

Characteristics, Environmental Impacts, and Evolution of Landfill Leachate Treatment Technologies: A Review

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Abstract: Landfilling is a global waste management strategy for municipal, hazardous, and industrial waste, which is normally opted for due to its economic viability over other methods. However, landfill operations generate leachate, a toxic solution containing high levels of organic and inorganic compounds, posing serious environmental problems if not managed effectively. This review comprehensively presents leachate characteristics and environmental impacts, as well as the evolution of treatment technologies to mitigate these impacts. The discussion begins with the properties and characteristics of leachate, emphasizing factors that influence its variability, including waste composition, climate, and landfill design. The second part of this review article highlights the environmental impacts of leachate on surface water, groundwater, soil, and ecosystems. The evolution of leachate treatment technologies is then outlined, and the progression and effectiveness of advanced and emerging technologies, as well as the limitations of conventional treatment methods, are discussed. This review also elucidates challenges and future directions in leachate management, including regulatory frameworks and sustainability considerations. It is expected that this review will provide practitioners and researchers with insights into the ongoing effort to develop sustainable treatment methods for leachate and safeguard environmental quality.

Keywords: landfill; leachate treatment; biological treatment; physical-chemical treatment; advanced oxidation processes.

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1. Introduction

Municipal solid waste (MSW) management is a critical challenge, particularly in developing countries, where population growth has increased waste generation. Sustainable management of MSW involves various strategies, such as waste-to-energy technologies, recycling, and waste valorisation. For instance, renewable waste-to-energy technologies have been identified as a significant opportunity in Southeast Asia, with substantial potential to generate 17.26 terawatt-hours by 2030 [1]. Additionally, the recovery and recycling of MSW

play a crucial role in sustainable waste management and environmental protection [2]. A lack of public participation and environmental awareness is the main cause of the failure of waste management strategies.

Landfilling and open dumping are the most common methods of waste management due to their lower operating costs and simple techniques, and they do not require high-tech equipment or machinery to operate, unlike incineration and biocomposting. These methods, however, generate harmful leachate and foul odour that pose the greatest risk to groundwater safety [3], especially if leakage occurs due to improper lining. Therefore, landfill design is one of the factors that needs to be emphasized. In addition, proper treatment of landfill leachate is also crucial to avoid surface water contamination and mitigate harmful effects on the environment and human health.

The primary objectives of this review are to assess the effectiveness of various leachate treatment technologies, compare their advantages and limitations, and identify the most suitable approaches for different scenarios. By examining both traditional and cutting-edge solutions, this review seeks to offer insights that can guide future research and practical applications in leachate management. It will also explore emerging technologies and innovations that show promise in improving treatment efficiency and sustainability.

2. Landfill Leachate Characteristics

Landfill leachate is a dark brown liquid that results from water seeping into and through waste and accumulating at the bottom of the landfill [4]. It has a significant impact on the quality of groundwater, surface water, and the ecosystem. It comprises a broad range of pollutants, including suspended particles, toxic and heavy metals, organic waste, phenols, ammoniacal nitrogen, phosphate, and sulphide [5]. It has been shown that these pollutants pose a major threat to the public and have ecotoxicological effects on both terrestrial and aquatic ecosystems [6].

The strength and properties of the leachate are dependent on the composition of the waste, volume of downpour, geographical conditions, and age of landfills [7]. In addition, the presence of recalcitrant organics, ammonia, metals, and inhibitory pollutants may affect the composition of leachate [8]. The pH of leachate is another aspect that should not be overlooked, as it may be connected to changes in the microbial population [9]. Conditions and location may also influence the composition and characteristics of leachate. Compared with landfills in regions with milder temperatures, there are significant variations in the quantitative and qualitative properties of leachate, as Frikha found in the semi-arid environment of Tunisia. This highlights the importance of considering specific environmental conditions when investigating leachate characteristics [10]. Both the quality and quantity of leachate vary, and these differences are directly linked to changes in the total amount of precipitation, the composition and characteristics of waste, the age of trash, and the operating patterns of landfills [11]. The composition of landfill leachate varies significantly by year, leachate collection system type, landfill age, and other factors, as summarized in Table 1.

Table 1. Factors influencing leachate characteristics.

| Factors | Remarks | References |
|-------------------|---|------------|
| Waste composition | Organic: i. Rubbish ii. Food and garden waste iii. Animal residues Inorganic: | [12, 13] |

| Factors | Remarks | References |
|------------------|---|------------|
| | i. Ash waste ii. Construction waste | |
| Depth of waste | A deeper landfill requires longer contact times between waste and liquid. | [14] |
| Moisture content | Moisture transports nutrients, dilutes chemicals, dissolves material, and exposes surface area. | [15, 16] |
| Dissolved oxygen | During anaerobic degradation, organic acids, ammonia, hydrogen, carbon dioxide, methane, and water are generated in high amounts. | [17] |
| Temperature | Optimum temperature influences chemical and bacterial reactions. | [18] |
| Processed waste | Shredded waste has a higher concentration of pollutants because of its increased surface area. | [19, 20] |
| Age of landfill | Leachate from the new landfill contains high BOD and COD levels, which will decrease over time. | [11] |
| Toxicity | MSW leachate is as toxic as hazardous waste | [21] |

Organic matter and ammonia are the two primary contaminants that may be found in leachate. As the landfill ages, the concentration of organic matter (COD) in the leachate decreases from 1800 mg/L in the second year to 610 mg/L in the sixth year. There is also an increase in ammonia nitrogen content, along with fluctuations in other parameters (phosphorus, chloride, calcium, magnesium, sulphate, dissolved solids, and heavy metals). Table 2 shows the relationship between the age of the landfill site and leachate concentration.

Table 2. Concentration of some leachate constituents at different phases [22].

| Leachate Constituent | Transition Phase (0-5 years) | Acid Formation Phase (5-10 years) | Methane Fermentation (10-20 years) | Final Maturation Phase (>20 years) |
|----------------------|------------------------------|-----------------------------------|------------------------------------|------------------------------------|
| BOD | 100-11000 | 1000-5700 | 100-3500 | 4-120 |
| COD | 500-22000 | 1500-71000 | 150-10000 | 30-900 |
| TOC | 100-3000 | 500-28000 | 50-2200 | 70-260 |
| Ammonia | 0-190 | 30-3000 | 6-430 | 6-430 |
| NO ₂ -N | 0.1-500 | 0.1-20 | 0.1-1.5 | 0.5-0.6 |
| TDS | 2500-14000 | 4000-55000 | 1100-6400 | 1460-4640 |

In general, the biological breakdown of landfilled waste takes longer as it matures. This process, which includes two substages and methanoic acid, can be broken down into three phases. Leachate from various phases contains a variety of substances; thus, humans tend to produce acidic leachate due to the presence of volatile fatty acids. Since low pH can make metals more readily soluble, the concentration of heavy metals in leachate tends to increase as conditions become more acidic. On the other hand, metal concentration decreases throughout fermentation and maturation, bringing the pH closer to its standard value.

Due to its complicated nature and composition, the landfill leachate treatment process is also fraught with difficulties. Depending on the leachate properties and the treatment technique used, the outcomes of various treatment procedures may differ [23]. Therefore, it is important to consider the specific characteristics of leachate when selecting a treatment method.

3. Environmental Impacts of Landfill Leachate

Discharge of leachate into the surrounding environment may contaminate soil, groundwater, and surface water, which in turn may cause serious harm to human health. The composition of leachate, including heavy metals, antibiotic-resistant bacteria, newly

discovered pollutants, and pharmaceutical and personal care items, poses a substantial risk to human health [24, 25, 26, 27] if ingested.

Moreover, contamination of water sources by landfill leachate is a major cause of concern. Drinking water quality may be negatively affected by leachate, which can alter pH and produce hazardous chemicals, such as trihalomethanes [28]. Ammonia is another organic contaminant in leachate that can lead to eutrophication, endangering aquatic ecosystems.

Leachate has the potential to contaminate not only water but also the surrounding air. Communities living in close proximity to dumpsites and landfills that leak are at risk of respiratory disorders and other health problems from inhaling volatile organic compounds and other hazardous pollutants released into the air by these facilities [25]. When evaluating the potential health risks associated with leachate exposure, the proximity of human populations to landfills and dumpsites is a critical factor to consider. Those living in close proximity to these sites are more likely to be exposed to leachate toxins. This includes those who work in the garbage industry as well as members of vulnerable groups, including small children and people with impaired immune systems [25]. It is imperative to implement efficient waste management practices and leachate treatment procedures to reduce its hazards to human health. This involves the use of appropriate treatment technologies to remove pollutants from leachate before discharge into the environment, as well as implementing measures to prevent leachate leakage from landfills [29]. It is also vital to conduct routine monitoring of leachate quality and its impact on the environment and human health.

Additionally, high leachate head in landfill systems can lead to environmental pollution issues and shorten the breakthrough time for liner systems. Proper management and control of old landfills are essential to avoid undesired environmental impacts, as indicated by a high Leachate Pollution Index (LPI), underscoring the importance of leachate treatment before final discharge [30].

4. Conventional Landfill Leachate Treatment

Conventional leachate treatments consist of leachate transfer and recycling, as well as biological and physical-chemical treatment. Currently, the most commonly used leachate treatments are biological, chemical, and physical processes, as well as combinations of these [31]. Various treatment methods have been explored to address the challenges associated with landfill leachate. Among the methods are physical and chemical processes, such as coagulation/flocculation, chemical precipitation, adsorption, chemical oxidations, air stripping, and sedimentation/flotation [21]. Additionally, biological treatment methods, including aerobic and anaerobic processes, have been considered for their effectiveness in treating landfill leachate [32]. The use of advanced treatment processes, such as electrocoagulation and electrooxidation, and the application of persulfate systems have also been reported to treat landfill leachate [33] effectively.

4.1. Leachate transfer and recycling.

Leachate transfer and recycling are crucial aspects of waste management, with implications for environmental and public health. The management of leachate from landfills and waste treatment facilities is essential to prevent groundwater contamination and environmental pollution [34]. Leachate recirculation has been identified as an effective method for waste-to-energy conversion, leachate management, and cost reduction. However, the

treatment of landfill leachate is strictly regulated due to its potential to transfer pollutants to the surrounding environment [35]. The use of leachate as mixed water in concrete production, together with recycled construction and demolition waste as aggregate, has been shown to reduce concrete compressive strength. Additionally, the application of leachate in crop production has been compared to chemical fertilizer, indicating the need for a well-managed system for leachate collection, monitoring, control, and treatment before disposal [36].

4.2. *Biological treatment process.*

The biological treatment process is a crucial method and is responsible for eliminating organic and inorganic matter from wastewater [37]. This process involves various stages, including primary sedimentation, followed by biological treatment using the activated sludge (AS) process. The activated sludge process, a widely used biological wastewater treatment method, involves both aerobic and anaerobic processes, which are fundamental to biological treatment techniques [38]. Furthermore, the biological treatment method has been successfully applied to contaminated wastewater using an acclimatized mixed culture, demonstrating its effectiveness in treating specific pollutants [39].

4.2.1. Aerobic treatment.

The aerobic process is an economical option commonly used to eliminate nitrogen from effluents, but it does not efficiently remove non-biodegradable organics or heavy metals. Growth system during aerobic treatment can be classified as suspended or attached. The suspended growth system consists of aerated lagoons, activated sludge, and a Sequential Batch Reactor (SBR). Aerated lagoons are a viable and affordable technique for treating pathogens and organic and inorganic compounds, whereas the activated sludge process is commonly used to treat wastewater and leachate. This procedure is effective at removing nutrients, but it has significant drawbacks, including excessive sludge generation, poor sludge settleability, high energy consumption, and extended contact time. The SBR method, which combines all treatment units into a single basin, is based on the activated sludge approach. SBR is used for leachate with a lower BOD/COD ratio, as its ability to treat leachate is significantly weaker than its ability to treat municipal and industrial waste [23].

A moving-bed biofilm reactor (MBBR) is an attached-growth system for aerobic treatment. MBBR uses suspended, porous polymer carriers that are maintained in constant motion in the aeration basin, where active biomass forms on their surfaces, such as biofilms. The growth system is also attached with trickling filters and rotating biological contractors [40]. It is a low-cost filter medium that can lower nitrogen concentrations in landfill leachate. The aerobic process involves oxidation of air particles, exposure to sunlight, and aerobic microorganisms that degrade leachate contaminants. To maximize the action of aerobic microorganisms, it is essential to aerate the leachate [41].

4.2.2. Anaerobic treatment.

Anaerobic biological treatment is the degradation of organic material by microorganisms in the absence of dissolved oxygen, resulting in the conversion of organic material into carbon dioxide, methane, and other metabolic products [42]. The decomposition extracts most of the toxins but still produces useful by-products, specifically methane for biogas. It consumes low energy and produces little sludge, thereby lowering the cost of sludge

management. In addition, it produces high amounts of biogas energy, which can serve as fuel, and has high organic loading, which can save space [43]. However, leachate treatment using an anaerobic system is not economically viable, as most treatments have been analyzed only at the laboratory scale. Although the anaerobic system is more effective than the aerobic system, it also has weaknesses, including a long hydraulic retention time (HRT), limited contaminant removal, and temperature sensitivity [44]. Other critical factors need to be considered, such as investment, service, and management of anaerobic leachate treatment plants. In addition, anaerobic treatment may not be sufficient to meet the discharge standards set by the Department of Environment (DOE), as leachate contains high concentrations of contaminants and complex refractory compounds. Therefore, it is crucial to combine other methods with the biological treatment process.

4.3. Physical-chemical treatment process.

The biological treatment process is not capable of handling old landfill leachate, as it is more stabilized and complex than new landfill leachate. Therefore, physical-chemical treatment processes are applied to stabilize landfill leachate, including flotation, coagulation-flocculation, chemical precipitation, adsorption, chemical oxidation, and air stripping [45]. Table 3 summarizes the leachate categories.

Table 3. Category of landfill leachate categories [46].

| Type of leachate | Young | Intermediate | Stabilized |
|---------------------------|----------|--------------|------------|
| Landfill age (year) | <1 | 1-5 | >5 |
| pH | <6.5 | 6.5-7.5 | >7.5 |
| BOD/COD | 0.5-1.0 | 0.1-0.5 | <0.1 |
| COD (mg/L) | >15000 | 3000-15000 | <3000 |
| NH ₃ -N (mg/L) | <400 | NA | >400 |
| TOC/COD | <0.3 | 0.30-0.5 | >0.5 |
| Kjedahl Nitrogen (mg/L) | 100-2000 | NA | NA |
| Heavy Metals (mg/L) | >2 | <2 | <2 |

4.3.1. Air stripping.

Air stripping is a widely used technique for removing ammonia from wastewater due to its efficiency and cost-effectiveness [47]. It has been shown to be effective in treating various types of wastewaters, including swine wastewater, municipal and industrial wastewaters [48], and livestock and poultry breeding wastewater. The process involves transferring ammonia from the liquid phase to the gas phase, which is then released into the atmosphere [47]. This method has been found to be particularly suitable for treating wastewater with low nitrogen concentration and is more favourable for ammonium nitrogen removal than other methods, such as chemical precipitation. Additionally, air stripping has been identified as an energy-efficient and robust technology for removing dissolved methane from anaerobically treated municipal wastewater, demonstrating its versatility in treating various contaminants [49].

4.3.2. Flotation.

Bubble attachment used in the flotation process extracts the heavy metals from the liquid phase. The primary flotation processes for removing metal ions from the solution are

dissolved air flotation (DAF), ion flotation, and precipitation flotation. DAF is primarily used to isolate suspended particles from the liquid by capturing them at the liquid surface [50][51]. Furthermore, this approach has also successfully reduced BOD, COD, and turbidity. Other benefits of DAF include the provision of high-quality treated water, rapid start-up, lower operating costs, and the generation of thicker sludge [51]. Most importantly, this system requires a smaller area compared to conventional clarifiers. However, this system has limitations in terms of high initial capital costs, expensive maintenance, and service fees.

4.3.3. Coagulation-flocculation.

In wastewater treatment, coagulation-flocculation is commonly used as its operation is effective. Factors influencing the efficiency of this treatment method include the type and dosage of coagulants or flocculants, pH, mixing speed, and retention time. Coagulation-flocculation destabilizes a particle colloidal suspension. The coagulants allow the particles to solidify and clot together. This occurs when the coagulants carry a charge opposite to that of the particles, causing them to clump together. The coagulants also allow the particles to coagulate with flocculants [52]. Then, the separation will accelerate and clarify the effluents. This treatment requires both coagulant and coagulant aid. The most common coagulants are poly-aluminium chloride (PAC), ferric chloride, and aluminium sulphate (alum) [53]. The polymer acts as a coagulant aid and is used in the pretreatment process before biological treatment. It is also commonly applied to fresh leachate to eliminate heavy metals and non-degraded organic compounds.

Research on coagulation and flocculation processes has made significant progress in removing various pollutants and contaminants from wastewater [54]. However, several gaps remain to be addressed. For instance, the type and dosage of coagulants/flocculants significantly affect the treatment performance, and further investigation is required to optimize their selection and application [55]. Comparative study of different coagulants and flocculants for the treatment of stabilized landfill leachate highlights the need for a more comprehensive understanding of their mixing and synergistic effects [56]. Another area that requires attention is understanding the mechanisms of the coagulant-flocculant composite and its adsorption characteristics [57].

Many types of coagulants can be used for wastewater treatment, including metal-based coagulants (e.g., metal salts), synthetic coagulants, and biopolymer coagulants [42]. Examples of metal-based coagulants are aluminium sulphate and ferric chloride, which contain polymerized metal salts such as poly-aluminium chloride or aluminium chlorohydrate. Synthetic coagulants may act as flocculants depending on their formulation. On the other hand, biopolymer coagulants can be derived from natural sources, such as plants (lignin, tannin, and starch). According to [58], coagulants can be categorized into metallic salts, polymeric metallic salts, and polymers. Metallic salt coagulants can be divided into aluminium salts and iron salts. Meanwhile, polymers can be divided into natural and synthetic polymers. A specific list of coagulants for water and wastewater treatment is presented in Table 4.

The coagulant aid is added and combined with the main coagulant to optimize the coagulation process. Most often, coagulant aid is added to metallic coagulants as it provides favorable conditions for an efficient coagulation-flocculation process. The coagulant aid assists in accelerating clarity, improving flocs, boosting sludge settleability, lowering the costs of coagulant dose and treatment, offering a broader range of efficient pH, and increasing pollutant removal efficiency [60].

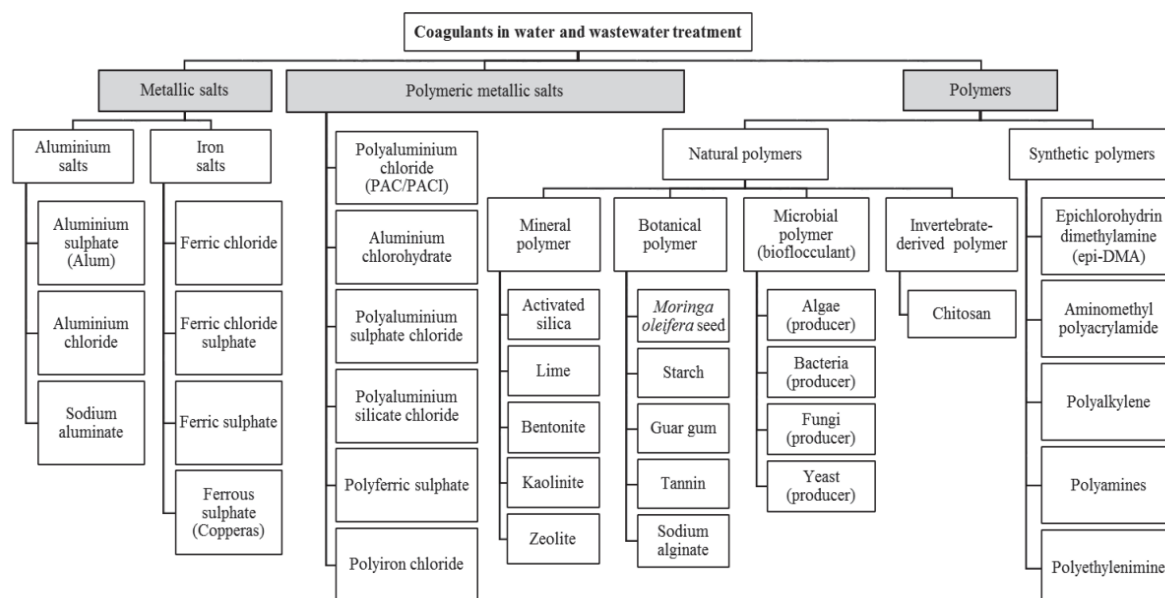


Figure 1. List of coagulants for wastewater treatment [59].

There are four types of standard coagulant aids: alkalinity substitutes, pH calibrators, polymers, and particulate additives [61]. The coagulant aid is categorized into two groups: molecular aggregation, where they act as primary coagulants and promote flocculation. It can also serve as a crystallizing agent and nucleation site to promote the formation of flocs.

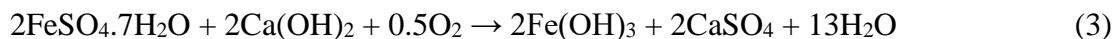
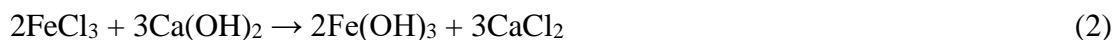
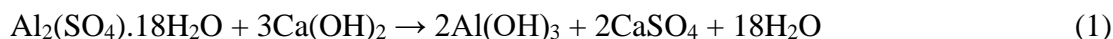
Environmentalists are exploring the potential of using ferrous sulphate heptahydrate ($\text{FeSO}_4 \times 7\text{H}_2\text{O}$) waste sustainably to protect the environment and reduce pollution. The use of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ residue has been studied as a portable water purifying agent, a reducing agent for hexavalent chromium, and a coagulant in municipal treatment plants [62]. Another study has shown that the $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ residue is an efficient coagulant for treating raw palm oil mill effluent (POME) and rubber effluent. Nevertheless, further research is needed on the use of $\text{FeSO}_4 \times 7\text{H}_2\text{O}$ residue as a possible and sustainable coagulant.

Moreover, ferrous sulphate also has a beneficial effect on bioelectricity generation, as increasing its concentration increases voltage output. This is because ferrous sulphate promotes the development and regeneration of microbial generation on the negative electrode, which boosts bioelectricity generation. Therefore, $\text{FeSO}_4 \times 7\text{H}_2\text{O}$ is introduced as an in-situ anodic coagulant for landfill leachate treatment [63]. The integration of physicochemical and biological methods has improved performance in coping with stabilized landfill leachate.

The reaction of water with calcium oxide will form calcium hydroxide, also known as slaked lime ($\text{Ca}(\text{OH})_2$) [54]. When combined with water, a small portion dissolves, forming lime water. Calcium hydroxide is used as an industrial alkali in mortars, plasters, and cement, and as a flocculant in wastewater treatment [64]. Lime is the most cost-effective coagulant studied. The coagulation process improves with an improvement in alkalinity. Lime is also a very strong pH enhancer [65]. Numerous studies have shown that lime is an effective means of removing wastewater colour [66].

There are three types of coagulants used with lime: aluminium sulphate (alum), ferric chloride, and ferrous sulphate for the coagulation-flocculation process [67]. As these coagulants hydrolyze in water during coagulation, gel-like hydroxides are formed. In addition, positively charged mononuclear and polynuclear species are formed. During charge neutralization, these positively charged molecules will interact with the negatively charged particles in wastewater. These hydroxides remove uncharged residues and charged colloidal

particles from wastewater during gravity settling. On the other hand, lime plays a critical role in flock production, improving clarity and greatly influencing the separation of liquids and solids. The chemical equations involved in this process are shown in Equations 1 to 3.



The addition of lime has shown a significant decrease in suspended solids and COD. However, the large quantity of sludge produced contributes to the disposal issue [68], which reported that the addition of lime to a ferrous sulphate solution resulted in a high rate of solids formation, known as iron hydroxides. This chemical combination also required a high quantity of raw materials and a high pH.

Polyelectrolytes are polymers with carboxyl, amino, or sulfonic functional groups. Their functional groups can be cationic (positive), anionic (negative), or amphoteric (both positive and negative). The most commonly used polyelectrolytes are synthetic polymers, such as polyacrylamide, polydiallyldimethylammonium chloride (poly-DADMAC), and polystyrene sulfonate. However, the use of polyacrylamides may produce acrylamide residues, which are genotoxic, neurotoxic, and carcinogenic [69]. These residues bring harm to the environment.

In addition, more affordable natural polymers, such as sodium alginate, moringa oleifera seed extract, starch, chitosan, and tannin, can be used as coagulant aids. Sodium alginate is specially adapted for use with ferric salts and may also be effective with alum. Meanwhile, Moringa oleifera seed and chitosan appear to increase settling time and reduce the coagulant dosage required. However, these natural polymers are less effective compared to synthetic polymers [69]. A detailed list of coagulant aids for water and wastewater treatment is shown in Table 5.

Table 5. List of synthetic polymers as coagulant aids [59].

| Types | Specific Names |
|-----------------------------|---|
| Synthetic cationic polymers | Polydiallyldimethyl ammonium chloride (poly-DADMAC) |
| | Polydimethyl, |
| | Aminomethyl, |
| | Polyacrylamide, |
| | Polyvinylbenzyl, |
| Synthetic neutral polymers | Trimethyl ammonium chloride |
| | Polyacrylamides, |
| Synthetic anionic polymer | Polyethylene oxide |
| | Anionic polymer, |
| | Hydrolysed polyacrylamides, |
| | Polystyrene sulfonate, |
| | Polyacrylic acid |
| | Polyacrylates |

5. Advanced Technologies for Landfill Leachate Treatment

5.1. Membrane technology.

Membrane technology is one of the most advanced treatment methods. It can be divided into several categories based on membrane pore size, including ultrafiltration (UF), microfiltration (MF), nanofiltration (NF), and reverse osmosis (RO) (Figure 1). Membrane technologies commonly used for landfill wastewater treatment are reverse osmosis, UF, and

NF. UF membranes are preferred due to their larger pore size compared to NF and RO, as well as their looser structure, which allows higher flux at lower operating pressures and lower operating costs [70].

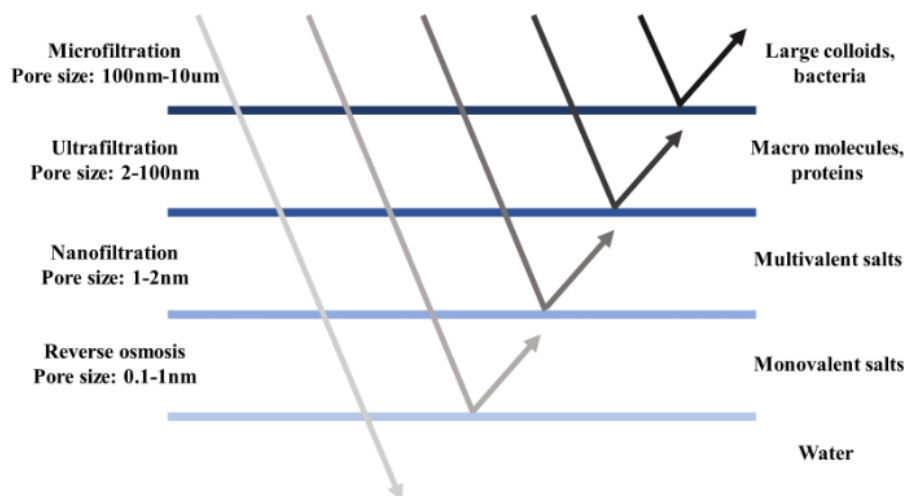


Figure 2. Classification of membranes for water purification in terms of pore size and retained species [71].

UF is a type of membrane filtration, where liquid is forced through a semi-permeable membrane by hydrostatic pressure. It is always used to remove materials with molecular weights between 1,000 and 1,000,000 Daltons. UF is frequently used for landfill leachate treatment, particularly as a pretreatment to biological treatment processes or RO, due to its effectiveness in removing contaminants from wastewater. In the UF process, water and low-molecular-weight solutes can pass through the membrane pore, while suspended solids and solutes with high molecular weight are trapped. Except for the molecular size it retains, UF is the same as conventional membrane filtration techniques. In general, the UF process exhibits significant efficacy in colour retention and removal of organic pollutants from landfill leachate with relatively high molecular weights. Due to its lower operating costs, UF is preferred for pretreatment in biological or other membrane processes, although it is less effective than NF and RO.

MF membrane is crucial in various industrial applications, particularly in water treatment and separation processes. This type of membrane is typically characterized by thickness, material composition, and performance in terms of fouling and filtration efficiency. Commercial ceramic MF membrane is known to have a thickness of about 10-20 μm [72]. Additionally, nanocellulose-based filtration membranes have attracted attention in industrial wastewater treatment for their efficiency and potential to address global water challenges [73]. Furthermore, the development of new ceramic MF membranes using locally available raw materials has shown promising results in removing bacteria such as *Escherichia coli* and *Staphylococcus aureus* [74].

NF displays the separation characteristics of RO and UF. The looser structure of the NF membrane, compared to the RO membrane, enables higher flux and lower operating pressure. Due to its lower packing density than that of a UF membrane, a NF membrane can filter small organic molecules with molecular weights as low as 200–300 Daltons [75]. For NF membranes, there are two methods of separation: steric exclusion, in which uncharged solutes are transported across the membrane by diffusion and convection driven by pressure differences and concentration gradients, respectively. Another separation method is the charging effect, in which an electrostatic interaction occurs between the component and the membrane for charged

components, as most NF membranes are primarily negatively charged [76]. As a result, NF membranes offer a flexible method for removing hard, non-biodegradable organic, inorganic, and heavy-metal pollutants from landfill leachate with high salt content.

Furthermore, RO, commonly referred to as hyperfiltration, is an energy-efficient, high-pressure membrane separation technique used to concentrate low-molecular-weight chemicals already present in solution or purified water. All solid and liquid suspensions can be concentrated using this technique. Ions, chemical molecules with oxygen and nitrogen, insecticides, and colloids smaller than 3.10 μm can all be separated using RO membranes [75]. Numerous studies have examined RO for leachate treatment, and the results indicate that RO is the most effective method for reducing COD. Furthermore, RO-based technology is also capable of removing heavy metals from leachate. Therefore, leachate can be effectively treated with RO.

5.2. Electrochemical oxidation.

Electrochemical oxidation techniques have been widely used to treat various wastewaters, disinfect drinking water, and improve polluted soil remediation. Electrochemical procedures are quite easy to use and can eliminate many undesirable pollutants before they reach the recipient aquatic environment. Since they use few or no chemicals for water treatment, they can also be considered green technology. The development of innovative electrode materials can greatly enhance treatment effectiveness. The method is relatively simple, in which oxidants are generated either directly on the electrode surface during treatment or indirectly from chemical compounds in the treated water [77]. Most contaminants in the electrolyte solution will lose stability and morphology through direct and indirect oxidation, leading to improved removal, as illustrated in Figure 3 [78].

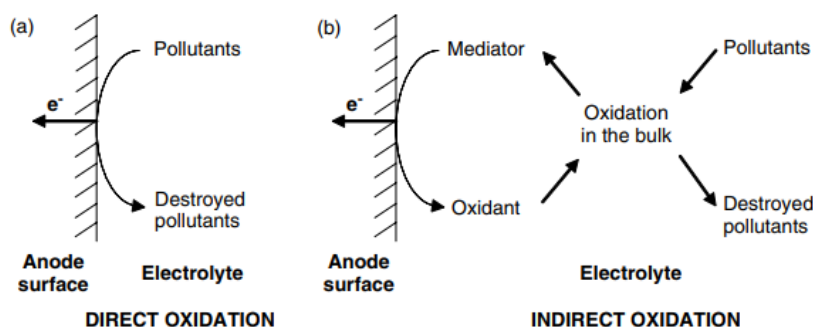
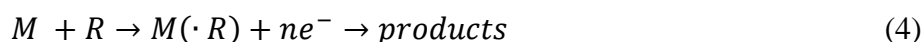


Figure 3. Schemes of (a) direct; (b) indirect electrolytic treatment of pollutants.

There are two steps in the degradation of organic matter through direct oxidation, as follows:

The anode surface absorbs contaminants that have been adsorbed and dispersed from the bulk solution.

Organic material is oxidized on the anode surface via a direct electron transfer reaction.



where R: organic compound and M: active site on the anode surface

Although the reaction rate relies on the composition of the anode material, the direct oxidation process is relatively slower, and the oxidation rate of pollutants is typically low. When some anodes, such as metal and metal oxide anodes, exhibit higher electricity with catalytic activity, the rate of electron transfer in the direct oxidation process will be faster.

However, when the electrode remains passive throughout the reaction, its electrocatalytic activity declines, thereby affecting the mass transfer rate of pollutants [79].

Indirect electrochemical oxidation involves the electrogeneration of a potent oxidising agent at the anode surface, which then oxidises contaminants in the bulk solution. Chlorine, which is created when chloride is oxidized at the anode, is probably the most prevalent electrochemical oxidant. Ammonia oxidation is typically considered to occur via this pathway, although the role of active chlorine in the oxidation of organic contaminants is unclear. Since chloride is present in wastewater and acts well, active chlorine is used extensively. Hydrogen peroxide, peroxodisulfuric acid ($H_2S_2O_8$), and ozone are frequent oxidants that can be created electrochemically [80].

5.3. Electrocoagulation.

Apart from membrane technology and electrochemical oxidation, electrocoagulation is also a method used for wastewater treatment. Electrocoagulation is an efficient method for treating water and wastewater, in which coagulants are generated on-site by electrolytic oxidation at a sacrificial anode. This technology significantly reduces sludge generation and, as a result, lowers sludge management costs, as pollutant removal is accomplished without the addition of chemicals [81]. Numerous advantages of electrocoagulation include compatibility, automation suitability, cost-effectiveness, energy efficiency, safety, and adaptability. Although electrocoagulation has garnered little scientific attention in the past few years, it has been widely utilized in recent years to treat diluted wastewaters containing heavy metals, organic matter from landfill leachate, suspended particles, and other contaminants [82].

Operating conditions for electrocoagulation are primarily determined by the aqueous medium's chemistry, particularly its conductivity and pH. Particle size, electrode type, retention time between plates, plate spacing, and chemical ingredient concentrations are other crucial parameters. The primary working principle is that the electrolytically generated cations from iron and/or aluminium anodes improve the coagulation of impurities from the aqueous medium. Positively charged particles tend to cluster near the cathode, and negatively charged particles near the anode during electrophoresis. Consumable metal anodes are employed to generate polyvalent metal cations in the anode region continually. Iron (Fe) and aluminium (Al) are two typical types of sacrificial anodes used in electrocoagulation [82].

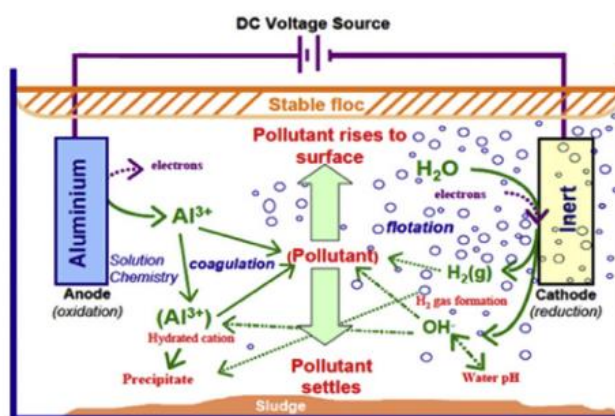


Figure 4. Interactions occurring within the electrocoagulation reactor.

At the anode, metal is oxidized into cations:



At the cathode, water is converted into hydrogen gas and hydroxyl anions.



In the equation above, Z is the number of electrons transferred in the anodic dissolution process per mole of metal. The most frequent result of metal cations released from the anode is the creation of metal hydroxides, which have poor solubility and precipitate easily. As a result, water-soluble pollutants may also chemically or physically adsorb onto the precipitates [83] by producing polyvalent cations from the oxidation of sacrificial anodes (Fe and Al) and from electrolysis gases, such as hydrogen, which evolves at the anode and oxygen, which evolves at the cathode (Figure 4). These cations neutralize the negative charge of particles transported towards the anodes. Depending on the pH of the water, the metal ions produced by electrochemical dissolution of a consumable anode undergo spontaneous hydrolysis, forming a variety of coagulant species, including hydroxide precipitates (capable of removing contaminants by adsorption/settling) and other ionic metal species [83].

5.4. Advanced oxidation processes (AOPs).

Advanced oxidation processes (AOPs) have been proven highly effective at degrading a wide range of organic and inorganic contaminants, including those commonly found in landfill leachate. AOPs are a group of treatment technologies that aim to efficiently decompose pollutants [84]. These processes involve the generation of highly reactive hydroxyl radicals to inactivate human pathogens [85]. AOPs are widely used to treat some organic pollutants that are difficult to remove due to their good treatment efficacy and short treatment cycles [86]. They can mineralize organic pollutants by generating highly reactive hydroxyl radicals. AOPs have been proven highly efficient at removing compounds and are among the processes capable of mineralizing a myriad of organic micropollutants or transforming them into easily biodegradable substances [87]. Additionally, these processes can be employed to degrade adsorbed organic pollutants, which simultaneously leads to regeneration. Treatment of contaminants of emerging concern by AOPs generates highly reactive, strong oxidants that rapidly mineralize pollutants, thereby reducing the formation of toxic by-products [88].

AOPs utilize the generation of reactive oxygen species, such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide anion radicals ($\text{O}_2\bullet^-$), which exhibit strong oxidation capabilities for wastewater treatment, including landfill leachate [89]. Hydroxyl radicals ($\bullet\text{OH}$) act as non-selective oxidants and can degrade compounds with complex chemical structures by hydrogen abstraction, electron transfer, and radical addition [90]. In AOPs, hydroxyl radicals ($\bullet\text{OH}$) are formed by the reaction of an oxidizing agent (hydrogen peroxide or ozone) with a reducing agent [91]. These hydroxyl radicals are highly reactive and effectively oxidize a wide range of organic and inorganic contaminants in leachate [92]. During hydroxyl radical formation, the reaction vessel is equipped with agitation and aeration systems to ensure efficient mixing and oxygenation of the leachate. The oxidation process breaks down complex pollutants into simpler, more biodegradable compounds. The high reactivity of hydroxyl radicals enables rapid degradation of various contaminants, including organic compounds, nitrogen, and pathogens, in leachate. After AOP treatment, the leachate undergoes post-treatment to remove residual ozone and remaining contaminants via aeration and filtration systems that effectively remove any remaining contaminants and ensure that the treated leachate meets the discharge standard requirements as illustrated in Figure 5. Various techniques, such as ozone, hydrogen peroxide, phytochemical and Fenton processes, are used as part of AOP-based leachate treatment.

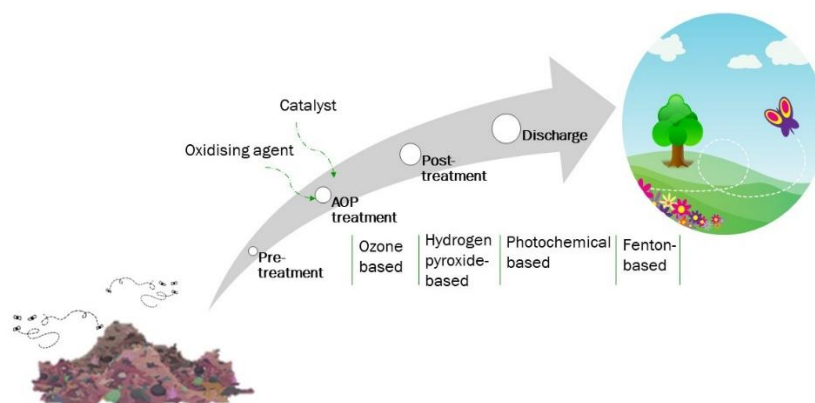
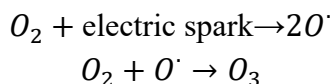


Figure 5. Process flow of advanced oxidation processes (AOPs) for landfill leachate treatment.

Ozone-based AOP uses ozone (O_3), a strong oxidant, to disinfect water and break down organic pollutants. Since ozone is an unstable gas, it is generated in situ using the corona discharge process in which high-voltage discharge is applied to a cold/dry gas phase containing oxygen (O_2 or air) as follows:



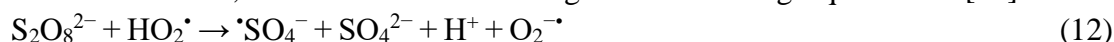
Then, ozone reacts with water to produce hydroxyl radicals as given in the following Equation 7 :



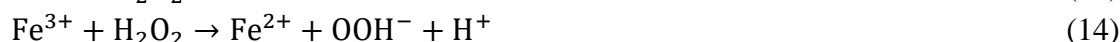
For hydrogen peroxide-based AOP, the reaction between hydrogen peroxide (H_2O_2) and catalysts, such as iron or other transition metals, generates hydroxyl radicals ($\cdot OH$) as shown in the following Equations 8 to 11:



From a previous study, the hydroxyl radicals generated enhanced the decolorization process due to the chemical reaction between the functional group of $-N=N$ in the azo dye contained in the leachate, which occurred according to the following Equation 12 [18]:



In Fenton-based AOPs, hydrogen peroxide is used and mixed with iron or other transition metals to generate hydroxyl radicals. Hydrogen peroxide is added to the leachate to initiate the Fenton reaction. The formation of hydroxyl radicals, as described in the equations below, occurs in acidic media, resulting in the decomposition of H_2O_2 into active oxygen species capable of oxidizing organic pollutants, for example, the oxidation of Fe^{2+} to Fe^{3+} :



According to a previous study, the use of chromium (Cr^{3+}) and H_2O_2 showed that up to 75% of total organic carbon and 99% of colour could be removed from synthetic dye effluent (Remazol Brilliant Violet 5R) within 30 min at a ratio of 1:30 and H_2O_2 dosage of 2.01 ml/L at pH 7. The AOPs offer significant advantages over conventional treatment methods for landfill leachate treatment; however, it is important to recognize their potential disadvantages, including sludge generation and by-product formation, as summarized in Table 6. Careful consideration of specific leachate characteristics and treatment objectives is critical for

selecting the most appropriate AOP for landfill leachate treatment. By evaluating the advantages and disadvantages of AOPs and aligning them with desired treatment outcomes, informed decisions can be made to address the complex challenges of landfill leachate management effectively.

Table 6. A comparison of advanced oxidation processes AOPs advantages and disadvantages for landfill leachate treatment [18, 93, 94].

| AOP-based technique | Advantage | Disadvantage |
|---|---|--|
| Ozone | | |
| O₃ + H₂O₂ O₃ + catalyst electro-peroxone | Sludge reduction Removal of recalcitrant organic contaminants High removal efficiency Fast response time | High cost of ozone generation Safety concerns Residual by-product Not selective Low utilization rate |
| Hydrogen peroxide | | |
| Alkaline- H₂O₂ process MW- H₂O₂ process Fe/MgO- H₂O₂ process | High removal efficiency Fast response time Ability to degrade a wide range of contaminants. H ₂ O ₂ readily available and inexpensive. | Safety concerns Not selective Residual by-products |
| Photochemical | | |
| UV + H₂O₂ UV + Cl₂ UV + O₃ UV + SO₄ UV+ catalyst | High removal efficiency Fast response time Ability to degrade a wide range of contaminants. Easily scaled up or down | Energy consumption Complexity Not selective |

5.5. Advantages and disadvantages of the leachate treatment technologies.

Table 7. A comparison of leachate treatment technologies' advantages and disadvantages for landfill leachate treatment [94].

| Leachate Treatment Technology | Advantages | Disadvantages |
|--------------------------------|--|--|
| Membrane Technology [95] | High Efficiency: Provides high levels of contaminant removal, including dissolved solids, bacteria, and viruses. Versatility: Can be used for various applications such as desalination, wastewater treatment, and industrial processes. Compact Size: Requires less space compared to conventional treatment methods. Scalability: Can be scaled up or down depending on the treatment needs. Minimal Chemical Use: Often requires fewer chemicals for operation and maintenance. | High Cost: Initial setup and operational costs can be high. Fouling and Scaling: Membranes can become clogged with contaminants, requiring regular cleaning and replacement. Energy Intensive: Some membrane processes, like reverse osmosis, require significant energy. Waste Concentrate: Produces a concentrated waste stream that requires proper disposal. Limited Lifespan: Membranes have a finite lifespan and need periodic replacement. |
| Electrochemical Oxidation [96] | Effective for Refractory Pollutants: Can degrade difficult-to-treat organic pollutants. No Chemical Addition: Does not require the addition of external chemicals. High Treatment Efficiency: Capable of achieving high levels of contaminant removal. Modularity: Systems can be easily scaled and customized. Environmentally Friendly: Produces fewer secondary pollutants. | High Energy Consumption: Requires significant electrical energy to operate. Electrode Wear: Electrodes can degrade over time, necessitating replacement. Cost: Initial installation and maintenance costs can be high. Complexity: Requires careful monitoring and control of operating conditions. Limited Applicability: It may not be suitable for all types of wastewater. |

| Leachate Treatment Technology | Advantages | Disadvantages |
|--|--|---|
| Electrocoagulation [97] | <p>Effective for a Wide Range of Pollutants: Can treat heavy metals, colloids, and organic pollutants.</p> <p>No Chemical Addition: Does not require chemical coagulants, reducing chemical handling and costs.</p> <p>Simple Operation: Relatively easy to operate and maintain.</p> <p>Sludge Reduction: Produces less sludge compared to conventional chemical coagulation.</p> <p>Environmentally Friendly: Generates minimal secondary pollution.</p> | <p>Electrode Wear: Electrodes corrode and need periodic replacement.</p> <p>Energy Consumption: Requires a consistent electrical power supply.</p> <p>Sludge Disposal: The sludge produced, although less, still requires proper disposal.</p> <p>Water Chemistry Sensitivity: Performance can be affected by the water chemistry, such as pH and conductivity.</p> <p>Scaling and Fouling: Electrodes can become scaled or fouled, affecting efficiency.</p> |
| Advanced Oxidation Processes (AOPs) [98] | <p>High Efficiency: Capable of degrading a wide range of organic contaminants and pathogens.</p> <p>No Residuals: produces no harmful residuals.</p> <p>Versatility: Can be applied to various types of wastewaters.</p> <p>Enhances Biodegradability: Can transform non-biodegradable compounds into biodegradable ones.</p> <p>Synergistic Effects: The combination of different oxidants can enhance treatment efficiency.</p> | <p>High Cost: Capital and operational costs can be high.</p> <p>Energy Intensive: Some processes, such as UV-based AOPs, require significant energy input.</p> <p>Complex Operation: Requires precise control and monitoring of operating conditions.</p> <p>Formation of By-products: Can generate harmful by-products if not properly managed.</p> <p>Chemical Handling: Requires careful handling and storage of chemicals like hydrogen peroxide and ozone. Advanced Oxidation Processes (AOPs)</p> |

6. Future Perspective

The future of leachate treatment technologies lies in developing more efficient, cost-effective, and sustainable processes. Innovations in materials, integration of renewable energy sources, and advancements in automation and control systems will play a crucial role in shaping the next generation of leachate treatment solutions. Collaboration among researchers, industry, and policymakers will be essential to address challenges and leverage opportunities in this field.

7. Conclusion

Open dumps and landfills remain common methods of MSW disposal, especially in developing countries, contributing to environmental pollution from landfill leachate and negatively impacting health. This review presents important insights into preventing contamination and protecting groundwater quality, which are crucial for waste management authorities seeking to control leachate production. The review also highlights the effectiveness of combining biological and physico-chemical methods for removing contaminants from leachate across different landfill ages. A multidisciplinary approach to wastewater system design promises to develop sustainable solutions. By integrating principles of sustainability, risk assessment, optimization, and decentralized systems, effective, environmentally friendly wastewater collection and treatment systems can be built. However, realizing these endeavours will require integrated, collaborative research to refine and implement these strategies on a larger scale, ensuring sustainable environmental benefits for future generations.

Author Contributions

Conceptualization, S.F.T.H.; methodology, M.H.C.H.; software, N.R.; validation, N.I.Y.; formal analysis, N.H.H.; investigation, W.M.H. and W.Y.; resources, A.W.M.; writing—original draft preparation, S.F.T.H.; writing—review and editing, S.F.T.H.; visualization, M.H.C.H.; supervision, S.H.; project administration, S.H.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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