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Current Status and Future Development Trends of Landfill Leachate Treatment Technologies

Ruqiong Qin

Guangxi Polytechnic of Construction, Nanning 530003, China

Abstract

With the comprehensive implementation of garbage classification policies in our country, the treatment of landfill leachate is encountering new challenges and opportunities. This paper systematically investigates the source characteristics, discharge standards, and current status of treatment technologies for landfill leachate. It also emphasizes the analysis of leachate treatment technologies under different scenarios, including incineration plants, landfill sites, wet waste treatment plants, and transfer stations. The study reveals that classified leachate exhibits high concentrations of organic matter, high salt content, and significant variations in water quality. Consequently, traditional single-stage treatment technologies struggle to meet increasingly stringent discharge standards. Through comparative analysis, a multi-stage collaborative treatment process combining "physical-chemical pretreatment + biological enhancement + advanced treatment" has demonstrated significant advantages. Notably, the application of membrane technologies such as MBR (Membrane Bioreactor) and DTRO (Disc Tube Reverse Osmosis) has effectively improved effluent quality. However, the issue of membrane fouling remains unresolved. Furthermore, the research highlights that resource utilization and low-carbon treatment are critical development directions in the future, exemplified by biogas energy recovery and nutrient extraction technologies. Finally, this paper outlines the research prospects for leachate treatment technology in terms of membrane material development and intelligent control, providing a theoretical foundation and technical reference for leachate treatment under the context of garbage classification.

Keywords

Landfill Leachate; Treatment Technology; Transfer Station; Wet Waste Treatment Plant; Development Trend.

1. Introduction

With the rapid acceleration of urbanization and the comprehensive implementation of waste classification policies, the treatment of landfill leachate has become an increasingly significant environmental challenge[3]. Landfill leachate primarily includes leachate from landfills, incineration plants, transfer stations, and biogas slurry generated during kitchen waste treatment. These sources exhibit complex compositions, characterized by high concentrations of organic matter, ammonia nitrogen, heavy metals, and salts, among other pollutants[8]. Notably, with the promotion of separate collection and treatment for kitchen waste, the volume of leachate has surged significantly, accompanied by elevated organic concentrations and salt content. This development poses severe challenges to traditional treatment technologies. Currently, the discharge standards for landfill leachate in China are governed by the "*Pollution Control Standard for Domestic Waste Landfills*" (GB 16889-2008)[1]. However, as environmental protection requirements have intensified, certain

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regions have adopted stricter local standards. For instance, Beijing mandates COD ≤ 60 mg/L and ammonia nitrogen ≤ 10 mg/L, thereby imposing higher demands on treatment methodologies[2].

In response to the diverse origins and characteristics of leachate, treatment technologies have evolved toward diversified approaches. Incineration plant leachate employs a process combining "regulated precipitation + two-stage AO + ultrafiltration + advanced treatment," achieving a COD removal rate exceeding 95%. Landfill leachate treatment selects processes based on landfill lifespan, such as "MBR + membrane advanced treatment" or "pretreatment + two-stage DTRO." Wet waste treatment plant biogas slurry utilizes a combined process of "MBR + NF + RO" to effectively reduce concentrated liquid production. Transfer station leachate achieves stable standard compliance through "enhanced pretreatment - EGSB anaerobic - two-stage nitrification and denitrification - MBR." It is noteworthy that advancements in waste classification have altered both the quality and quantity of leachate, presenting new opportunities for optimizing treatment processes.

2. Sources and Water Quality Characteristics of Landfill Leachate

Landfill leachate originates predominantly from landfills, waste transfer stations, and kitchen waste treatment facilities. During landfilling, interactions between precipitation, surface runoff, groundwater, and the degradation water of waste itself lead to the dissolution and migration of soluble organic and inorganic substances, forming high-concentration organic wastewater. The implementation of China's waste classification policy has markedly increased the proportion of food waste collected and treated, resulting in a substantial rise in food waste leachate output. This type of leachate is distinguished by its high organic concentration, high salt content, and susceptibility to corruption, making it more challenging to treat compared to traditional mixed landfill leachate[19].

Table 1. summarizes the water quality characteristics of landfill leachate from various sources

Sources		Index				
		pH	COD/(mg/L)	BOD_5/COD	TN/(mg/L)	Electric conductivity
Incinerator		5~6	>20000	>0.3	>2500	>1
landfill	<5a(Early-stage)	6~6.5	>20000	>0.3	>2500	>1
	5~10a(Intermediate-stage)	6.5~7.5	4000~10000	0.1~0.3	2000~3000	1~1.5
	>10a(aging)	>7.5	<5000	<0.1	2500~4000	2~3
Wet garbage biogas slurry		7~8	2000~4000	<0.3	2000~3000	2~3
Waste transfer stations		<6.5	5000~50000	>0.3	200~2000	0.2~4
Domestic sewage		6.5~7.5	250~500	0.4~0.5	30~60	0.15~0.2

3. Landfill Leachate Discharge Standards

The landfill leachate discharge standard system serves as a critical technical foundation for environmental management, and its evolution exhibits distinct stage characteristics. China's current "*Pollution Control Standard for Domestic Waste Landfill*" (GB 16889-2008) categorizes the emission limits into three tiers, with the first-tier standard being the most stringent. This standard requires chemical oxygen demand (COD) ≤100 mg/L, ammonia nitrogen ≤25 mg/L, and total nitrogen ≤40 mg/L. With advancements in technology and increasing environmental demands, regions such as Beijing and Shanghai have established more rigorous local standards. For instance, Beijing's local standard mandates COD ≤60 mg/L and ammonia nitrogen ≤10 mg/L.

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4. Status of Landfill Leachate Treatment Technology

4.1 Leachate Treatment Technology for Incineration Plants

Following the implementation of waste classification, the volume of garbage entering waste incineration plants has decreased significantly, similar to the reduction observed in landfill sites. This has led to a marked decline in both the quantity of leachate produced in incineration plants and the organic content within it. Currently, the typical leachate treatment process employed in domestic waste incineration plants is illustrated in Fig. 1. This process can be categorized into three primary modules: the pretreatment stage, the biological treatment stage, and the advanced treatment stage[10]. The system achieves a total COD removal efficiency exceeding 95%, ensuring that the effluent water quality complies with the discharge standards outlined in the "*Pollution Control Standard for Domestic Waste Landfills*" (GB 16889-2008).

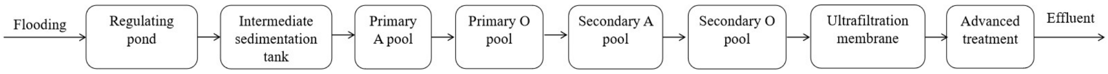

Fig. 1 Leachate treatment process of waste incineration plant

Since the content of organic matter is significantly reduced, the leachate can undergo pre-precipitation in the regulating tank without anaerobic reactions and subsequently enter the intermediate sedimentation tank for biochemical treatment. In this process, the two-stage AO tank within the biochemical system undergoes ultrafiltration membrane filtration after biochemical treatment, followed by advanced effluent treatment. During the pretreatment stage, the regulating pre-settling pool balances water quality and quantity, creating stable conditions for subsequent biological treatment through pH regulation (maintained at 6.5–7.5) and temperature regulation (kept at 25–35°C). The pool is equipped with a scum removal device that removes approximately 15% of suspended solids.

In the biological treatment stage, the first phase of the AO process involves an activated sludge aeration tank. Here, organic materials are converted into inorganic substances via aeration, utilizing microorganisms present in the sewage. This process requires substantial oxygen supply to maintain microbial growth and metabolism. The second phase of the AO process includes a secondary activated sludge aeration tank and sedimentation tank. In this stage, residual organic matter, nitrogen, phosphorus, and other substances not fully removed during the first phase are eliminated through further aeration and sedimentation processes. Oxygen injection is required to promote microbial metabolism, and sludge settling occurs in the sedimentation tank for subsequent treatment.

The ultrafiltration membrane has a pore size of 0.01–0.1 μm, a flux of 15–20 L/(m^2·h), and retains organic matter with molecular weights greater than 10 kDa, ensuring effluent turbidity remains below 0.5 NTU. Advanced treatment options include RO/NF membranes (desalination rate >95%) or advanced oxidation processes (e.g., ozone-catalyzed oxidation with COD removal rates of 30%–50%)[17].

With fluctuations in both leachate volume and quality, the volume of water treated by the advanced treatment system decreases, leading to idle periods for some membrane system equipment, reduced power and chemical consumption, and lower operating costs for the entire leachate treatment system. A reduction in leachate volume also decreases concentrate production, addressing long-standing issues related to concentrated liquid management.

4.2 Landfill Leachate Treatment Technology

Landfill leachate varies significantly in water quality based on the characteristics of landfill waste and landfill age. In some regions, stringent discharge standards are enforced, necessitating diverse treatment technologies for landfill leachate[11]. For leachate from early-stage or intermediate-stage landfill sites, which exhibits biodegradability, the process of "biochemical treatment + advanced

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membrane treatment" is predominantly utilized. Additionally, some projects incorporate advanced oxidation processes for further treatment. The process flow diagram is presented in Fig. 2.

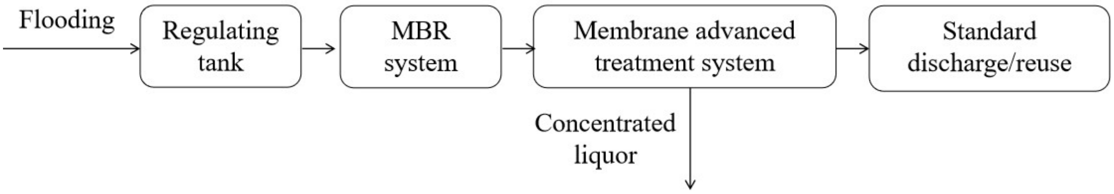

Fig. 2 Process Flow Diagram of the "MBR + Membrane Advanced Treatment" System

The MBR (membrane bioreactor) replaces the conventional sedimentation tank through membrane filtration. By means of membrane interception and enrichment, the sludge concentration in the biochemical reactor can be increased to 20–30 g/L, which effectively reduces the land area required for treatment. This technology is widely used as a bioreactor for treating high-concentration organic wastewater. However, the biochemical system imposes stringent requirements on operation and management; improper operation or management may compromise effluent quality, lead to severe membrane fouling, and shorten the service life of the membrane. Furthermore, the biochemical system is sensitive to the carbon-to-nitrogen ratio. To remove nitrogen from leachate generated by aging landfills, additional carbon sources must be introduced, thereby increasing operational costs. As an advanced treatment facility, the membrane system ensures stable and compliant effluent quality. Nevertheless, most of the concentrated liquid produced remains untreated and is continuously recirculated back into the landfill, leading to an increase in conductivity, COD, and ammonia nitrogen concentrations in the leachate, as well as continuous pollutant accumulation, which exacerbates the difficulty of leachate treatment.

For old landfill leachate, land-limited scenarios, or emergency treatment projects, the "pretreatment + two-stage DTRO" membrane treatment process is predominantly employed[5]. The specific process flow diagram is presented in Fig. 3. Following pretreatment, metal ions that could potentially cause membrane blockage are removed via coagulation and precipitation before entering the two-stage DTRO system. The first-stage DTRO produces clear liquid with a yield of 75%, while the second-stage DTRO achieves a clear liquid yield of up to 90%. To further reduce the concentrated liquid yield, the concentrated liquid from the second-stage DTRO can be recycled back to the first-stage DTRO for additional processing, resulting in an overall system clear liquid yield of approximately 75%. The remaining 25% concentrate requires subsequent treatment[19].

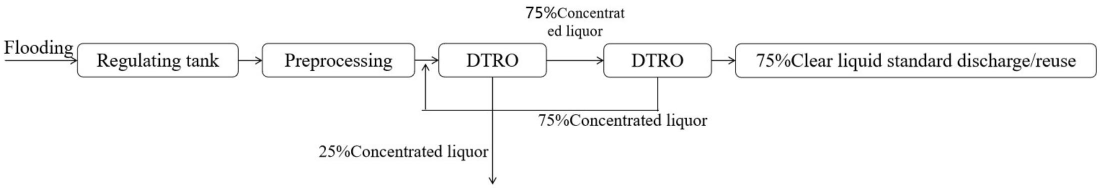

Fig. 3 Process flow chart of " Pretreatment + two-stage DTRO treatment"

4.3 Biogas Slurry Treatment Technology in Wet Waste Treatment Plants

In view of the water quality characteristics of biogas slurry in wet waste treatment plants, which include high organic matter content and favorable biochemical properties, as well as the need for effective ammonia nitrogen removal, the biochemical treatment method is deemed more suitable. Drawing on decades of experience from similar high-concentration organic wastewater treatment projects both domestically and internationally, along with practical insights from garbage leachate treatment projects that closely resemble biogas slurry, the primary biogas slurry treatment technology in wet waste treatment plants is based on membrane bioreactor (MBR) systems. The specific process route involves an integrated MBR system combined with nanofiltration (NF) and reverse osmosis (RO)[12]. Advanced treatment employs membrane technology, offering advantages such as a small footprint, low operating costs, and consistently stable effluent quality[6].

The biogas slurry, after solid-liquid separation, enters the system's regulating tank and is subsequently pumped into the MBR system via a lift pump. Following biological nitrification and denitrification processes, pollutants such as chemical oxygen demand (CODCr), biochemical oxygen demand (BOD5), ammonia nitrogen (NH3-N), and total nitrogen (N) in the wastewater are effectively removed. Finally, further pollutant removal is achieved through NF+RO membrane filtration to meet discharge standards. The treated effluent is utilized as supplementary water for the cooling tower of the incineration plant. The detailed process flow is illustrated in Fig. 4.

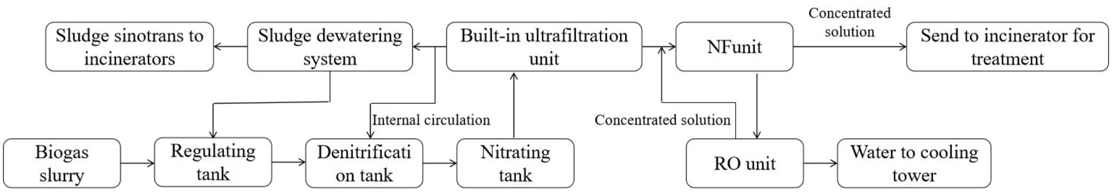

Fig. 4 Schematic Flow Diagram of the "MBR + NF + RO Treatment Process"

The anaerobic biogas slurry derived from kitchen waste exhibits a significantly higher concentration of NH3-N. In comparison to the conventional two-stage nanofiltration (NF) process, adjusting one stage to a reverse osmosis (RO) process achieves superior NH3-N removal efficiency in a weakly acidic environment, thereby ensuring the stability of the effluent quality. Furthermore, both the NF and RO units generate concentrated liquid during this process. Prior to returning the RO concentrated liquid to the NF unit, the entire system's outgoing concentrated liquid is solely produced by the NF unit, with the water recovery rate of NF being higher than that of RO. This approach effectively minimizes the total volume of concentrated liquid generated within the system, consequently reducing the treatment costs associated with concentrated liquid management.

With the advancement of household waste classification systems, centralized food waste treatment facilities are progressively being enhanced, and the anaerobic treatment process is increasingly being adopted for food waste management. The biogas slurry resulting from anaerobic digestion still contains high concentrations of pollutants, including CODCr and NH3-N, which differ markedly from traditional high-concentration organic wastewaters such as landfill leachate. Implementing this method not only enhances the removal efficiency of NH3-N but also reduces the system's concentrated liquid output, further lowering operational costs and making it more suitable for the treatment of biogas slurry derived from kitchen waste[18].

4.4 Landfill Leachate Treatment Technology at Transfer Stations

Refuse transfer stations serve as intermediate hubs in the garbage collection and final disposal process, playing a crucial role in connecting various stages of sanitation management [1]. The wastewater primarily originates from garbage compression liquid, vehicle washing water, deodorization facility effluents, and domestic sewage. Given the complex composition of municipal solid waste, the wastewater generated during the compression process is characterized by high levels of impurities, organic pollutants, total nitrogen (TN), heavy metals, and animal/vegetable oils[12]. This results in a high-concentration organic wastewater with a complex chemical composition. Consequently, discharging such wastewater into the environment without harmless treatment would lead to severe pollution issues. Due to the short time interval between waste collection and transfer, the wastewater produced after compression treatment at transfer stations is predominantly "fresh wastewater" with minimal storage and natural fermentation time. As such, this type of wastewater exhibits good biodegradability, making it suitable for biological treatment processes[4].

Considering the water quality characteristics and process stability requirements of wastewater from refuse transfer stations, an integrated pretreatment system combined with an EGSB (Expanded Granular Sludge Bed) anaerobic reactor, two-stage nitrification-denitrification, and MBR (Membrane Bioreactor) membrane technology was adopted as the primary treatment process[7]. The compressed domestic waste wastewater contains significant debris and grease residues, while the wastewater from vehicle and site cleaning includes residual garbage and mud. To ensure stable operation of the process equipment, a combined pretreatment system consisting of coarse screens, fine screens, sedimentation tanks, and air flotation units was employed. After pretreatment, the wastewater flows into a regulating tank equipped with a submersible stirring device. Following adjustment of water quality and quantity, the wastewater is pumped into the EGSB anaerobic reactor, subsequently flowing into the two-stage nitrification-denitrification and MBR membrane tanks. The MBR effluent is then discharged into the municipal sewage network. Sludge from the sedimentation tank, air flotation scum, and residual sludge from the anaerobic and aerobic reactors are directed to the sludge thickening tank. After centrifugal dewatering, the sludge is transported for incineration, as illustrated in Fig. 5. The operational performance of this process is excellent, with effluent water quality meeting the Class A standard specified in GB/T 31962-2015. Additionally, the operational cost is relatively low. The biogas generated by the reactor can be utilized for boiler combustion, and the resulting hot water can be employed for heating and insulation of the anaerobic reactor, thereby conserving substantial energy resources[16].

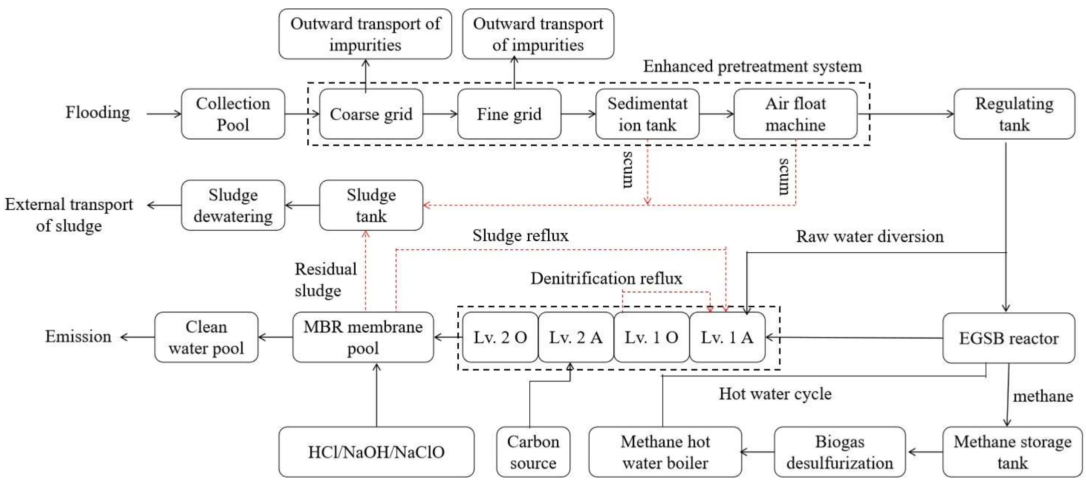

Fig. 5 Process flow chart of enhanced pretreatment -EGSB anaerobic reactor - two-stage nitrification and denitrification -MBR membrane treatment

5. Development Trends

With the comprehensive implementation of the garbage classification policy, landfill leachate treatment technology is evolving in three primary directions[8,9]. First, there is a shift from single-treatment approaches to multi-level collaborative transformations. Combined processes have become mainstream, with the organic integration of physical and chemical pretreatment, bioenhancement, and deep purification significantly improving treatment efficiency. Second, resource utilization has emerged as a critical trend, transitioning from mere pollution control to energy recovery and material recycling, such as biogas energy utilization and nutrient element recovery technologies. Finally, low-carbon and intelligent transformations are gaining prominence, with innovative methods like solar-driven technology and AI-based dynamic regulation reducing energy consumption while enhancing system stability and economic viability[8].

Future technological advancements will emphasize precision and customization, developing differentiated treatment solutions tailored to the characteristics of various types of landfill leachate. Simultaneously, as emission standards continue to tighten, advanced oxidation processes (AOPs) and electrochemical technologies will see broader applications. Notably, key technical bottlenecks, such as membrane fouling control and high-salinity suppression, remain to be addressed. This necessitates strengthening fundamental research on new materials and processes to drive treatment technology toward greater efficiency and sustainability[14,15].

In summary, landfill leachate treatment technology is progressing toward the dual goals of "near-zero emissions" and "energy-resource" dual recycling. These objectives not only align with current environmental protection policies but also provide essential technical support for the sustainable development of waste classification systems. Future efforts must focus on enhancing interdisciplinary collaboration and promoting the seamless integration of technological innovation with engineering applications.

6. Conclusion

The enforcement of garbage classification policies has introduced new requirements and challenges for landfill leachate treatment. This study systematically examines the water quality characteristics of leachate from diverse sources, reviews the existing discharge standard framework, and highlights treatment processes in typical scenarios, including incineration plants, landfills, wet waste treatment facilities, and transfer stations. Findings indicate that advancements in garbage classification have led to significant changes in leachate water quality characteristics, rendering traditional single-treatment technologies insufficient. In contrast, multi-stage collaborative treatment processes combining "physical-chemical + biological + membrane technology" demonstrate substantial advantages. The widespread adoption of membrane technologies, such as MBR and DTRO, has markedly improved effluent quality; however, membrane fouling remains a critical issue requiring resolution. Additionally, resource utilization and low-carbon treatment have become pivotal development directions, exemplified by the application of biogas energy recovery, nutrient extraction, and similar technologies, which enhance treatment efficiency while achieving waste valorization. Future research should prioritize the development of novel anti-fouling membrane materials, optimization of efficient desalination technologies, and establishment of intelligent operation management systems. These efforts will propel leachate treatment technology toward a more efficient and sustainable trajectory, providing robust technical support for the enhancement of waste classification systems.

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