color and strong odor (Wijekoon et al., 2022). In

**TABLE 1** Characteristics of landfill leachate and implications for treatment (Andreottola and Cannas, 2024; Castrillón et al., 2010; Naveen et al., 2017; Luo et al., 2020; Subiza-Pérez et al., 2023).

Aspect	Characteristics	Implications for treatment
Physical	Liquid matrix, varying appearance and viscosity, pH, temperature, conductivity	Influences treatment process selection, affects solubility and treatment effectiveness
Chemical	Dissolved organic/inorganic matter, heavy metals, xenobiotics (e.g., pharmaceuticals, pesticides), COD, BOD, ammonia	Requires targeted removal or neutralization of specific compounds, challenges due to persistence and toxicity of pollutants
Biological	Microbial communities, biodegradation of organic matter, presence of pathogenic organisms	Utilization of microbial activity for degradation, management of pathogenic or harmful microorganisms

**TABLE 2** Physical and chemical properties of landfill leachate across different continents (Abunama et al., 2021a).

Parameter		Africa	Asia	Europe	North America	Oceania	South America
Organic	BOD (mg/L)	566.22	1305.85	1281.98	270.11	60.66	875.73
	COD (mg/L)	3026.81	5,983.26	5,890.65	1628.52	1594.5	3117.69
Inorganic	pH	7.72	7.72	8.03	7.95	7.81	8.13
	TKN (mg/L)	26.485	34.55	42.66	26.485	28.33	34.55
	AN (mg/L)	297.89	450.22	525.77	297.89	350.55	450.22
	TDS (mg/L)	10,403.1	11,456.3	15,382.9	3077.1	17,487.5	4364.6
Heavy metals	Cl (mg/L)	84.32	98.72	103.21	72.33	55.66	84.12
	Fe (mg/L)	7.11	25.99	41	22.04	4.88	26.28
	Cu (mg/L)	0.256	0.489	0.323	0.141	0.022	1.131
	Ni (mg/L)	0.45	0.56	0.52	0.32	0.24	0.45
	Zn (mg/L)	0.65	2.738	2.105	0.91	0.159	1.66
	Pb (mg/L)	0.331	0.55	0.54	1.441	0.006	2.524
	Cr (mg/L)	0.49	0.62	0.49	42.585	0.32	1.66
	Hg (mg/L)	0.221	0.33	0.32	0.723	0.0003	3.783
	As (mg/L)	0.0433	0.225	0.0525	33.8	0.1	0.221
	Cy (mg/L)	0.261	0.216	0.075	0.025	0	0.055

contrast, older leachate may appear clearer but contain higher concentrations of dissolved inorganic compounds (Abdel-Shafy et al., 2024). The physical properties of leachate, such as pH, temperature, and conductivity, are critical indicators of its overall composition and the potential challenges it presents for treatment (Abdel-Shafy et al., 2024). For instance, high conductivity in leachate signifies a high concentration of dissolved ions such as chlorides, sulfates, and ammonia, which can affect the efficiency of certain treatment processes. Similarly, pH levels can influence the solubility of metals and the effectiveness of chemical treatments, with acidic or alkaline conditions necessitating specific adjustments in the treatment strategy (Deng et al., 2020).

Chemically, leachate is a cocktail of dissolved organic and inorganic matter, heavy metals, and xenobiotic compounds (Sil and Kumar, 2017). The organic fraction is typically dominated by biodegradable substances like carbohydrates, fats, proteins, and persistent organic pollutants that resist natural degradation processes (Dignac et al., 2000). COD and BOD are key parameters used to quantify the organic strength of leachate, reflecting its

potential impact on receiving environments and treatment systems (Naveen et al., 2017). Inorganic components include a range of salts, metals, and nutrients, with ammonia being particularly prevalent due to the nitrogenous decomposition of organic waste (Borah et al., 2020). Heavy metals such as arsenic, cadmium, chromium, lead, and mercury are of significant concern due to their toxicity and propensity to accumulate in ecosystems (Rahman and Singh, 2019). Moreover, the presence of xenobiotics—synthetic chemicals like pharmaceuticals, pesticides, and industrial chemicals—poses a unique challenge, as these compounds often exhibit resistance to degradation and can disrupt biological processes in treatment systems and natural environments (Priya et al., 2024). Table 2 presents a detailed analysis of the physical and chemical properties of landfill leachate from various regions around the world, showing significant variability across different regions (Abunama et al., 2021a). These variations highlight the importance of regional assessments in understanding leachate pollution potential and tailoring appropriate management strategies.

Biologically, leachate is a living, evolving entity, teeming with microorganisms, such as bacteria, fungi and protozoa, which are adapted to its unique chemical milieu. The microbial communities within leachate play a pivotal role in the biodegradation of organic matter, facilitating the natural attenuation of some pollutants (Qi et al., 2023). However, the diversity and activity of these microbial populations can be both a boon and a bane for leachate treatment (Dave et al., 2020). Bacteria such as *Pseudomonas* and *Clostridium* spp., and fungi like *Aspergillus* and *Penicillium* spp., are integral to breaking down organic pollutants and transforming hazardous substances. While certain bacteria and fungi are harnessed in biological treatment processes to degrade organic pollutants, the presence of pathogenic organisms or those capable of generating harmful byproducts necessitates careful management to prevent environmental and health risks (Mani et al., 2020). The methanogenic archaea, including *Methanobacterium* and *Methanosarcina* spp., also play a crucial role by converting waste into methane, highlighting the importance of microbial activity in both waste reduction and potential energy recovery.

The interplay between the physical, chemical, and biological characteristics of leachate significantly influences the selection and design of treatment processes. Physical attributes like suspended solids and temperature necessitate pre-treatment steps such as sedimentation and filtration to prevent system clogging and optimize subsequent treatment stages. Chemical properties, including pH, organic load, and the presence of toxic compounds, determine the need for neutralization, biological treatment, or advanced oxidation processes to ensure effective contaminant removal. Biological factors, such as microbial content and biodegradability, guide the choice of biological treatment methods, which might require nutrient supplementation for optimal microbial activity. Consequently, tailored and integrated treatment strategies are developed to address the specific challenges presented by leachate's complex composition, ensuring efficient and sustainable management to mitigate its environmental impact.

## 2.2 Factors on the composition of landfill leachate

The composition of landfill leachate is influenced by a myriad of factors, including the age of the landfill, the types of waste it contains, climatic conditions, and the specific landfill operating technologies employed (Mor and Ravindra, 2023). Each of these factors plays a critical role in determining the leachate's physical, chemical, and biological characteristics, thus influencing its potential environmental impact and the strategies required for its effective management and treatment (Table 2) (Cano et al., 2020; Golwala et al., 2022; Ma et al., 2022; Abdel-Shafy et al., 2024).

The age of a landfill significantly affects the composition of the leachate produced. In the initial stages of landfilling, leachate tends to have a high organic content, characterized by a high BOD and COD, due to the abundance of readily degradable organic matter (Lindamulla et al., 2022). As the landfill matures, the rate of organic matter decomposition decreases, leading to a reduction in BOD levels (Kulikowska and Klimiuk, 2008). However, the concentration of inorganic compounds, such as ammonia, chlorides, and heavy

metals, may increase over time due to the continued degradation and leaching processes (Prieto-Espinoza et al., 2022). This temporal evolution in leachate composition necessitates adaptable treatment approaches that effectively address the shifting balance between organic and inorganic constituents (Saxena et al., 2022) (Table 3). In 2022, Liu et al. conducted a study on the molecular differences between young landfill leachate (YL) and mature landfill leachate (ML) (Liu J. et al., 2022). The results indicated that the COD of YL was 74,853 mg/L, while the COD of ML was 3,098 mg/L, suggesting a higher concentration of organic matter in young leachate. Regarding molecular composition, YL contained lower molecular weight organic compounds, primarily consisting of CHO compounds and aliphatic compounds. In contrast, ML predominantly contained CHON compounds and high oxygen highly unsaturated and phenolic compounds. The molecular structure of YL was relatively simple, with higher bioavailability and more straight-chain structures. ML, however, featured more oxygen-containing functional groups and benzene-ring structures, indicating a more complex molecular structure. In terms of chemical properties, YL exhibited lower nominal oxidation state of carbon and modified aromaticity index, indicating that its organic matter was in a more reduced state. Conversely, ML's organic matter had higher oxidation states and aromaticity, reflecting that over time, the organic matter in mature leachate had undergone extensive biochemical reactions, leading to more complex structures (Table 4).

Moreover, the nature of the waste material disposed of in a landfill is another critical determinant of leachate composition. Landfills containing a high proportion of organic waste, such as food scraps and yard waste, tend to produce leachate with high levels of organic pollutants and a greater potential for biological activity (Kjeldsen et al., 2002). Conversely, landfills with significant industrial or hazardous waste may generate leachate with higher concentrations of toxic metals and xenobiotic organic compounds (El-Saadony et al., 2023). The diversity of waste types, including e-waste, pharmaceuticals, and plastics, contributes to the complexity of leachate, requiring targeted treatment solutions capable of addressing a broad spectrum of contaminants (Srivastava et al., 2021).

Also, climatic conditions, including precipitation, temperature, and humidity, play a pivotal role in the generation and composition of leachate. High rainfall areas will likely produce larger volumes of leachate, potentially diluting its contaminant concentrations but increasing the overall load of pollutants that must be managed (Wijekoon et al., 2022). Temperature affects the rate of biochemical reactions within the landfill, with warmer conditions typically accelerating organic matter decomposition and, consequently, influencing the rate of leachate generation and its organic content (Mohammad et al., 2022). Humidity can also impact the moisture content within the landfill, affecting leachate production rates and composition (Abunama et al., 2021b).

Finally, a landfill's design and operational practices can significantly influence leachate composition (Ma et al., 2022). Modern landfills equipped with engineered liners and leachate collection systems are designed to minimize the direct contact of waste with groundwater, thereby reducing leachate generation and its potential contamination (Abdel-Shafy et al., 2024). Additionally, using daily covers can limit rainwater infiltration, further controlling

TABLE 3 Impact of various factors on the composition of landfill leachate (Kulikowska and Klimiuk, 2008; Lindamulla et al., 2022; Prieto-Espinoza et al., 2022; Saxena et al., 2022).

Factors	Options	Leachate composition
Landfill Age	Young Landfill (<10 years)	High in volatile organic compounds, BOD, and COD due to active decomposition of organic matter
	Middle-Aged Landfill (10–20 years)	Reduced levels of BOD and COD as the rate of organic decomposition decreases, increase in inorganic compounds such as ammonia
	Old Landfill (>20 years)	Lower BOD, higher concentrations of inorganic compounds, heavy metals, and stabilized organic compounds
Type of Waste Material	Organic Waste	High levels of BOD, COD, and volatile organic compounds due to decomposition of organic matter
	Industrial and Hazardous Waste	Increased concentrations of toxic metals, xenobiotics, and specific industrial chemicals
	Construction and Demolition Waste	Elevated levels of inorganic compounds, such as salts and heavy metals, lower organic content
	E-Waste	Presence of heavy metals (e.g., lead, mercury, cadmium) and potentially hazardous chemicals from electronic components
Climatic Condition	High Rainfall/High Humidity	Diluted concentrations of contaminants due to increased volume, potential for higher leachate production
	Arid/Dry	Concentrated leachate due to lower precipitation, reduced leachate volume but higher concentration of contaminants
	Cold Temperatures	Slowed decomposition rates leading to lower BOD and COD in the short term, potential for seasonal variation in leachate composition
Design or Operational Practice	Engineered Liners and Leachate Collection Systems	Minimizes the infiltration of external water, reducing leachate volume and potentially concentrating contaminants
	Daily Covers	Reduces rainwater infiltration, controlling leachate production and influencing its composition by limiting dilution
	Landfill Gas Management Systems	Affects the biochemical degradation processes within the landfill, potentially altering the organic content of the leachate

TABLE 4 Comparative Molecular Characteristics of Young and Mature Landfill Leachates in the example landfills in southwest China (Liu J. et al., 2022).

Property	Young landfill leachate	Mature landfill leachate	
Age	New Landfill for temporary stockpile	27 years	
COD	74,853 mg/L	3098 mg/L	
DOM Species Count	1122	5,075	
Main Compounds	Aliphatic Compounds, LOHUPC	HOHUPCs	
Bioavailability	Higher	Lower	
Nominal Oxidation State of Carbon	−0.8010	−0.0692	
Aromaticity ( $AI_{mod}$ )	0.1254	0.2464	
Straight-chain Structures	More	Fewer	
Benzene-ring Structures	Fewer	More	
Proportion of different DOM classes	Low O HUPC	417.96 (23.75%)	2881.86 (27.86%)
	High O HUPC	0%	3863.53 (37.55%)
	Polyphenols and Polycyclic Aromatics	1%	8%
	Aliphatic Compounds	1320.62 (75.03%)	2767.64 (26.76%)

leachate volume and composition (Khasawneh et al., 2022). Landfill gas management systems, which capture and treat or utilize the methane produced during organic decomposition, can also impact the biochemical processes within the landfill, indirectly affecting leachate composition (Japperi et al., 2021).

In sum, the composition of landfill leachate results from complex interactions between the age of the landfill, the types of waste it contains, prevailing climatic conditions, and the technologies employed in landfill operation. Understanding these factors is crucial for the development of effective leachate

management strategies, as they directly influence the environmental impact of landfills and the technical and economic feasibility of leachate treatment solutions.

### 2.3 Typical values of pollutants in leachate from different regions

To provide a global perspective, typical values for different classes of contaminants in leachate reported from around the world are described below. These values highlight the variability in leachate composition and typical values for different classes of contaminants in leachate from different regions are critical for designing effective treatment strategies.

Organic pollutants like BOD and COD are critical for assessing the pollution levels. For instance, in tropical regions, average BOD values reported were 2435.16 mg/L in Africa, 3455.77 mg/L in America, and 2127.79 mg/L in Asia, while COD values were 7985.1 mg/L in Africa, 6185.17 mg/L in America, and 7504.32 mg/L in Asia (Lindamulla et al., 2022). In China, BOD<sub>5</sub> concentrations varied from 750 to 25,000 mg/L, with an average of 8,500 mg/L, and COD levels ranged from 2,000 to 62,000 mg/L, averaging 19,250 mg/L (Ma et al., 2022).

Inorganic pollutants like Total Dissolved Solids (TDS) and Ammonium Nitrogen (NH<sub>4</sub><sup>+</sup>-N) also show significant variability. Polish landfills reported TDS values from 2,225 mg/L to 7,830 mg/L, while NH<sub>4</sub><sup>+</sup>-N concentrations in tropical regions varied widely, with higher concentrations in younger leachates (Wdowczyk and Szymańska-Pulikowska, 2021). China reported NH<sub>4</sub><sup>+</sup>-N levels ranging from 100 to 3,100 mg/L, with a mean of 1,300 mg/L (Ma et al., 2022). Brazil's ammonium nitrogen levels ranged between 0.4 and 1,800 mg/L, reflecting the diversity of landfill conditions and waste compositions across the country (Lindamulla et al., 2022).

Heavy metals, another major pollutant category, had varied concentrations with iron ranging from 0.019 mg/L in inactive Polish landfills to 38.73 mg/L in active ones, and zinc reaching up to 2,560 mg/L in Polish active landfills (Wdowczyk and Szymańska-Pulikowska, 2021). In Thailand, heavy metals like cadmium, chromium, copper, nickel, lead, and zinc were generally below 1 mg/L, though still posing potential ecological and health risks (Ma et al., 2022). This highlights the need for careful monitoring and tailored remediation strategies to address potential environmental and health impacts.

The Leachate Pollution Index (LPI) further highlights the pollution potential of leachate, being higher in open dumps compared to engineered landfills (Lindamulla et al., 2022). Young leachates typically show higher LPI values than older leachates, indicating a higher pollution potential in newer landfills. This global variability in leachate composition underscores the importance of site-specific assessments and tailored treatment approaches for effective leachate management.

## 3 Regulations and standards

Countries around the world are increasingly recognizing the importance of effective landfill leachate treatment as a critical

component of waste management and environmental protection. The significant number of research publications on this topic, particularly from nations with large populations, underscores their commitment to addressing the challenges posed by waste and pollutants. Figure 1 shows the research on “landfill leachate treatment” collected from the Scopus database from 2014 to 2023. The top five countries are China (1,675 articles), India (500 articles), the United States (498 articles), Malaysia (418 articles), and Brazil (302 articles). These all reflect a positive stance in mitigating the impact of rapid industrial and urban development on the environment, and countries have also invested heavily in research to develop efficient landfill leachate treatment technologies, further highlighting the global recognition of the need for advanced and sustainable waste management practices. This joint effort is not only aimed at improving public health and environmental quality, but also at promoting global sustainable development.

### 3.1 Global regulations on landfill leachate management

International and national regulations governing the disposal and treatment of landfill leachate are crucial for protecting the environment and public health from the potential hazards posed by waste management practices (Daniel et al., 2021). These regulations are designed to set minimum standards for leachate management, ensure the safe handling of this potentially toxic byproduct, and encourage sustainable practices in the waste management industry (Table 5) (Oakes and Shank, 1979; Directive, 2003; Protection, 2003; Obradović et al., 2010; Pollutants, 2011; Gas, 2017; Bergesen et al., 2018; Bhawan and Nagar, 2020; Lin et al., 2022; Santana et al., 2022).

At the international level, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their disposal is one of the most significant treaties (Ahmed, 2019). It impacts leachate management by restricting the international movement of hazardous wastes, which includes leachate, and encouraging proper disposal (Amos et al., 2024). Another important piece of international legislation is the Stockholm Convention on Persistent Organic Pollutants, which addresses the treatment and disposal of leachate due to its potential to carry organic pollutants that can persist in the environment (Omoto, 2014). The European Union (EU) has established stringent directives for waste management, including the Landfill Directive (1999/31/EC), which sets the standards for waste disposal in landfills, including the collection and treatment of leachate (Schiopu and Gavrilesco, 2010). It specifies that landfills must be designed and operated to collect and treat leachate to prevent groundwater and environmental contamination. Furthermore, the EU's Water Framework Directive (2000/60/EC) also affects leachate management by setting out a framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater, requiring that leachate be treated to prevent the pollution of water bodies (Kyriakopoulos, 2021).

The Resource Conservation and Recovery Act (RCRA) provides the framework for properly managing solid and hazardous waste in the United States (Hinds, 2022). Under Subtitle of RCRA, the Environmental Protection Agency (EPA) has established regulations that require municipal solid waste landfills to use

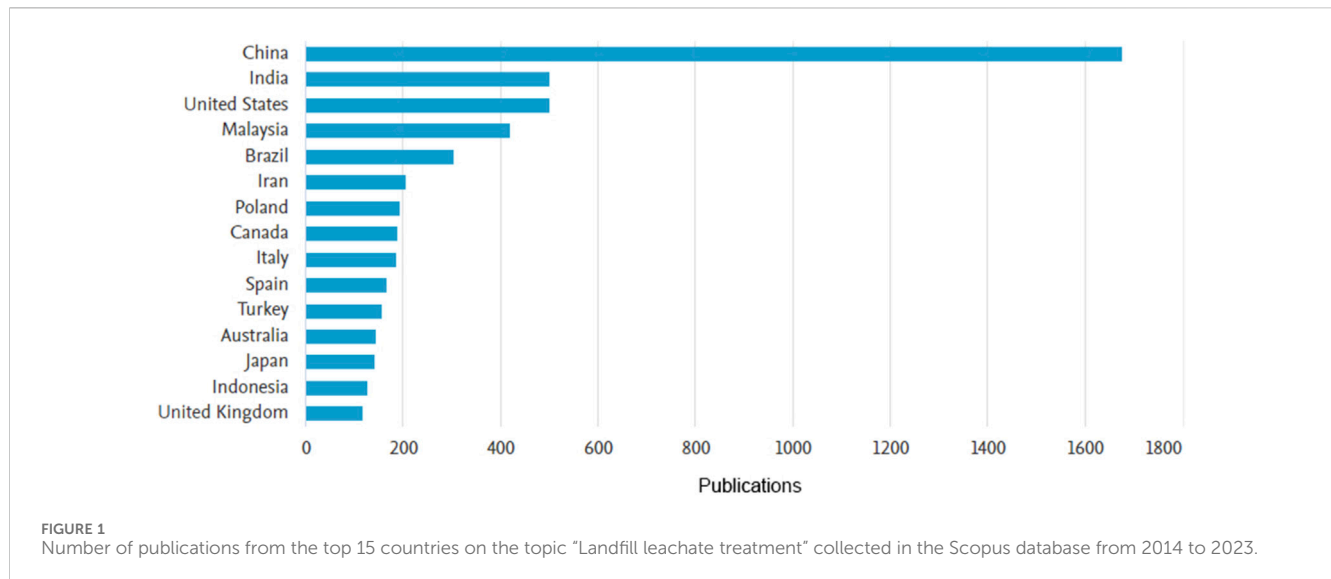


TABLE 5 Global laws and regulations on landfill leachate management (Oakes and Shank, 1979; Directive, 2003; Protection, 2003; Obradović et al., 2010; Pollutants, 2011; Gas, 2017; Bergesen et al., 2018; Bhawan and Nagar, 2020; Lin et al., 2022; Santana et al., 2022).

Country	Regulation/Law	Key provisions
European Union	Landfill Directive (1999/31/EC)	Sets standards for waste disposal in landfills, including leachate treatment to prevent groundwater contamination
United States	Resource Conservation and Recovery Act (RCRA)	Requires municipal solid waste landfills to use liners and leachate collection systems to protect groundwater
China	Standard for Pollution Control on the Landfill Site of Municipal Solid Waste (GB 16889–2008)	Details requirements for leachate collection, treatment, and discharge, including limitations on contaminants
India	Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016	Specifies criteria for handling, treatment, and disposal of hazardous waste, including leachate from landfills
Brazil	National Solid Waste Policy (Política Nacional de Resíduos Sólidos - PNRS, Law No. 12,305/2010)	Emphasizes the treatment and environmentally sound disposal of waste, including leachate management
Canada	Canadian Environmental Protection Act (CEPA)	Provides a framework for the safe management of hazardous waste and substances, including leachate
Australia	National Environment Protection (Assessment of Site Contamination) Measure 1999	Establishes guidelines for the assessment and management of site contamination, including leachate
Germany	Technical Instructions on Municipal Waste (TA Siedlungsabfall)	Specifies technical requirements for waste treatment facilities, including leachate management systems
Japan	Waste Management and Public Cleansing Law	Regulates waste disposal and cleaning operations, ensuring proper leachate control and treatment
South Africa	National Environmental Management: Waste Act, 2008	Lays down waste management measures to protect health and the environment, including leachate standards

composite liners and leachate collection systems to protect groundwater (Bonaparte et al., 2024). The National Pollutant Discharge Elimination System (NPDES), part of the Clean Water Act, regulates the discharge of leachate into surface waters, requiring permits and setting treatment standards (Hudiburgh, 2020). The EPA's treatment standards for hazardous wastes subject to land disposal restrictions include several key parameters that must be monitored under applicable regulations (Agency, 2024). These standards specify regulated hazardous constituents, which are chemicals or compounds that need to be treated to meet specific numerical limits before disposal. For instance, chloroform must be

reduced to a concentration of 0.046 mg/L for wastewaters and 6.0 mg/kg for nonwastewaters. Characteristic wastes, such as those exhibiting ignitability, corrosivity, reactivity, or toxicity, require deactivation of these characteristics and treatment of any underlying hazardous constituents (UHCs) to meet universal treatment standards (UTS). Ignitable wastes must be treated by methods such as combustion or deactivation, depending on their total organic carbon content, to remove the ignitability characteristic. Corrosive wastes need deactivation to eliminate corrosivity, with high-level radioactive corrosive wastes requiring vitrification. Reactive wastes are generally treated by deactivation,

with reactive cyanide wastes having specific concentration-based standards, such as 590 mg/kg total cyanide and 30 mg/kg amenable cyanide for nonwastewaters, and 0.86 mg/L amenable cyanide for wastewaters. Toxicity characteristic wastes must be treated to meet numerical standards for metals, pesticides, and organics, as well as the UTS for UHCs. Additionally, alternative treatment standards are available for certain waste types like contaminated soil and debris, allowing for a reduction in hazardous constituent concentration by 90% or to levels not exceeding 10 times the UTS. These parameters ensure that hazardous wastes are adequately treated to minimize their environmental impact before land disposal.

In China, the Environmental Protection Ministry released the “Standard for Pollution Control on the Landfill Site of Municipal Solid Waste” (GB 16889–2008), which sets out leachate collection, treatment, and discharge requirements (Liu Q. et al., 2022). These include specific limitations on contaminants such as BOD, COD, ammonia nitrogen, total phosphorus, and heavy metals in the discharged leachate (Shi et al., 2021). India has enacted the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, which set forth the criteria for identifying hazardous waste and its handling, treatment, and disposal standards, including leachate from landfills (Sadala et al., 2023). The Central Pollution Control Board (CPCB) of India provides technical guidelines for the secure landfill of hazardous waste, emphasizing the need for a comprehensive leachate management system (Kumar et al., 2007). In Brazil, the National Solid Waste Policy (Política et al. - PNRS) established under Law No. 12,305/2010 requires proper leachate management and emphasizes the treatment and environmentally sound disposal of waste (Galavote et al., 2022).

These examples demonstrate the common goal across different regulatory frameworks: minimizing environmental and health risks associated with leachate from landfills. National regulations often incorporate or build upon international guidelines, tailoring requirements to local conditions and available technologies. However, the effectiveness of these regulations often depends on the robustness of enforcement mechanisms and the commitment of local authorities to uphold standards. The significance of these regulations extends beyond environmental protection. They also have profound economic and social implications. Strict regulatory standards drive innovation in the waste management sector, leading to the development of new treatment technologies and practices that can reduce the volume and toxicity of leachate. Moreover, by requiring the safe disposal of leachate, regulations also prevent the long-term social costs associated with environmental cleanup and healthcare for communities affected by pollution (Fang et al., 2021).

### 3.2 Regulatory influence on landfill leachate treatment technology selection

Regulatory standards significantly influence the selection of landfill leachate treatment technologies. These regulations protect the environment and public health from the potential hazards posed by untreated or inadequately treated leachate (Tenodi et al., 2020). As such, they set specific benchmarks that leachate must meet before it can be released into the environment or treated further for potential reuse.

The impact of regulatory standards on the choice of treatment technology is multifaceted. Initially, these standards determine the permissible levels of various pollutants, such as organic matter, heavy metals, and nitrogen compounds, that can be present in the treated leachate (Salem et al., 2008). This directly affects the technology selection, as different processes vary in their ability to remove or neutralize specific contaminants (Ahmed et al., 2017). For instance, high BOD and COD levels might necessitate biological treatment processes, such as activated sludge systems (Haydar et al., 2007). At the same time, the presence of heavy metals may require chemical precipitation or ion exchange technologies (Saleh et al., 2022). Furthermore, regulations often specify the methods that must be used for testing and monitoring leachate quality (Brennan et al., 2016). These requirements can influence the choice of technology by necessitating systems that treat leachate effectively and allow for easy sampling and monitoring. Technologies that offer more control and predictability in their operation, such as membrane bioreactors, can become preferred options under stringent monitoring requirements (Galinha et al., 2018). Advanced treatment technologies like reverse osmosis, nanofiltration, and advanced oxidation processes become more prevalent in jurisdictions with strict environmental standards (Valdés et al., 2021). These technologies can achieve the low contaminant levels required for discharge into sensitive environments or for meeting the high-quality standards necessary for leachate reuse in irrigation or industrial processes (Torretta et al., 2017).

Moreover, regulations also impact the economic aspects of technology choice. Compliance with stringent standards often comes with higher operational and maintenance costs (Siddiqi et al., 2022). As a result, regulatory frameworks can indirectly incentivize the development and adoption of more cost-effective and energy-efficient technologies (Pan et al., 2015). For example, the push to meet low nitrogen limits could encourage the adoption of innovative nitrogen removal processes that consume less energy than traditional methods (Nourmohammadi et al., 2013). Regulatory standards also influence the long-term planning and scalability of treatment solutions. Facilities must consider current regulations and potential future tightening of standards (Bunce et al., 2018). This foresight leads to the selection of technologies that are compliant now and adaptable to future regulatory changes, thereby protecting the investment in treatment infrastructure over time. Environmental policies and regulatory standards can also foster the integration of multiple treatment technologies. To meet comprehensive standards that cover a wide range of contaminants, treatment plants may combine physical, chemical, and biological processes in a tiered treatment strategy. Such integration can achieve higher levels of purification than standalone systems.

In addition to these factors, regulations may promote sustainable practices by advocating for treatment technologies that minimize waste generation or allow for resource recovery (Capodaglio, 2017). Techniques that enable the recovery of byproducts, such as biogas production or the retrieval of precious metals, might be preferred in regions where sustainability is a regulatory goal (Chrispim et al., 2021).

In conclusion, the impact of regulatory standards on the choice of landfill leachate treatment technology is profound, driving innovation and influencing every aspect from the design phase to operational strategy. By setting the bar for environmental



TABLE 6 Conventional landfill leachate treatment technologies (Torretta et al., 2017; Dogaris et al., 2020; Ahmed et al., 2021; Younas et al., 2021; Siddiqi et al., 2022).

Treatment	Brief overview	Advantages	Limitations	Applicability	Representative technologies	Typical target pollutants	Removal efficiency
Physical	Involves the separation of substances without a chemical reaction, such as screening, sedimentation, and flotation	<ul style="list-style-type: none"> <li>— Low energy requirement</li> <li>— Simple operations</li> </ul>	<ul style="list-style-type: none"> <li>— Often requires subsequent treatment</li> <li>— Limited effectiveness for dissolved contaminants</li> </ul>	<ul style="list-style-type: none"> <li>— Preliminary treatment</li> <li>— Suitable for large suspended solids</li> </ul>	<ul style="list-style-type: none"> <li>— Screening</li> <li>— Sedimentation</li> <li>— Flotation</li> </ul>	<ul style="list-style-type: none"> <li>— Suspended solids</li> <li>— Particulate matter</li> <li>— Colloidal particles</li> </ul>	<ul style="list-style-type: none"> <li>— Sedimentation: 50%–70% suspended solids</li> <li>— Filtration techniques: 85%–95% COD, 80%–90% BOD</li> </ul>
Chemical	Uses chemical reactions to remove pollutants, including precipitation, oxidation, and ion exchange	<ul style="list-style-type: none"> <li>— Effective for specific contaminants</li> <li>— Can achieve high levels of purification</li> </ul>	<ul style="list-style-type: none"> <li>— Can produce secondary waste</li> <li>— Chemicals used can be hazardous</li> </ul>	<ul style="list-style-type: none"> <li>— Versatile, can treat a range of leachate types</li> <li>— Used for heavy metals</li> </ul>	<ul style="list-style-type: none"> <li>— Precipitation</li> <li>— Oxidation</li> <li>— Ion Exchange</li> </ul>	<ul style="list-style-type: none"> <li>— Heavy metals</li> <li>— Dissolved organics</li> <li>— Inorganic compounds</li> </ul>	<ul style="list-style-type: none"> <li>— Coagulation-flocculation: 60%–90% suspended solids and 50%–70% COD</li> <li>— Precipitation: 80%–95% heavy metals</li> <li>— Oxidation-reduction: 80%–90% color and 70%–85% COD</li> <li>— Fenton's reagent: 75%–90% COD and 80%–95% organic pollutants</li> </ul>
Biological	Employs microorganisms to degrade organic pollutants, categorized into aerobic and anaerobic processes	<ul style="list-style-type: none"> <li>— Cost-effective</li> <li>— Environmentally friendly</li> </ul>	<ul style="list-style-type: none"> <li>— Sensitive to toxic compounds</li> <li>— May require long treatment times</li> </ul>	<ul style="list-style-type: none"> <li>— Ideal for organic-rich leachate</li> <li>— Commonly used in municipal wastewater</li> </ul>	<ul style="list-style-type: none"> <li>— Aerobic and Anaerobic Digestion</li> <li>— Membrane Bioreactors</li> </ul>	<ul style="list-style-type: none"> <li>— Organic matter (BOD, COD)</li> <li>— Nitrogen</li> <li>— Phosphorus</li> </ul>	<ul style="list-style-type: none"> <li>— Activated sludge: 70%–90% BOD and 60%–80% COD</li> <li>— Digesters: 80%–90% BOD and 70%–85% COD</li> <li>— Constructed wetlands: 60%–80% BOD, 50%–70% COD, and 40%–60% ammonia</li> </ul>

compliance, regulations ensure that the selected technologies not only mitigate the potential impact of leachate on the environment but also align with the broader goals of sustainability and public health protection.

## 4 Conventional landfill leachate treatment technologies

Landfill leachate treatment is a crucial component of modern waste management systems, aiming to mitigate the environmental impact of leachate discharge from landfills. As leachate comprises a complex mixture of dissolved and suspended contaminants, its treatment requires a multifaceted approach involving various conventional technologies. These include physical, chemical, and biological methods, each with principles, advantages, limitations, and practical considerations (Table 6) (Torretta et al., 2017; Dogaris et al., 2020; Ahmed et al., 2021; Younas et al., 2021; Siddiqi et al., 2022).

### 4.1 Physical methods

Physical methods for landfill leachate treatment involve processes that primarily rely on physical separation or filtration mechanisms to remove suspended solids and particulate matter (Renou et al., 2008). These methods typically include sedimentation, filtration, and membrane technologies (Bashir et al., 2016). Sedimentation involves allowing suspended solids to settle out of the leachate under the influence of gravity, facilitating their removal from the liquid phase (Wang et al., 2021). Filtration techniques, such as sand or activated carbon filtration, employ porous media to trap suspended solids and organic compounds as the leachate passes through the filter bed (Loh et al., 2021). Membrane technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, utilize semi-permeable membranes to remove contaminants based on their molecular size and charge selectively (Rai and Shrivastav, 2022). Air stripping is a physical treatment process that removes volatile contaminants, such as VOCs and ammonia, from landfill leachate by passing air through the liquid (De et al., 2019a; 2022). The process relies on Henry's Law to transfer contaminants from the liquid to the gas phase, using packed towers or aeration tanks to maximize contact surface area. Air stripping is effective, simple to operate, and can achieve high removal efficiencies (up to 90% for ammonia). However, it produces off-gas that requires further treatment to prevent air pollution and can be energy-intensive. Despite these challenges, air stripping is an essential part of leachate treatment, often used alongside other technologies to improve overall performance.

In terms of efficiency, sedimentation can remove 50%–70% of suspended solids. Filtration techniques, such as activated carbon filtration, can achieve removal efficiencies of 85%–95% for COD and 80%–90% for BOD (De et al., 2019b; Mojiri et al., 2019). Membrane technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, utilize semi-permeable membranes to selectively remove contaminants based on their molecular size and charge. Microfiltration and ultrafiltration can remove 90%–99% of suspended solids and bacteria, while

nanofiltration is effective in removing 70%–90% of divalent ions and 50%–70% of monovalent ions (Peng, 2017). Reverse osmosis offers the highest removal efficiencies, capable of removing 95%–99% of dissolved solids, heavy metals, and organics (Peng, 2017).

The principal advantage of physical treatment methods lies in their ability to achieve high levels of contaminant removal, particularly for suspended solids and larger organic molecules (Saravanan et al., 2021). These methods are often effective in reducing turbidity and removing colloidal particles, thereby improving the treated leachate's visual clarity and overall quality (Zakaria et al., 2023). Additionally, physical treatment processes are generally straightforward to implement and operate, requiring minimal chemical additives and relatively low energy inputs compared to some chemical and biological methods (Nyabadza et al., 2023). However, physical treatment methods also have certain limitations and practical considerations. The potential for membrane fouling or clogging, particularly in membrane-based processes, can reduce treatment efficiency and increase operational costs (Asif and Zhang, 2021). Moreover, physical methods may not effectively remove dissolved contaminants such as heavy metals or organic compounds, which may require additional treatment steps (Saleh et al., 2022). Furthermore, membrane technologies' high capital and operational costs can limit their widespread adoption, particularly in regions with limited financial resources (Othman et al., 2022).

### 4.2 Chemical methods

Chemical methods for landfill leachate treatment involve the addition of chemical reagents or agents to facilitate the precipitation, coagulation, flocculation, oxidation, or neutralization of contaminants present in the leachate (Aziz et al., 2022). These methods aim to enhance the removal of dissolved metals, organic compounds, and other pollutants through chemical reactions that transform them into insoluble precipitates or aggregates that can be separated from the liquid phase (El-Saadony et al., 2023; Chen et al., 2024). Common chemical treatment processes include coagulation-flocculation, precipitation, oxidation-reduction, and advanced oxidation processes (AOPs) (Sengupta and Pal, 2021).

Coagulation-flocculation involves the addition of coagulants, such as ferric chloride or aluminum sulfate, followed by the addition of flocculants, such as polymers, to promote the aggregation of suspended solids and colloidal particles into larger flocs that can be easily separated from the leachate (Abujazar et al., 2022). Precipitation methods rely on adding chemicals that react with dissolved contaminants to form insoluble precipitates, which can then be removed by sedimentation or filtration (Pohl, 2020). Oxidation-reduction processes, such as ozonation or chlorination, involve adding oxidizing agents to degrade organic pollutants or reduce the concentration of toxic compounds (Wang and Chen, 2020). AOPs utilize powerful oxidants such as hydrogen peroxide or ozone, combined with UV radiation or catalysts, to generate highly reactive hydroxyl radicals that can mineralize organic contaminants into simpler, less harmful compounds (Pandis et al., 2022).

Regarding removal efficiency, coagulation-flocculation can remove 60%–90% of suspended solids and 50%–70% of COD (Teh et al., 2016). Precipitation is highly effective in removing

heavy metals, achieving removal efficiencies of 80%–95% for metals such as lead, cadmium, and chromium (Fu and Wang, 2011). Oxidation-reduction processes like ozonation can remove 80%–90% of color and 70%–85% of COD (Miklos et al., 2018). Advanced oxidation processes, such as the use of Fenton's reagent, can remove 75%–90% of COD and 80%–95% of organic pollutants (Babunonusami and Muthukumar, 2014).

The primary advantage of chemical treatment methods lies in their versatility and effectiveness in targeting a wide range of contaminants present in leachate (Pisharody et al., 2022). Chemical processes can achieve high removal efficiencies for dissolved metals, organic compounds, and recalcitrant pollutants that may not be effectively treated by physical or biological methods alone (Nidheesh et al., 2022). Additionally, chemical treatment processes can often be tailored to specific leachate compositions and treatment objectives by adjusting the type and dosage of chemical additives used (Khoo et al., 2020). One of the common disadvantages of chemical treatment methods, particularly coagulation-flocculation and precipitation, is the generation of sludge. This sludge, a byproduct of the treatment process, consists of the aggregated contaminants and excess chemical reagents, posing a significant disposal challenge (Sharma et al., 2022). Using chemical reagents can also increase operational costs and pose health and safety risks to operators if improperly handled. The management of this sludge is crucial as it requires appropriate handling, treatment, and disposal to avoid secondary pollution. Chemical sludge typically needs to be dewatered and may require further stabilization or treatment before disposal in landfills or use in other applications. The disposal costs and environmental impacts associated with sludge management must be considered when evaluating the overall feasibility and sustainability of chemical treatment methods (Hou et al., 2023).

### 4.3 Biological methods

Biological methods for landfill leachate treatment harness the metabolic activity of microorganisms to degrade organic pollutants and remove nutrients from the leachate (Wu D. et al., 2015). These methods typically involve aerobic treatment, anaerobic treatment, and constructed wetlands, which utilize different microbial communities and environmental conditions to facilitate the leachate's biodegradation and transformation of contaminants (Kurniawan et al., 2010). Aerobic treatment involves exposing the leachate to oxygen-rich conditions, allowing aerobic bacteria to metabolize organic compounds and oxidize them into simpler, less harmful substances (Bhambore and Suresh Kumar, 2022). On the other hand, anaerobic treatment processes operate under oxygen-free conditions and rely on anaerobic bacteria to degrade organic matter through fermentation and methanogenesis, producing methane gas as a byproduct (Zamri et al., 2021). Constructed wetlands are engineered systems that mimic natural wetland ecosystems and utilize wetland vegetation, soil, and microbial communities to remove contaminants from the leachate through physical, chemical, and biological processes (Hassan et al., 2021). These systems provide an ideal habitat for the growth of wetland plants and microorganisms, which can absorb, adsorb, and metabolize pollutants in the leachate,

improving its quality (Bakhshoodeh et al., 2020). Additionally, constructed wetlands can enhance nutrient removal and promote groundwater recharge by facilitating water infiltration and retention in the soil (Chand et al., 2022).

When it comes to biological methods for landfill leachate treatment, aerobic treatment processes, such as activated sludge, can remove 70%–90% of BOD and 60%–80% of COD (Peng, 2017). Anaerobic treatment using digesters can achieve removal efficiencies of 80%–90% of BOD and 70%–85% of COD, with the added benefit of producing biogas as a byproduct (Mukherjee et al., 2015). Constructed wetlands offer another effective solution, capable of removing 60%–80% of BOD, 50%–70% of COD, and 40%–60% of ammonia (Wu S. et al., 2015).

Here we need to mention a mature biological treatment technology that has been widely used in the field of wastewater treatment for many years, biological nutrient removal (BNR). BNR harnesses the metabolism of microorganisms to remove nutrients, notably nitrogen and phosphorus, from wastewater (Deng et al., 2023). BNR is crucial for preventing eutrophication in aquatic environments caused by nutrient overloads (Kabuba et al., 2022). BNR operates through various biological mechanisms, including nitrification, denitrification, and phosphorus uptake by specific bacteria, under different operational conditions to remove these nutrients (Rout et al., 2021a). Factors influencing the efficiency of BNR include biomass concentration, hydraulic retention time, temperature, and pH, which need to be optimized to enhance microorganism activity and nutrient removal (Mishra et al., 2022). The complexity of BNR systems, which can include multiple tanks and stages for different phases of nutrient removal, requires careful design and operation to achieve the desired outcomes (Al-Hazmi et al., 2022). BNR offers a cost-effective and environmentally friendly approach to nutrient removal, avoiding using chemicals and leveraging natural biological processes (Al-Hazmi et al., 2024). This technology requires for a large footprint due to the extensive infrastructure needed and the complexity of operation and maintenance, which demands skilled personnel and continuous monitoring (Abyar and Nowrouzi, 2023).

Biological treatment methods can achieve sustainable and cost-effective leachate treatment through natural processes (Chand et al., 2022). Biological processes are highly efficient in removing organic pollutants and nutrients from the leachate, often achieving high removal efficiencies under favorable environmental conditions (Li et al., 2021). Moreover, biological treatment methods are generally environmentally friendly and produce minimal secondary waste or harmful byproducts compared to chemical or physical methods (Sathya et al., 2023). Nevertheless, compared with chemical or physical methods, the required processing time is longer because the microbial degradation process can be relatively slow, especially under certain environmental conditions (Sharma, 2020). Additionally, biological treatment systems may be sensitive to fluctuations in temperature, pH, and other environmental parameters, which can affect treatment performance and reliability (Sundui et al., 2021). Moreover, toxic or inhibitory substances in the leachate, such as heavy metals or recalcitrant organic compounds, may limit the effectiveness of biological treatment processes and require additional pre-treatment or post-treatment steps to achieve desired treatment objectives (Ilmasari et al., 2022).

TABLE 7 Membrane technology in landfill leachate treatment (de Almeida et al., 2020; Magalhães et al., 2020; Yusuf et al., 2020; El Batouti et al., 2022).

Process	Introduction	Mechanism	Target pollutants	Removal efficiency	Factors affecting removal efficiency	Advantages	Limitations
RO	RO is a high-efficiency filtration process that removes contaminants by applying pressure to push water through a semi-permeable membrane	Solution/diffusion; Size exclusion	Dissolved salts, metals, organics, and some microorganisms	Remove exceeding 99% for various contaminants	Membrane fouling level, feed water quality, operating pressure	High removal efficiencies for a wide range of contaminants; Produces high-quality effluent	High energy consumption; Generates concentrated waste stream
NF	NF is a selective filtration technology that removes specific ions and small molecules from water	Size exclusion; Electrostatic exclusion	Hardness ions (e.g., Ca, Mg), heavy metals, certain organic compounds	Up to 99.62% removal of PFAS.	Membrane fouling level, feed composition, operating pressure	Lower pressure and energy requirements than RO; Can selectively remove contaminants	Less effective for monovalent ions; Still produces a waste concentrate
UF	UF uses a semi-permeable membrane to remove suspended solids, bacteria, viruses, and large molecules	Size exclusion	Suspended solids, bacteria, viruses, macromolecules	Remove 90%–99% of suspended solids and bacteria	Membrane fouling level, pore size of the membrane, feed water turbidity	Low energy requirement; Effective pre-treatment for RO/NF; High removal of particulates and microorganisms	Limited in removing dissolved ions and small molecules
MBR	MBR combines biological treatment with membrane filtration to degrade organic pollutants and remove solids	Biological degradation; Size exclusion	Organic pollutants, nutrients (N, P), suspended solids	High removal rates for BOD (85%–95%) and COD (70%–85%)	Biomass concentration, membrane fouling level, hydraulic retention time	High-quality effluent; Compact design; High organic and nutrient removal efficiency	Higher operational and maintenance costs due to fouling; Energy-intensive

In conclusion, conventional landfill leachate treatment technologies encompass diverse physical, chemical, and biological methods, each offering unique advantages, limitations, and practical considerations. Physical methods rely on separation or filtration mechanisms to remove suspended solids and colloidal particles from the leachate. In contrast, chemical methods involve the addition of chemical reagents to facilitate the precipitation, coagulation, or oxidation of contaminants. Biological methods harness the metabolic activity of microorganisms to degrade organic pollutants and remove nutrients from the leachate through natural processes. While each treatment method has its strengths and weaknesses, selecting an appropriate treatment technology depends on factors such as leachate composition, treatment objectives, regulatory requirements, and site-specific considerations. By understanding each treatment method's principles, advantages, limitations, and practicality, stakeholders can make informed decisions to design and implement effective leachate treatment systems that meet environmental standards and protect human health and the environment.

## 5 Advanced landfill leachate treatment technologies

### 5.1 Common technology

#### 5.1.1 Membrane technology

Membrane technology has emerged as a pivotal solution in treating landfill leachate (Chen et al., 2021). This technology offers a versatile and efficient approach to removing contaminants,

including dissolved salts, heavy metals, organic compounds, and particulates (El Batouti et al., 2021). The application of membrane technology in leachate treatment primarily involves reverse osmosis, nanofiltration, ultrafiltration, and membrane bioreactors, each serving unique roles in the purification process (Table 7) (de Almeida et al., 2020; Magalhães et al., 2020; Yusuf et al., 2020; El Batouti et al., 2022).

#### 5.1.2 Reverse osmosis (RO)

Reverse osmosis is a cornerstone of membrane technology for leachate treatment, renowned for its ability to remove a wide array of contaminants, including dissolved salts and organic molecules (Feria-Díaz et al., 2021). The principle of RO involves applying pressure to the leachate across a semi-permeable membrane, which allows water molecules to pass while retaining the majority of dissolved solids (Mengesha and Sahu, 2022). This process is particularly effective in reducing leachate conductivity, making it a critical step in compliance with stringent discharge regulations (Keyikoglu et al., 2021). RO systems can achieve removal efficiencies exceeding 99% for various contaminants, rendering them indispensable in scenarios requiring high-quality effluent (Srivastava et al., 2022). However, the performance of RO systems is significantly influenced by factors such as membrane fouling, feed water quality, and operating pressure (Odabaşı et al., 2022). Membrane fouling, caused by the accumulation of particles and microorganisms on the membrane surface, can lead to decreased efficiency and increased operational costs (Sengar and Vijayanandan, 2022). To mitigate these effects, pre-treatment processes and regular maintenance are crucial. Additionally, generates a concentrated brine that requires further management

or treatment, presenting an environmental and operational challenge (Sengar and Vijayanandan, 2022). RO is particularly suitable for final polishing of treated leachate to meet discharge standards.

### 5.1.3 Nanofiltration (NF)

Nanofiltration occupies a niche between reverse osmosis and ultrafiltration, with a pore size that allows it to selectively remove divalent and multivalent ions, some monovalent ions, and organic molecules (Zhao et al., 2021). NF is particularly valued for its ability to soften water by removing hardness ions, such as calcium and magnesium, alongside a significant reduction in organic content and color (Patel et al., 2023). NF's selectivity allows it to target pollutants with lower pressure and energy requirements than RO, making it a cost-effective option for many treatment scenarios (Yadav et al., 2022). The process is well-suited for pre-treatment in RO systems or as a standalone treatment for leachates with moderate contamination levels (Ali, 2021). Like RO, NF also produces concentrate streams that require careful disposal or further treatment (Song et al., 2020). The efficiency of NF is contingent upon membrane fouling, feed composition, and operating pressure (Yang et al., 2024). Similar to RO, the presence of pre-treatment processes is vital to prevent fouling and ensure consistent performance. While NF offers the advantage of selective contaminant removal with reduced energy consumption, its limitations include less effectiveness for monovalent ions and the production of a waste concentrate that requires further treatment (Tian et al., 2021).

### 5.1.4 Ultrafiltration (UF)

Ultrafiltration is a membrane filtration process employing larger pore sizes than NF and RO, making it ideal for removing suspended solids, bacteria, viruses, and high molecular weight solutes (Urošević and Trivunac, 2020). Factors like membrane fouling, pore size, and feed water turbidity can impact UF's removal efficiency (Peters et al., 2021). Nonetheless, UF systems require lower energy to operate and serve as an excellent pre-treatment step for RO and NF processes by reducing the load of suspended solids and microbial content, thereby extending the lifespan of downstream membranes (El Batouti et al., 2022). UF is often used as a pre-treatment step to protect downstream RO or NF systems from fouling. It can typically remove 90%–99% of suspended solids and bacteria. The primary advantage of UF lies in its ability to operate at lower pressures, thereby reducing energy costs (Fan et al., 2020). It is also less susceptible to chemical damage, allowing for a broader range of chemical cleaning agents. Although UF is highly effective in removing particulates and microorganisms, its limitations lie in its inability to address dissolved ions and small molecules, underscoring the need for a comprehensive treatment approach that may include subsequent NF or RO stages (Castro-Muñoz, 2020).

### 5.1.5 Membrane bioreactors (MBR)

The membrane bioreactor technology integrates biological treatment processes with membrane filtration, offering a compact and efficient solution for degrading organic pollutants and removing solids (Neoh et al., 2016). In an MBR

system, a bioreactor degrades organic pollutants through microbial activity, while a membrane filtration unit separates treated water from biomass and suspended solids (Deng et al., 2022). MBRs can achieve high levels of organic and nutrient removal, with the added benefit of producing a clarified, disinfected effluent (Hai et al., 2014). Integrating biological treatment and membrane separation enhances system stability and reduces the footprint compared to conventional treatment setups (Waqas et al., 2020). MBRs are suitable for leachate with high organic loads and in locations where space is limited. They can achieve high removal rates for BOD (85%–95%) and COD (70%–85%), along with effective solids separation. The performance of MBRs is influenced by factors such as biomass concentration, membrane fouling, and hydraulic retention time. Despite the challenges of operational and maintenance costs associated with fouling and energy consumption, MBRs provide significant advantages, including high-quality effluent, compact design, and efficient removal of organic matter and nutrients (Meng et al., 2007).

## 5.2 Advanced oxidation processes

The treatment of landfill leachate using AOPs has garnered significant attention due to the complexity and variability of leachate composition (Fang et al., 2021). AOPs are characterized by their ability to generate highly reactive species, particularly hydroxyl radicals, which can non-selectively degrade a wide range of pollutants (Anandan et al., 2020). Usually there are four primary AOPs: the Fenton process, ozonation, photocatalysis, and electrochemical oxidation (Table 8) (Rekhate and Srivastava, 2020; Wang and Zhuan, 2020; Pandis et al., 2022).

### 5.2.1 Fenton process

The Fenton process is a chemical treatment method that involves the reaction of hydrogen peroxide ( $H_2O_2$ ) with ferrous iron ( $Fe^{2+}$ ) to produce hydroxyl radicals ( $\cdot OH$ ) (Benassi et al., 2021). These radicals are extremely reactive and can break down various organic pollutants, including dyes, pharmaceuticals, and other complex organic compounds in landfill leachate (Ateş and Argun, 2021). The mechanism of action in the Fenton process is homogeneous catalysis, where the reaction occurs in solution, allowing for the widespread generation of hydroxyl radicals (Liu et al., 2021). This process is particularly effective for treating organic-rich leachate, offering several advantages, such as high efficiency in degrading organic pollutants and operating under ambient conditions (Soltani et al., 2022). The Fenton process is effective for treating leachate with high concentrations of refractory organic compounds. It can remove 75%–90% of COD and 80%–95% of organic pollutants. However, the process is highly sensitive to operational conditions such as pH, temperature, and the ratios of Fe to  $H_2O_2$  and reaction time (O'Dowd and Pillai, 2020). A major limitation of the Fenton process is sludge production from iron salts, necessitating further treatment steps (Ziembowicz and Kida, 2022). Additionally, precise control over the reaction conditions is crucial to prevent the consumption of hydrogen peroxide by excessive iron, which would otherwise reduce the efficiency of pollutant degradation (Liu et al., 2024).

TABLE 8 AOPs in landfill leachate treatment (Rekhate and Srivastava, 2020; Wang and Zhuan, 2020; Pandis et al., 2022).

Process	Introduction	Mechanism of action	Target pollutants	Removal efficiency	Factors affecting removal efficiency	Advantages	Limitations
Fenton Process	A chemical process using hydrogen peroxide (H <sub>2</sub> O <sub>2</sub> ) and iron (Fe) catalysts to produce hydroxyl radicals for the oxidation of pollutants	Homogeneous catalysis	Organic pollutants, dyes, pharmaceuticals	Remove 35%–90% of COD and 80%–95% of organic pollutants	pH, temperature, Fe and H <sub>2</sub> O <sub>2</sub> ratio, reaction time	Highly efficient in degrading organic pollutants; Can operate at ambient conditions	Production of sludge; Requires post-treatment to remove iron; Sensitive to operational conditions
Ozonation	The application of ozone (O <sub>3</sub> ), a strong oxidizing agent, to break down organic and inorganic materials	Direct oxidation	Color, odor, microorganisms, some organic compounds	Remove 80%–90% of color and 70%–85% COD.	Ozone dosage, contact time, water quality	Effective for color and odor removal; Can disinfect; No sludge production	High energy consumption for ozone generation; May form by-products
Photocatalysis	Uses light to activate a catalyst (typically TiO <sub>2</sub> ), generating reactive species that degrade contaminants	Heterogeneous catalysis	Organic pollutants, bacteria, viruses	achieved up to 86.14% removal of endosulfan, 96.2% of methylene blue, 97.3% of rhodamine B, and 84.67% of crystal violet dye	Light intensity, catalyst type and concentration, pH	Can be powered by solar energy; Low energy cost; No sludge	Catalyst recovery and reuse; May require UV light
Electrochemical Oxidation	An electrochemical reaction where pollutants are oxidized at the anode surface or in the bulk solution	Direct and indirect oxidation	Dyes, pharmaceuticals, complex organic molecules	Remove 75%–95% of COD and up to 90% of ammonia	Electrode material, current density, conductivity, pH	No chemical addition needed; Precise control over process	High energy consumption; Electrode degradation; Sludge generation; Management

### 5.2.2 Ozonation

Ozonation employs ozone (O<sub>3</sub>), a potent oxidizing agent, to oxidize pollutants directly (Tripathi and Hussain, 2022). This process is highly effective for removing color, odor, and microorganisms from landfill leachate and degrading some organic compounds (Yang C. et al., 2021). The direct oxidation mechanism of ozonation allows for rapid reaction rates, making it a valuable option for enhancing the biodegradability of recalcitrant organic compounds in leachate (Yang Y. et al., 2021). Ozonation can remove 80%–90% of color and 70%–85% of COD. The efficiency of ozonation is influenced by ozone dosage, contact time, and the quality of water being treated. Its advantages include effective color and odor removal, disinfection capabilities, and the absence of sludge production (Hussain et al., 2022). However, ozonation requires significant energy to generate ozone gas, and the potential formation of by-products during the oxidation of certain pollutants can be a concern (Wang and Chen, 2020). Despite these limitations, ozonation remains a favored choice for specific applications within leachate treatment, particularly when targeting pollutants susceptible to oxidation by ozone.

### 5.2.3 Photocatalysis

Photocatalysis involves using light (typically UV) and a catalyst (commonly titanium dioxide, TiO<sub>2</sub>) to produce reactive species capable of degrading pollutants (Gopinath et al., 2020). This process is governed by heterogeneous catalysis, where the catalyst remains in a solid phase, distinct from the liquid phase in which the pollutants are dissolved (Iervolino et al., 2020). Photocatalysis is

effective against many contaminants, including organic pollutants, bacteria, and viruses, making it an attractive option for treating landfill leachate (Han et al., 2020). Factors affecting the efficiency of photocatalysis include light intensity, catalyst type and concentration, and the pH of the solution (Gusain et al., 2020). Photocatalysis offers the potential for low energy costs, especially when powered by solar energy, and the absence of sludge production (Ahmad et al., 2020). Catalyst recovery and reuse and dependence on UV light for optimal performance limit its widespread application (Kefeni and Mamba, 2020). Despite these challenges, photocatalysis presents a sustainable option for leachate treatment, especially in sunny climates where solar radiation can be effectively harnessed.

### 5.2.4 Electrochemical oxidation

Electrochemical oxidation utilizes an electrical current to facilitate the oxidation of pollutants at an electrode surface or within the bulk solution (Fitch et al., 2022). Through direct and indirect oxidation mechanisms, this method can target a broad spectrum of pollutants, including dyes, pharmaceuticals, and complex organic molecules (da Silva et al., 2021). This process is effective for treating leachate with a high load of organic pollutants and ammonia. Electrochemical oxidation can remove 75%–95% of COD and up to 90% of ammonia. One of the primary advantages of electrochemical oxidation is the absence of chemical additives coupled with precise control over the treatment process (Yang L. et al., 2021). This method offers an environmentally friendly approach to leachate treatment, albeit with considerations for

TABLE 9 Emerging technologies in landfill leachate treatment (Bhambri and Karn, 2020; Deng et al., 2020; Hasan et al., 2021; Rajesh Banu et al., 2021).

Technology	Introduction	Mechanism of action	Target pollutants	Removal efficiency	Factors affecting removal efficiency	Advantages	Limitations
Adsorption	A process where pollutants are captured on the surface of a material	Surface adsorption; Physical and chemical adsorption	Organic compounds, metals, dyes	Achieve up to 99% removal of emerging contaminants and 95.1% for strontium	Adsorbent material, contact time, concentration of pollutants, temperature	Low cost; Simplicity of design; No harmful by-products	Limited capacity; Requires regeneration or disposal of adsorbents
Ion Exchange	Involves the exchange of ions between a solid phase and a liquid phase to remove dissolved ions	Electrostatic exclusion	Heavy metals, hardness, radionuclides	Remove nutrients up to 98% for ammonium, 91.38% for arsenic, and over 99% colorants	Ion exchange capacity, flow rate, water chemistry	High specificity; Efficient for targeted contaminants	Regeneration of resins needed; Sensitive to competing ions
Simultaneous Partial Nitrification, Anammox, and Denitrification	An innovative biological process integrating partial nitrification, anammox, and denitrification to treat high-strength nitrogenous leachate efficiently	Partial Nitrification, Anammox, and Denitrification	Ammonia (NH <sup>4+</sup> ) Nitrite (NO <sup>2-</sup> ) Nitrate (NO <sup>3-</sup> )	SNAD achieves nitrogen removal efficiencies of 80%–94.56% for total inorganic nitrogen and over 90% for total nitrogen	Dissolved Oxygen Levels, Temperature, pH, Organic Carbon Availability, ammonia and Nitrite Concentrations	Cost-effective; High Efficiency; Low Sludge Production; Sustainable	Complex Control; Environmental Sensitivity; Startup Time; Monitoring Needs

high energy consumption and potential electrode degradation over time (Deng et al., 2020).

### 5.3 Other technologies

As environmental standards become increasingly stringent, adopting innovative and efficient treatment technologies is essential. Emerging technologies for treating landfill leachate are pivotal in addressing the environmental challenges posed by the complex and variable composition. These technologies, including adsorption, ion exchange, and biological nutrient removal (BNR), offer innovative solutions to remove many pollutants, from organic compounds and heavy metals to nitrogen and phosphorus (Table 9) (Bhambri and Karn, 2020; Deng et al., 2020; Hasan et al., 2021; Rajesh Banu et al., 2021).

#### 5.3.1 Adsorption

Adsorption is a versatile and widely implemented method for contaminant removal, characterized by the adherence of pollutants onto the surface of an adsorbent material (Shen et al., 2023). This process can occur through physical adsorption, driven by weak van der Waals forces, or chemical adsorption, involving stronger covalent bonds (Rathi and Kumar, 2021). The mechanism is influenced by the surface area, porosity, and chemical nature of the adsorbent, as well as the properties of the pollutants (Ambaye et al., 2021). Adsorption is particularly effective for removing organic compounds, heavy metals, and dyes from leachate, making it a valuable tool for improving water quality (Saravanan et al., 2021). The adsorption efficiency is determined by factors such as the type and concentration of pollutants, contact time, adsorbent material, and environmental conditions like temperature (Rathi and Kumar, 2021). Activated carbon is among the most commonly used

adsorbents due to its high surface area and porosity, although other materials like biochar, zeolites, and engineered nanomaterials are also employed (Sharma et al., 2022). The primary advantages of adsorption include its simplicity, cost-effectiveness, and the absence of harmful by-products. The finite adsorption capacity of materials, which necessitates their periodic regeneration or replacement (Sharma et al., 2024). Similar to coagulation-flocculation, the adsorption method also generates sludge, which consists of spent adsorbent materials saturated with contaminants (Kurniawan et al., 2021a). The management of this adsorption sludge is a critical issue, as it involves the disposal or regeneration of spent adsorbents. Regeneration can often be achieved through thermal, chemical, or biological methods to restore the adsorbent's capacity for reuse. However, these processes can be energy-intensive and costly, and not all adsorbents can be regenerated effectively. Disposal of non-regenerable adsorbents must be conducted in an environmentally safe manner, often requiring landfilling or incineration, which introduces additional costs and environmental concerns. The environmental impact and cost of managing adsorption sludge are important factors in assessing the overall sustainability of the adsorption process.

#### 5.3.2 Ion exchange

Ion exchange is a specialized technique designed for removing dissolved ions from wastewater, functioning through the reversible exchange of ions between a liquid and a solid phase (Liu et al., 2023). Ion exchange relies on electrostatic interactions between charged particles, making it particularly suitable for targeting specific ionic contaminants such as heavy metals, hardness-causing ions (e.g., calcium and magnesium), and radionuclides (Liu et al., 2023). The performance of ion exchange systems is influenced by the resin or medium's ion exchange capacity, the leachate's flow rate, and the water's chemical composition, including the presence of competing

ions (Xu et al., 2024). Factors such as resin specificity, regeneration requirements, and operational parameters must be carefully managed to optimize performance (Clark et al., 2024). Ion exchange resins, synthetic or natural, are chosen based on their selectivity for certain ions, offering high specificity and efficiency in contaminant removal (Wang et al., 2024). Ion exchange offers the advantage of high specificity and efficiency for targeted contaminants, providing a tailored approach to leachate treatment (Aziz et al., 2023). The need for regular resin regeneration with chemicals like brine, which can generate secondary waste streams (Sahu, 2021). It is sensitive to competing ions, which can reduce the efficiency of targeted ion removal, requiring careful water chemistry management (Chen et al., 2023).

### 5.3.3 Simultaneous partial nitrification, anammox, and denitrification (SNAD)

SNAD is an emerging biological treatment technology that integrates partial nitrification, anaerobic ammonium oxidation (anammox), and denitrification processes within a single reactor (Singh et al., 2022). This integrated approach shows great potential for treating landfill leachate with high ammonia concentrations. The SNAD process involves three main steps: partial nitrification, which converts part of the ammonia into nitrite; anammox, which utilizes the remaining ammonia and the produced nitrite to generate nitrogen gas; and denitrification, which reduces any remaining nitrate to nitrogen gas. These processes occur simultaneously in the same reactor, achieving efficient nitrogen removal. SNAD achieves nitrogen removal efficiencies of 80%–94.56% for total inorganic nitrogen and over 90% for total nitrogen, while also reducing oxygen demand and sludge production compared to conventional methods (Zheng et al., 2016). SNAD technology offers several advantages for landfill leachate treatment, including high nitrogen removal efficiency, energy savings due to lower oxygen and organic carbon requirements compared to traditional nitrification-denitrification processes, reduced operational costs, smaller footprint due to the integration of three processes in one reactor, and less sludge production, which lowers sludge handling costs (Su et al., 2022). Despite its promising prospects, SNAD technology faces challenges such as the need for precise control of parameters like dissolved oxygen and pH, long startup times due to the slow growth of anammox bacteria, and sensitivity to temperature. Future research will focus on optimizing operational parameters, enhancing system stability, and exploring innovative reactor designs to further improve the application of SNAD technology in landfill leachate treatment.

In summary, when selecting an appropriate landfill leachate treatment technology, it is essential to consider the balance between efficiency, cost, and sustainability (Özdemir et al., 2020; Cherni et al., 2021; Dereli et al., 2021; Saadatlu et al., 2023). Membrane technologies are highly effective, capable of removing up to 99% of dissolved salts and other specific pollutants. However, their application involves significant capital and operational costs, particularly with RO, due to the expenses associated with energy use, membrane replacement, and maintenance. Despite these costs, advancements in technology are gradually improving the sustainability of membrane processes, although energy use and membrane disposal remain concerns. AOPs offer another robust

solution, particularly for degrading resistant organic compounds and pathogens. Nevertheless, they come with high operational costs, mainly due to the chemical inputs and energy demands, such as for ozone generation or UV lamps. These factors also contribute to moderate sustainability concerns, especially regarding potential secondary pollution. Emerging technologies provide a more cost-effective and sustainable approach. While their efficiency varies depending on the materials and infrastructure used, they excel in targeting specific contaminants like heavy metals and nutrients. These technologies emphasize the use of recyclable materials and natural processes, thereby enhancing environmental friendliness. The choice of leachate treatment technology should be guided by specific treatment goals, regulatory requirements, and sustainability objectives, balancing efficiency with environmental and economic considerations to achieve effective and responsible leachate management.

## 6 Comprehensive treatment system

The cornerstone of addressing the leachate challenge lies in implementing a comprehensive treatment system that synergistically combines various treatment methodologies to remove contaminants effectively and meet or exceed regulatory discharge standards (Abdelfattah and El-Shamy, 2024). These systems are designed not only to mitigate the adverse environmental impacts of leachate but also to contribute to the sustainability of landfill operations by enabling the possibility of resource recovery and reuse of treated water (Mojiri et al., 2020).

### 6.1 Comprehensive treatment system

A comprehensive landfill leachate treatment system is a multi-faceted and dynamic approach that mitigates leachate contaminants' environmental impacts through a well-orchestrated sequence of processes (Figure 2) (Britz, 2020; Babaei et al., 2021; Fang et al., 2021; Righetto et al., 2021; Teng et al., 2021; Nath and Debnath, 2022). Initiating with pretreatment, the system begins by addressing the more tangible aspects of leachate—easily separable solids are removed, and the pH is carefully adjusted. This foundational step is about preparing the leachate for the complex journey ahead and safeguarding the intricate mechanisms of downstream processes from potential abrasion, blockages, and harmful chemical interactions. As the leachate advances, it encounters the primary treatment phase, a sophisticated interplay between biology and chemistry. Here, living microbes engage in a digestive ballet, utilizing both aerobic and anaerobic pathways to metabolize organic pollutants, thereby reducing the load of substances that demand oxygen in the water. Concurrently, a suite of physical-chemical treatments, each a targeted strike—coagulation, flocculation, and flotation—work in concert to clear out suspended solids, strip away color, and separate particulate organic matter. This systematic approach continues into the secondary treatment, where a more refined attack is launched on dissolved organic compounds that have eluded the grasp of biological processes. This stage employs the precision of AOPs, the fine sieve of membrane filtration technologies like reverse



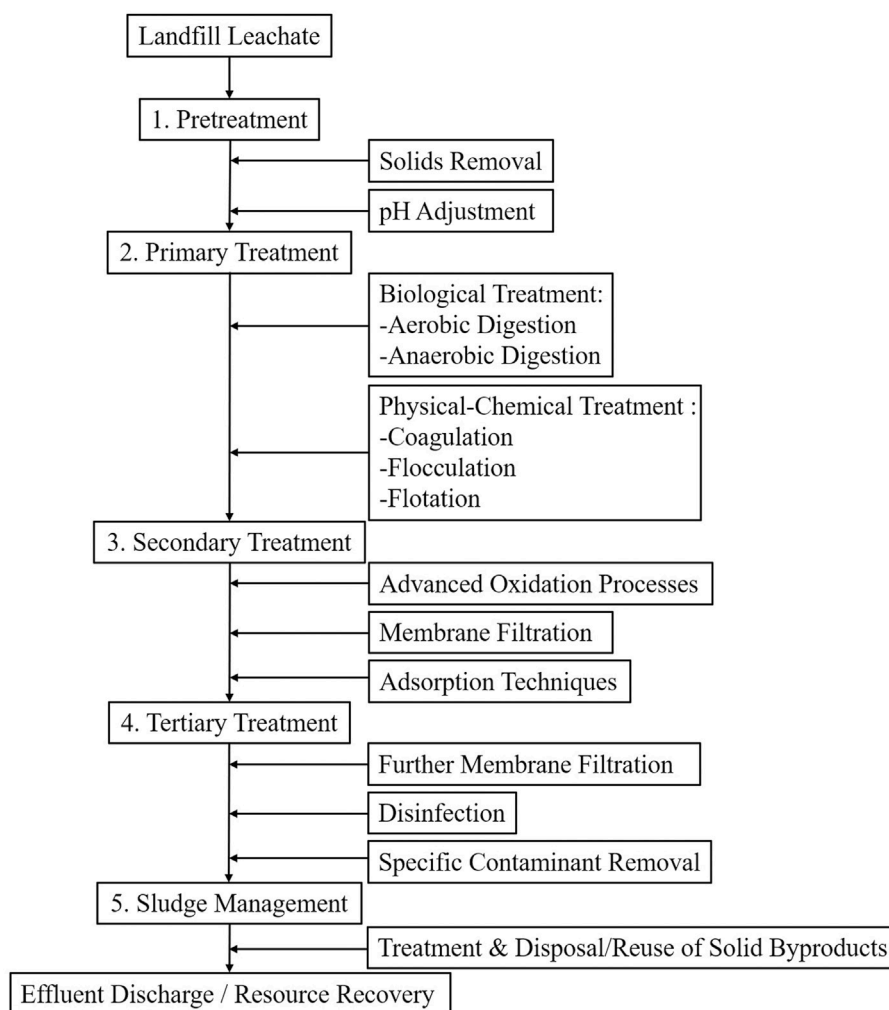
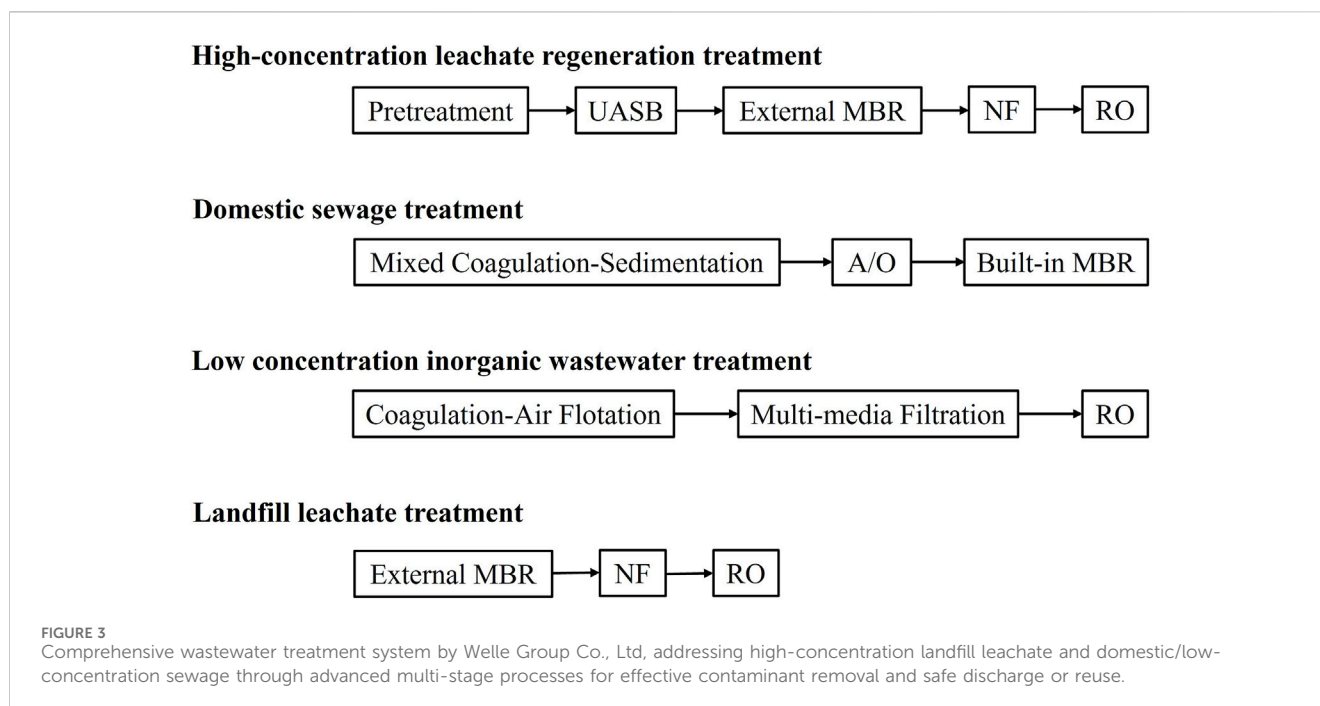


FIGURE 2  
Components of a comprehensive treatment system.

osmosis, and the binding affinities of adsorption techniques, each method meticulously selected to ensure no contaminant is left unchallenged. Nearing the end, the leachate undergoes tertiary treatment—an exemplary display of purification, where the effluent is polished to meet stringent quality standards. Further, membrane filtration stands sentinel against the minutest of pollutants, disinfection processes wage war on pathogenic microorganisms, and additional specific treatments meticulously remove any lingering traces of heavy metals or nitrogen compounds.

The comprehensive landfill leachate treatment system's responsibility does not end with the effluent; sludge management remains a testament to the ethos of sustainability that underpins the entire operation (Torretta et al., 2017). This critical phase manages the solid byproducts of the leachate's treatment to minimize further environmental impact, reclaim valuable resources, and embody the cyclic nature of waste transformed into worth (Remmas et al., 2023). Implementing a comprehensive landfill leachate treatment system is a paragon of environmental responsibility and technological ingenuity, offering multifarious benefits that resonate far beyond the confines of waste management. Such systems are critical in preventing the percolation of hazardous contaminants into the groundwater and

surface waters, safeguarding the aquatic ecosystems and public health against the potential onslaught of toxic substances (Ravindiran et al., 2023). By utilizing progressively targeted treatments that include biological degradation, chemical transformation, and physical separation, these systems adeptly reduce the concentrations of organic and inorganic pollutants, heavy metals, and pathogens to meet stringent regulatory standards (Rathod et al., 2024). Beyond the immediate environmental benefits, these systems embrace the principles of a circular economy, often allowing for the recovery of resources such as biogas, which can be converted to energy, and treated water, which can be repurposed for industrial or agricultural use (Zarei, 2020). This contributes to the conservation of natural resources and offers economic advantages by offsetting operational costs and generating revenue (Ekins and Zenghelis, 2021). Comprehensive treatment systems are committed to sustainable development as they adapt to the ever-changing waste composition and emerging contaminants, ensuring resilience against future environmental challenges. Thus, these systems' significance lies in their immediate efficacy in pollution control and their strategic contribution to long-term environmental sustainability and economic viability (Mojiri et al., 2020).



## 6.2 Example of comprehensive treatment system for landfill leachate

In the bustling urban environment of Changsha City, the capital of Hunan Province, China (28.2282°N, 112.9388°E), located 35 km north in Qiaoyi Town, Wangcheng District, the Changsha Municipal Solid Waste Treatment Site stands as a pivotal solution to the city's waste management challenges. Operated by Welle Environmental Protection Technology Group Co., Ltd., this project exemplifies a cutting-edge approach to handling landfill leachate treatment (Welle Environmental Protection Technology Group Co.L, 2024). As the sole comprehensive co-processing site for municipal solid waste in Changsha, it is responsible for managing domestic waste from the city's expansive area, municipal sludge from 13 sewage treatment plants, and all leachate in the reservoir area. The facility is ingeniously divided into two functional units: landfill and incineration plant, with 80% of domestic waste processed through incineration for electricity generation and the remaining 20% allocated for landfilling. The core challenge in managing landfill leachate stems from its highly concentrated and variable composition, which can severely impact local water sources and the broader environment.

To tackle this, Welle Group Co., Ltd has designed a comprehensive leachate treatment system addressing both landfill leachate and domestic/low-concentration sewage (Figure 3). The process for high-concentration leachate regeneration is a testament to engineering excellence, employing a sophisticated combination of "pretreatment + up-flow anaerobic sludge blanket (UASB) + external membrane bioreactors (MBR) + nanofiltration (NF) + reverse osmosis (RO). This multi-stage approach ensures the thorough removal of contaminants, making the leachate safe for discharge or reuse. In addition to the high-concentration leachate treatment, the facility also addresses the treatment of domestic and low-concentration inorganic sewage. The domestic sewage treatment follows a "mixed coagulation and sedimentation + anaerobic-aerobic (A/O) + built-in

MBR" process. In contrast, the low-concentration inorganic sewage is treated through "coagulation and air flotation + multi-media filtration + RO." These processes are designed to efficiently handle the varied waste streams entering the facility, ensuring that all forms of wastewater are effectively managed. The landfill leachate treatment, in particular, employs an "external MBR + NF + RO" process. This specific treatment path is crucial for dealing with the highly contaminated leachate from the landfill, effectively reducing its pollutant load before release or reuse. The concentrated liquid produced from these treatment processes undergoes advanced oxidation/reduction treatment, showcasing the facility's commitment to minimizing environmental impact. This liquid is then cleverly returned to the factory for consumption, embodying the principles of sustainability and resource recovery. The achievements of this project are both tangible and impactful. After undergoing the comprehensive treatment processes, the landfill leachate meets the stringent emission standards outlined in Table 2 of the "Pollution Control Standards for Domestic Waste Landfills" (GB16889-2008) (Table 10). Similarly, the effluent from the three sewage systems at the incineration plant complies with the "Water Quality for Industrial Water for Recycling of Urban Wastewater" (GB/T19923-2005), which sets the water quality standards for supplementary water in open circulating water systems. The project addresses the immediate need for waste and leachate treatment and contributes to resource conservation and pollution reduction goals. It stands as a testament to the power of technology and strategic planning in solving the complex environmental challenges of our time.

## 6.3 Optimizing integrated landfill leachate treatment systems

In environmental management, optimizing and modeling an integrated system for landfill leachate treatment serve as

TABLE 10 Emission standards in Table 2 of the 'pollution control standards for municipal solid waste landfills' (GB16889-2008).

Pollutant control item	Emission concentration limit
Color (Dilution times)	40
Chemical Oxygen Demand (COD <sub>Cr</sub> ) (mg/L)	100
Biochemical Oxygen Demand (BOD <sub>5</sub> ) (mg/L)	30
Suspended Solids (SS) (mg/L)	30
Total Nitrogen (TN) (mg/L)	30
Ammonia Nitrogen (NH <sub>3</sub> -N) (mg/L)	25
Total Phosphorus (TP) (mg/L)	3
Fecal Coliform Group (CFU/L)	10,000
Total Mercury (Hg) (mg/L)	0.001
Total Cadmium (Cd) (mg/L)	0.01
Total Chromium (Cr) (mg/L)	0.1
Hexavalent Chromium (Cr <sup>6+</sup> ) (mg/L)	0.05
Total Arsenic (As) (mg/L)	0.1
Total Lead (Pb) (mg/L)	0.1

cornerstones for enhancing system efficiency, curbing expenditures, and adhering to environmental norms (Awewomom et al., 2024). The essence of this optimization lies in crafting a flexible treatment architecture that proficiently manages the intricate and diverse makeup of leachate while remaining nimble to fluctuations in waste inputs and legislative edicts. A synergy of suitable treatment modalities—such as UASB, MBR, NF, and RO—complements the specific leachate profile, ensuring that downstream processing is primed for optimal treatment (Huang et al., 2024). Operational parameters like retention time, aeration rate, and chemical dosing are meticulously fine-tuned to bolster the removal of pollutants, and real-time monitoring systems are deployed for on-the-fly adjustments. The model's sophistication extends to embodying resource recovery, advocating for repurposing byproducts like biogas into energy and advocating for the reuse of treated water.

The modeling facet delves into the assimilation of comprehensive data, which informs the simulation of the system's multifaceted treatment dynamics through advanced mathematical constructs (Ergene et al., 2022). These models are enriched with predictive analytics and scenario simulations, courtesy of machine learning algorithms, paving the way for a thorough understanding of potential operational outcomes. Validation through empirical data ensures the model's fidelity, while optimization algorithms distill the operational sweet spot that marries environmental efficacy with economic prudence (Podlasek, 2023). This ongoing, iterative process is honed by real-world performance feedback and shifting regulatory frameworks, propelling landfill leachate treatment toward unparalleled operational finesse.

## 7 Challenges and future

In addressing the complex challenges of landfill leachate treatment, it is crucial to consider the economic, operational, and emerging contaminant-related hurdles that impede the efficacy of current systems. This section delves into the multifaceted issues faced by waste management facilities, highlighting the significant financial burdens, operational difficulties due to leachate variability, and the rising threat of emerging contaminants like pharmaceuticals and microplastics. These challenges necessitate innovative solutions and strategic approaches to ensure effective, sustainable leachate management in the future.

### 7.1 Comprehensive challenges in landfill leachate treatment: Economic, operational, and emerging contaminant

The foremost economic challenge in landfill leachate treatment lies in the high capital and operational costs associated with advanced treatment systems (El-Saadony et al., 2023). Technologies such as RO, NF, and MBRs are effective in removing a wide range of contaminants but require substantial financial investment. These systems are not only expensive to install but also incur ongoing costs related to energy consumption, maintenance, and the need for skilled personnel to operate and monitor the processes. The financial burden is further amplified by the variability in leachate composition, which demands adaptable systems capable of handling fluctuations in pollutant concentrations. This variability necessitates continuous system optimization, leading to additional costs associated with adaptive management and process upgrades (Yadav et al., 2021). Table 11, which outlines the costs of various representative leachate treatment technologies, underscores the financial strain on waste management facilities (Gerald et al., 1998; Randall and Ubay Cokgor, 2000; Mahamuni and Adewuyi, 2010; Ju-Chang Huang, 2017; Ighalo et al., 2022; Pérez et al., 2022; Kurniawan et al., 2023). Moreover, the costs are not merely limited to initial capital outlays but extend to operational expenses that accumulate over the system's lifecycle (Abdelfattah and El-Shamy, 2024). As such, the economic challenges of landfill leachate treatment call for innovative approaches to reduce costs while maintaining treatment efficacy.

Operationally, the treatment of landfill leachate is fraught with difficulties due to the high variability of leachate quality. This variability is influenced by factors such as seasonal changes, waste composition, and the age of the landfill, all of which affect the concentration and types of pollutants present in the leachate. The dynamic nature of leachate composition requires continuous monitoring and adjustment of treatment processes to ensure consistent performance (Upadhyay et al., 2023). Operators must continuously monitor and adjust treatment processes, requiring skilled personnel and sophisticated control systems. The potential for system failure or suboptimal performance poses significant environmental risks, including groundwater contamination and non-compliance with discharge regulations, leading to potential fines and reputational damage. Addressing these operational challenges requires a holistic approach that integrates cost-effective treatment technologies with operational efficiency and

TABLE 11 Costs of representative leachate treatment technologies (Gerald et al., 1998; Randall and Ubay Cokgor, 2000; Mahamuni and Adewuyi, 2010; Huang, 2017; Ighalo et al., 2022; Pérez et al., 2022; Kurniawan et al., 2023).

Treatment method	Approximate cost (/m <sup>3</sup> of treated wastewater)
Adsorption	0.038–51,120 USD The main cost is depended on the adsorbent Adsorbent Cost Performance: - Very cheap: <1 \$/mol chemical species - Most adsorbents: 1–200 \$/mol chemical species - Very expensive: >200 \$/mol chemical species
Air-stripping	0.0134 USD
Reverse osmosis	0.5 USD
Biological nutrient removal	0.615USD
Ultrafiltration	0.69 USD
Advanced oxidation processes	US/UV/O <sub>3</sub> : 23.717 USDUS/UV/H <sub>2</sub> O <sub>2</sub> : 17.216 USDUS/UV: 6.821 USD

environmental stewardship (Kundariya et al., 2021). The development of more energy-efficient membrane technologies or the adoption of natural treatment solutions, such as constructed wetlands, offers promising avenues for reducing operational difficulties and associated costs (Kataki et al., 2021). For instance, the development of more energy-efficient membrane technologies or the adoption of natural treatment solutions, such as constructed wetlands, offers promising avenues for reducing operational difficulties and associated costs. Moreover, embracing circular economy principles, where treated leachate is reused for industrial or agricultural purposes, can help mitigate operational challenges while contributing to sustainability goals. (Bakan et al., 2022; Das et al., 2023).

The emergence of new contaminants, such as pharmaceuticals, personal care products, microplastics, and other micropollutants, presents a significant challenge to traditional wastewater and landfill leachate treatment systems (Kumar et al., 2023). These substances, often called emerging contaminants (ECs), have become a focal point for environmental scientists and engineers due to their potential to bypass conventional treatment processes and enter the aquatic environment, posing risks to wildlife and human health (Ahmed et al., 2021; Morin-Crini et al., 2021). Traditional wastewater and landfill leachate treatment systems were designed to remove organic matter, nutrients, and major pollutants (Lindamulla et al., 2022). However, these systems often lack the specificity to capture and degrade ECs effectively, many of which are designed to be biologically active and resistant to degradation (Teng and Chen, 2023). Pharmaceuticals, for example, are engineered to resist metabolic breakdown to ensure their efficacy, making them persistent in the environment (González-González et al., 2022). Microplastics, conversely, are resistant to biodegradation due to their synthetic polymer composition, accumulating in water bodies and potentially entering the food chain (Huang et al., 2021). The presence of ECs in water and leachate streams can significantly reduce the treatment efficiency of these systems (Rout et al., 2021b). Certain contaminants can inhibit microbial activity in biological treatment processes, reducing the degradation rate of

organic pollutants and altering the microbial community structure (Aragaw, 2021). For example, antibiotics in wastewater can inhibit the growth of bacteria critical to the biological treatment processes, leading to a decrease in overall treatment efficiency (Zhu et al., 2021). Moreover, some ECs can form complex compounds with other elements in the wastewater, making them more difficult to remove and requiring additional treatment stages or more advanced treatment technologies (Shahid et al., 2021). Notably, based on the environmental risks and regulatory status of chemicals, and following technical feasibility and socioeconomic assessments, the Ministry of Ecology and Environment of China published the latest list of key controlled emerging contaminants in 2023 (Table 12) (China, 2022). The newly listed contaminants are now subject to environmental risk management measures, including those related to their manufacture, use, import, or export. Some contaminants have transition periods or exemptions. This initiative highlights the government's commitment to addressing emerging contaminants and urges relevant departments to take action to prevent environmental and public health risks. For landfill leachate treatment, the presence of these new pollutants complicates the process, often requiring upgrades or advanced technologies to effectively manage them. Proactively addressing these contaminants can improve treatment efficiency and reduce environmental contamination risks. It is worth mentioning that, Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals widely used for their water- and grease-resistant properties, found in various consumer products and industrial applications (Venkatesh Reddy et al., 2024). Their strong carbon-fluorine bonds make them highly persistent and resistant to conventional water treatment methods, posing significant challenges for removal (Jin et al., 2021). Traditional processes like coagulation, sedimentation, and standard filtration are largely ineffective against PFAS, necessitating the use of advanced technologies (Nguyen and Le Tran, 2024). Methods such as granular activated carbon adsorption, ion exchange, and high-pressure membrane filtration (nanofiltration and reverse osmosis) show varying degrees of success but often involve high operational costs and complex waste management (Lee et al., 2022). Emerging technologies like electrochemical treatment, plasma-based processes, and combined treatment approaches offer potential but require further development and investment (Blotevogel et al., 2023). The inclusion of PFAS-specific treatments increases operational complexity and costs for water treatment facilities, which must adapt to stringent regulatory standards. Research continues to focus on more efficient and cost-effective removal technologies to address the persistent nature of PFAS and protect public health and the environment.

The impact of emerging contaminants on the efficiency of wastewater and landfill leachate treatment systems presents a complex challenge that requires immediate and sustained attention. While these contaminants pose significant environmental and public health risks, they also provide an impetus for innovation in treatment technologies and strategies. Addressing this challenge will require a combination of technological advancement, regulatory action, public education, and international cooperation to ensure the safety and

TABLE 12 2023 List of Key Controlled New Pollutants posted by Ministry of Ecology and Environment of the People's Republic of China (China, 2022).

No.	New pollutant name	CAS no.	Main environmental risk control measures
1	Perfluorooctane sulfonic acid (PFOS) and its salts and perfluorooctane sulfonyl fluoride	1763–23–1 307–35–7 2795–39–3 29,457–72–5 29,081–56–9 70,225–14–8 56,773–42–3 251,099–16–8	<ol style="list-style-type: none"> <li>1. Prohibit production.</li> <li>2. Prohibit processing and use (except for certain uses such as firefighting foam until 31 Dec 2023).</li> <li>3. Conduct mandatory clean production audits for companies using PFOS for firefighting foam.</li> <li>4. Require environmental management clearance for import/export until 1 Jan 2024.</li> <li>5. Manage as hazardous waste if no longer in use or declared as waste</li> <li>6. Establish soil pollution prevention measures for enterprises involving PFOS.</li> </ol>
2	Perfluorooctanoic acid (PFOA) and its salts and related compounds	—	<ol style="list-style-type: none"> <li>1. Prohibit new production facilities.</li> <li>2. Prohibit production and use (except for certain uses in semiconductor manufacturing, photography coatings, protective textiles, invasive medical devices, and other specified uses).</li> <li>3. Conduct mandatory clean production audits for companies using PFOA.</li> <li>4. Require environmental management clearance for import/export.</li> <li>5. Manage as hazardous waste if no longer in use or declared as waste</li> <li>6. Establish soil pollution prevention measures for enterprises involving PFOA.</li> </ol>
3	Decabromodiphenyl ether	1163–19–5	<ol style="list-style-type: none"> <li>1. Prohibit production and use (except for certain uses in textiles, plastic casings, polyurethane foam until 31 Dec 2023).</li> <li>2. Conduct mandatory clean production audits for companies using decabromodiphenyl ether.</li> <li>3. Require environmental management clearance for import/export until 1 Jan 2024.</li> <li>4. Manage as hazardous waste if no longer in use or declared as waste</li> <li>5. Establish soil pollution prevention measures for enterprises involving decabromodiphenyl ether</li> </ol>
4	Short-chain chlorinated paraffins	85,535–84–8 68,920–70–7 71,011–12–6 85,536–22–7 85,681–73–8 108,171–26–2	<ol style="list-style-type: none"> <li>1. Prohibit production and use (except for certain uses in rubber, leather, lubricants, decorative lights, paints, adhesives, metal processing, and flexible PVC until 31 Dec 2023).</li> <li>2. Conduct mandatory clean production audits for companies using short-chain chlorinated paraffins.</li> <li>3. Require environmental management clearance for import/export until 1 Jan 2024.</li> <li>4. Manage as hazardous waste if no longer in use or declared as waste</li> <li>5. Establish soil pollution prevention measures for enterprises involving short-chain chlorinated paraffins</li> </ol>
5	Hexachlorobutadiene	87–68–3	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export.</li> <li>2. Ensure compliance with emission standards for related enterprises.</li> <li>3. Manage as hazardous waste if no longer in use or declared as waste</li> <li>4. Establish soil pollution prevention measures for enterprises involving hexachlorobutadiene</li> </ol>
6	Pentachlorophenol and its salts and esters	87–86–5 131–52–2 27,735–64–4 3772–94–9 1825–21–4	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export</li> <li>2. Manage as hazardous waste if no longer in use or declared as waste</li> <li>3. Establish soil pollution prevention measures for enterprises involving pentachlorophenol</li> </ol>
7	Trifluralin	115–32–2 10,606–46–9	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export.</li> <li>2. Manage as hazardous waste if no longer in use or declared as waste</li> </ol>
8	Perfluorohexane sulfonic acid (PFHxS) and its salts and related compounds	—	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export.</li> <li>2. Manage as hazardous waste if no longer in use or declared as waste</li> </ol>
9	Dechlorane Plus and its isomers	13,560–89–9 135,821–03–3 135,821–74–8	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export from 1 Jan 2024</li> <li>2. Manage as hazardous waste if no longer in use or declared as waste</li> </ol>
10	Dichloromethane	75–09–2	<ol style="list-style-type: none"> <li>1. Prohibit production of paint removers containing dichloromethane</li> <li>2. Prohibit use in cosmetics</li> <li>3. Ensure compliance with volatile organic compounds content limits and emission standards.</li> <li>4. Conduct regular environmental risk assessments.</li> <li>5. Establish soil pollution prevention measures for enterprises involving dichloromethane.</li> <li>6. Strictly control soil pollution risks</li> </ol>

(Continued on following page)

TABLE 12 (Continued) 2023 List of Key Controlled New Pollutants posted by Ministry of Ecology and Environment of the People's Republic of China (China, 2022).

No.	New pollutant name	CAS no.	Main environmental risk control measures
11	Chloroform	67-66-3	<ol style="list-style-type: none"> <li>1. Prohibit production of paint removers containing chloroform</li> <li>2. Ensure compliance with volatile organic compounds content limits and emission standards.</li> <li>3. Conduct regular environmental risk assessments.</li> <li>4. Establish soil pollution prevention measures for enterprises involving chloroform.</li> <li>5. Strictly control soil pollution risks</li> </ol>
12	Nonylphenol	25,154-52-3 84,852-15-3	<ol style="list-style-type: none"> <li>1. Prohibit use as pesticide adjuvants.</li> <li>2. Prohibit use in the production of nonylphenol ethoxylates.</li> <li>3. Prohibit use in cosmetics</li> </ol>
13	Antibiotics	—	<ol style="list-style-type: none"> <li>1. Strictly enforce prescription requirements for antibacterial drugs.</li> <li>2. Manage antibiotic residues as hazardous waste.</li> <li>3. Ensure compliance with emission standards for pharmaceutical industries</li> </ol>
14	Phased-out group (hexabromocyclododecane, chlordane, mirex, hexachlorobenzene, DDT, $\alpha$ -hexachlorocyclohexane, $\beta$ -hexachlorocyclohexane, lindane, endosulfan as a raw material and its isomers, and polychlorinated biphenyls)	—	<ol style="list-style-type: none"> <li>1. Prohibit production, use, and import/export.</li> <li>2. Manage as hazardous waste if no longer in use or declared as waste.</li> <li>3. Strictly control soil pollution risks according to soil pollution risk management standards</li> </ol>

sustainability of water resources in the face of emerging environmental threats.

## 7.2 Future research

Embracing the future of landfill leachate treatment demands a multi-faceted approach: pioneering new materials for adsorption and catalysis, harnessing microbial genetic engineering for targeted bioremediation, and committing to process intensification for enhanced efficiency. These innovative pathways herald a new era of sustainability and effectiveness in managing complex waste challenges.

### 7.2.1 New materials for adsorption and catalysis

Future research in landfill leachate treatment increasingly focuses on developing new materials for adsorption and catalysis, driven by the need for more efficient, cost-effective, and sustainable treatment solutions. These materials are at the forefront of addressing complex pollutants, including emerging contaminants that traditional treatment methods struggle to remove. Advanced adsorbents, such as modified biochars, nanocomposites, and metal-organic frameworks (MOFs), are being explored for their high surface area, porosity, and tunable surface chemistry, which can significantly enhance the adsorption of pollutants (Zango et al., 2020). For instance, biochars produced from agricultural waste can be engineered at the nano-scale to improve their adsorption capacity for specific contaminants like pharmaceuticals and heavy metals (Bhandari et al., 2023). Catalytic materials are equally crucial for breaking down pollutants through AOPs. New photocatalysts, including quantum dots and graphitic carbon nitride (g-C<sub>3</sub>N<sub>4</sub>), offer the potential for more efficient light absorption and utilization, enabling the degradation of contaminants under visible light and thus reducing energy consumption (Wang et al., 2020). The development of these materials aims to enhance the efficiency and specificity of contaminant removal and minimize secondary pollution and the use of harsh chemicals in the treatment

process (Ahmed et al., 2021). Research also focuses on the regeneration and reuse of these materials to ensure the sustainability of the treatment processes (Baskar et al., 2022). Innovative approaches to regenerate spent adsorbents and catalysts, such as thermal, chemical, and ultrasonic methods, are being studied to extend their life and reduce operational costs (Ferella, 2020). Overall, exploring new materials for adsorption and catalysis represents a dynamic and promising area of landfill leachate treatment, offering potential breakthroughs in efficiency, sustainability, and tackling a broader spectrum of pollutants.

### 7.2.2 Microbial genetic engineering

Microbial genetic engineering stands at the forefront of biotechnological innovations in landfill leachate treatment (Saeed et al., 2022). The natural biodegradation processes employed by microorganisms offer a sustainable and efficient means of removing organic pollutants from leachate (Pisharody et al., 2022). However, leachate's complex and toxic nature often limits the effectiveness of native microbial communities (Nimonkar et al., 2022). Genetic engineering presents an opportunity to overcome these limitations by enhancing the metabolic capabilities of microorganisms, enabling them to degrade a wider array of contaminants, including recalcitrant and emerging pollutants (Haripriyan et al., 2022). The manipulation of microbial genomes involves introducing genes responsible for producing specific enzymes that can break down complex molecules or modifying existing metabolic pathways to increase their efficiency and specificity (Michalska et al., 2020). This can lead to the creation of microbial strains capable of rapid pollutant degradation, reduced biomass production, and enhanced tolerance to high pollutant concentrations and toxic substances (Maqsood et al., 2023). Ongoing research focuses on identifying key enzymatic pathways for the degradation of specific contaminants, developing genetic tools for efficient genome editing, and integrating genetically engineered microbes into existing treatment processes (Saravanan et al., 2022). Additionally, the ecological safety of releasing genetically modified organisms into environmental treatment

systems is a critical consideration, necessitating rigorous containment strategies and risk assessments.

### 7.2.3 Process enhancement

Process intensification in landfill leachate treatment aims to enhance the efficiency and effectiveness of treatment processes by integrating and optimizing physical, chemical, and biological methods. The goal is to achieve more with less—reducing the footprint, energy consumption, and operational costs of treatment systems while maximizing pollutant removal efficiency (Cardoso et al., 2021). This can involve the development of novel reactor designs that facilitate enhanced contact between the leachate and treatment agents, using AOPs to break down complex organic molecules, and integrating membrane technologies for selective pollutant removal and water recovery (Titchou et al., 2021). Process intensification can leverage the synergies between different treatment modalities, such as combining adsorption processes with biodegradation to handle a broader range of contaminants more effectively.

Future research directions include exploring hybrid treatment systems that integrate emerging materials for adsorption and catalysis with genetically engineered microbial processes, developing energy-efficient AOPs, and optimizing process parameters through advanced modeling and control strategies. The aim is to develop compact, modular treatment systems that can be easily adapted to varying leachate compositions and volumes, ensuring robust and sustainable leachate management strategies for the future.

### 7.2.4 Circular economy and sustainability in future landfill leachate treatment

The circular economy and sustainability principles are increasingly influencing the development and adoption of future landfill leachate treatment technologies, steering them towards more environmentally friendly and resource-efficient solutions (Bandala et al., 2021). This shift is a response to the growing awareness of the environmental impacts of waste management practices and the urgent need to transition towards more sustainable models of production and consumption. The role of circular economy concepts in shaping future leachate treatment technologies is profound, focusing on waste minimization, resource recovery, and the closed-loop reuse of materials and water (Yusuf et al., 2020).

At the heart of the circular economy is reducing waste and preventing pollution (Dincă et al., 2022). Future landfill leachate treatment technologies are being designed with a preventative approach, aiming to minimize the generation of leachate and its associated contaminants at the source (Bandala et al., 2021). This can be achieved through better landfill design, including impermeable liners and covers and waste pre-treatment to reduce its leachate-generating potential. By addressing the problem at its source, these technologies contribute to a more sustainable and less resource-intensive waste management system. Another cornerstone of the circular economy is the recovery and reuse of resources, which plays a significant role in shaping leachate treatment technologies (Puntillo et al., 2021). Emerging technologies are not only aimed at treating leachate to meet environmental discharge standards but also at recovering valuable resources from it (Li and Liu, 2021). Nutrient recovery, for example, can transform leachate into a source of nitrogen and phosphorus for agricultural use (Kurniawan et al., 2021b).

Similarly, advanced treatment processes can recover water for irrigation or industrial applications, contributing to water conservation and reducing the demand for freshwater resources (Meese et al., 2022). The recovery of energy in the form of biogas from the anaerobic treatment of leachate further underscores the potential of these technologies to contribute to a more sustainable and energy-efficient waste management system (An et al., 2023). The circular economy encourages a systemic view of waste management, promoting the integration of leachate treatment technologies within broader waste and water management systems (Smol et al., 2020). Future technologies will likely be characterized by their ability to integrate with other treatment and recovery processes, creating synergies that enhance overall efficiency and sustainability (Kehrein et al., 2020). For example, integrating leachate treatment with solid waste management processes can facilitate the co-treatment of organic waste and leachate, optimizing resource recovery and minimizing environmental impacts (Mishra et al., 2023).

Collectively, the influence of circular economy and sustainability principles on the future of landfill leachate treatment technologies is transformative, driving innovation towards solutions that are effective in treating leachate and minimizing waste, recovering resources, and integrating seamlessly into a circular and sustainable waste management framework. As these principles continue to gain traction, they will undoubtedly shape the development of more sustainable, efficient, and integrated leachate treatment technologies, aligning waste management practices with the broader goals of environmental sustainability and resource conservation.

## 8 Conclusion

The environmental impact of untreated leachate is significant, with potential contamination of groundwater, surface water, and overall ecosystem health, necessitating robust and dynamic treatment solutions.

This comprehensive review of landfill leachate treatment technologies presents a global perspective, focusing on the physicochemical properties of leachate, regulatory frameworks, and specific country examples. The study highlights the complex composition of landfill leachate, which includes a mix of organic and inorganic pollutants, heavy metals, and xenobiotic compounds. The review also underscores the importance of global regulatory frameworks in shaping landfill leachate management practices. International agreements, such as the Basel Convention and the Stockholm Convention, along with national regulations from countries like the United States, China, India, and Brazil, are setting standards and encouraging the adoption of advanced treatment technologies.

Key findings emphasize the evolution of conventional and advanced treatment technologies. Traditional methods such as physical, chemical, and biological treatments remain fundamental. Physical methods, including sedimentation and membrane filtration, effectively remove suspended solids and larger organic molecules. Chemical treatments like coagulation-flocculation and advanced oxidation processes are crucial for targeting dissolved pollutants and heavy metals. Biological treatments utilize microbial processes to degrade organic pollutants and are particularly effective for nutrient removal.

Advanced treatment technologies, including MBRs, NF, RO, and AOPs), provide higher efficiency and are essential for meeting stringent regulatory standards. These technologies can remove a broader range of contaminants, including emerging pollutants such as pharmaceuticals and microplastics, which traditional methods may not adequately address. Economic considerations are also crucial in the treatment process. The high capital and operational costs of advanced leachate treatment systems pose significant challenges. Technologies such as RO, NF, and MBR are effective but require substantial investment in equipment, maintenance, and energy consumption. Addressing these economic challenges necessitates the development of cost-effective, energy-efficient solutions and the integrating of resource recovery practices, such as biogas production and water reuse, to offset operational costs. A case study from Changsha City illustrates the practical application and effectiveness of a comprehensive treatment system that integrates various technologies. This example provides valuable insights into designing integrated systems capable of meeting diverse regulatory requirements and addressing complex environmental challenges.

In conclusion, the continuous improvement of landfill leachate treatment technologies is vital. Adopting innovative and sustainable practices is essential to reduce the environmental footprint of landfills. Future research should focus on developing cost-effective, energy-efficient solutions and exploring emerging technologies for better pollutant removal. By emphasizing a global perspective and integrating multiple treatment processes, this review significantly contributes to advancing sustainable waste management practices and protecting environmental health.

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